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Creativity and innovation in STEAM education

Edited by
Weihua Niu, Weiping Hu and Li Cheng

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Creativity and innovation in STEAM education

Topic editors
Weihua Niu — Pace University, United States
Weiping Hu — Shaanxi Normal University, China
Li Cheng — Beijing Normal University, China

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EDITED BY
Ting-Chia Hsu,
National Taiwan Normal University, Taiwan

REVIEWED BY
Yu-Shan Chang,
National Taiwan Normal University, Taiwan

*CORRESPONDENCE
Weihua Niu
wniu@pace.edu

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Editorial: Creativity and innovation in STEAM education

Weihua Niu[1]* and Li Cheng[2,3]

[1]Pace University, New York, NY, United States, [2]Faculty of Education, Beijing Normal University, Beijing, China, [3]Developmental and Educational Research Center for Children's Creativity, FE, Beijing Normal University, Beijing, China

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creativity, innovation, STEAM competence, STEAM program, culture

Editorial on the Research Topic
Creativity and innovation in STEAM education

STEAM is an acronym for Science, Technology, Engineering, Arts, and Mathematics. The acronym STEM (Science, Technology, Engineering, and Mathematics) proceeds STEAM, was introduced in 2001 by scientific administrators at eh US National Science Foundation (NSF), replacing an old acronym SMET, referring to the career fields in disciplines such as Science, Technology, Engineering, and Mathematics (Hallinen, 2021). Soon, the acronym entered schools as STEM education, aiming to prepare students for entering STEM career fields that often lead to economic stability and upward social mobility. Educators and researchers quickly realized that humanity was missing in STEM education. The "A" was added to represent the art/humanities to emphasize the importance of integrating STEM and art into the curriculum (Conradty and Bogner, 2018; Mejias et al., 2021). A hallmark of the STEAM program is to engage students in inquiry-based learning and incorporate innovation and creativity into teaching. Since the introduction of STEAM, the STAEM-focused curriculum has become popular not only in the United States but also around the globe, including in Europe, Asia, and Australia.

This special issue includes 13 original studies, the majority from Chinese-speaking regions (i.e., nine from mainland China and two from Taiwan), exploring creativity and innovation in STEAM (Science, Technology, Engineering, Arts, and Mathematics) education, focusing on teaching innovation and creative outcomes for students. It provides a perspective outside the United States viewing STEAM education. This special issue may contribute to the literature on STEAM education in the following three areas.

First, how to evaluate the effectiveness of STEAM education; in other words, what is the primary goal of STEAM education?

To Chinese scholars, the primary goal of STEAM or STEM education is to cultivate critical competencies of students so that they may adapt to the future's flexible and complex social environment (Hu and Guo). Most contributors to this special issue pointed out creativity (Cheng et al.; Jia et al.; Park et al.; Ruan et al.; Sha et al.; Tran et al.; Xia et al.; Ngoc et al.) and critical thinking (Park et al.; Shen et al.) as two essential targeted skills for STEAM education. Cheng et al. argued that creativity should be measured at individual and group levels using a multi-method approach as a crucial STEAM competence. Jia et al. proposed that motivation, self-efficacy, and interdisciplinary knowledge acquisition can be considered STEAM competence, and

Liu et al. added subjective experiences, such as happiness, onto the list. Hu and Guo presented a model to illustrate STEAM competencies, including scientific thinking, inquiry practice, information literacy competencies, and attitudes and accountability in the STEAM area. They suggested using both formative and summative approaches to evaluate student STEM competencies.

Unlike Chinese scholars, Leroy and Romero argued that teachers' competencies, especially their awareness of the mindset and automatic engagement in creative activities, are essential in STEAM teaching. Teachers' creative competencies are equally critical to, if not more important than, students' competencies in STEAM education. This view represents a uniquely French perspective.

The second contribution of this special issue is the inclusion of studies exploring factors that affect the effectiveness of STEAM competencies. The first important factor is the creative environment the teacher sets up in classrooms. Hu and Guo advocated six criteria to evaluate effective STEM teaching: (1) setting up a learning situation, (2) asking student questions, (3) encouraging independent inquiry, (4) emphasizing cooperation, (5) encouraging summary and reflection in communication, and (6) promote consolidation and transfer of information.

The second factor is the teacher's characteristics. Leroy and Romero explored aspects that would effectively help teachers develop their creative competence (both divergent and convergent thinking). Besides assessing teachers' divergent and convert thinking, they asked participants to engage in self-reflection about their engagement in the creative activities and the difficulties they had in solving creative problems. They argue that teachers' automatic engagement in creative activities and willingness to overcome their conservative perspective can effectively predict their creative competencies. A short teacher training session allowing teachers to increase their awareness of the necessary prerequisite for the creative process could improve their creative competencies and subsequently enhance students' creativity. Accordingly, teachers must consider these factors when developing and delivering their courses.

The third factor is the students' experience. In a cross-cultural investigation, Park et al. explored how college experience affects the development of critical thinking and creativity. They found that whereas Chinese students outperform American students in measures of critical thinking, Americans outperform Chinese students in standards of creativity. They also demonstrate that having some college research experience (such as taking research method courses) could positively influence these two essential skills of students from the United States and China.

This special issue's third and final contribution showcases ten different STEAM programs outside the United States. These studies can be further grouped into three categories: short-term longitudinal studies, cross-sectional studies, and descriptive studies. Here, we would like to highlight four short-term longitudinal studies examining the effectiveness of STEAM-based curricula in science teaching.

Cheng et al. compared two pedagogical approaches: one adopting STEAM-based teaching (Integration of multiple disciples and inquiry-based learning) and the other a more traditional science teaching model (knowledge-based multidisciplinary education) regarding their effectiveness in science achievement, creative potential, and creative behaviors at both individual and group levels. In two 4th-grade science classrooms adopting one of the two distinct teaching approaches, students were expected to acquire skills in multiple disciplines, including physics, engineering, mathematics, music, and arts, and apply what they learned to complete a project: a musical instrument by the end of the 6-week intervention. Their results demonstrated the advantage of STEAM-based pedagogy over the traditional approach in creativity but science achievement.

Tran et al. recruited elementary school students from Taiwan and had them go through two stages of the science course: one traditional science course (learning concepts and principles in multiple disciples, including science, technology, engineering, and mathematics) and the other STEAM-based course (assembling installing and painting house-shaped money saving tube and engaging in inquiry-based learning), each stage lasted about 2 weeks. Half of the participants took the STEAM-based course first, then the traditional science course (the experimental condition), and the other half went in the opposite order (the control condition). Their results showed students from both conditions significantly improved their scientific creativity, especially the fluency and flexible scores.

Similarly, Ngoc et al. examined the effectiveness of a STEAM-based curriculum on junior high school students' scientific creativity. Like Tran et al., they also had all their participants go through the two-stage course with one group taking the STEAM-based course first, then the traditional science course (the experimental condition), and the other group in the opposite order (the control condition) with an end product of designing a gear wheel. Their results indicated that students benefited more from their scientific creativity in the experimental group than in the control condition.

In response to the global pandemic, universities must adapt online and offline teaching. Liu et al. use qualitative and quantitative methods to compare two teaching models: the industrial innovation and entrepreneurship talent cultivation (IIETC) model (combining online practical training from companies and theoretical guidance from professors) and the traditional teaching model (without online practical training). Their results demonstrate that ILETC positively impacts biology students' academic performance, self-evaluation of their future success, and overall happiness.

This special issue also includes four cross-sectional studies examining social conditions' influence on creativity. For example, priming multiple identities of high school students could enhance their creative performance (Ruan et al.). Emotional design in multimedia facilitates middle school students' appreciation and understanding of Chinese poetry (Wang et al.). Teachers' informative feedback could effectively improve college students' creativity in 3D printing technology (Shen et al.). Design training improves students' ability to generate ideas but does not improve their ability to evaluate the usefulness of these ideas (Xia et al.).

The last category of the STEAM programs includes two descriptive studies. Jia et al. demonstrated that an integrated design STEAM course could promote elementary school students' motivation, self-efficacy, and acquisition of interdisciplinary knowledge. Sha et al. showed that students' engagement in STEAM courses positively influenced critical thinking.

Overall, this special issue provides a unique perspective from scholars outside the United States on the definition of STEAM competencies, influencing factors on STEAM education, and a sample of different STEAM programs in promoting STEAM competencies, which could shed some light on the current status of STEAM education and the role of creativity and innovation in STEAM education.

Author contributions

Both authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Teachers' Creative Behaviors in STEAM Activities With Modular Robotics

*Anaïs Leroy** and *Margarida Romero*

Laboratoire d'Innovation et Numérique pour l'Education (LINE), Université Côte d'Azur, Nice, France

As STEAM activities require both the teachers and learners to be creative, it is important to train teachers to instruct and guide creativity not only when students begin a task, but also throughout its entire process persistently to maintain creative behaviors. To assess the creative process in teacher education, a currently limited topic within the literature, we examined 37 in-service teachers, who were participating in a creative pedagogy course, through a divergent creativity test (Alternative Uses Test) and a CreaCube task (a creative problem-solving task involving modular robotics). We used CreaCube as a digital manipulative task that was performed twice to ensure the creative assessment's authenticity in relation to STEAM education. In the second execution, the participants did not know whether they had to reproduce the same solution or find a new one. Our results show that only a quarter of the teachers proposed new solutions during the task repetition, and that this conservative and repetitive behavior increased the task completion speed. However, this suggests that even in the context of creative pedagogy courses, teachers' tendencies to prioritize speed and the application of existing solutions tendency remains a barrier to engaging in more creative behaviors that require inhibiting previous solutions and exploring new ideas. This study sheds light on the importance of teachers experimenting with this conservative behavior bias during their training and the significance of persistently applying creative behaviors in STEAM activities. Accordingly, it is essential that teachers consider these factors when developing and delivering their courses.

Keywords: creativity, maker education, teacher education, steam, modular robotics

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Edited by:
Weihua Niu,
Pace University, United States

Reviewed by:
Matthew Ryan Lavery,
South Carolina Education Oversight Committee, United States
Macarena-Paz Celume,
Université de Paris, France

****Correspondence:***
Anaïs Leroy
anais.leroy@univ-cotedazur.fr

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INTRODUCTION

As the world is rapidly changing and evolving, its citizens must prepare themselves to work in currently unknown positions, and solve many new environmental, economic, and social problems (World Economic Forum, 2020). As such, 21st century competencies such as creativity aim to develop citizen and professional opportunities in uncertain contexts (Beghetto, 2019), a goal that has increased in importance since the COVID-19 pandemic. In this context, it is crucial for students to develop their creative competency, as they are linked to transversal competencies that are considered essential for today's citizenship (Bicer et al., 2019; Kim and Choi, 2019). Creativity refers to the ability to produce new and appropriate ideas or products through different cognitive process such as divergent thinking and convergent thinking (Sternberg and Lubart, 1995). Creativity is required to solve complex problems by combining divergent thinking (idea generation) as well as convergent thinking (selecting ideas) and persevere by developing concrete outcomes (Grohman et al., 2017; Lille and Romero, 2017). Creativity engages a higher level of learning and comprehension than other non-creative activities, as it involves planning a main solution and developing new options by suppressing previous processes, all functions of high cognition that are primordial in the learning and development of metacognition (Benedek et al., 2012). As noted in Bloom's revised taxonomy (Krathwohl et al., 2002), this cognitive process involves according to different skills that partly follow a progression in the complexity of the underlying brain processes such as understand, apply, analyze, evaluate, and create. In education, teachers' creativity can support learners' creativity development (Davies et al., 2014). Teachers can develop their ability to support learners' creativity and innovation potentials. Creativity is not only an individual potential but can be developed as group creativity (Nijstad and de Dreu, 2002). Through group creativity children can develop their capacity to solve complex problems (Sawyer, 2006). In other words, teachers' creativity can support learners' creativity, which will be observed by their capacity to generate new and useful ideas (Runco, 2004) and artefacts (Lille and Romero, 2017).

To be competitive, learners must not only apply a program or a method, but also understand the functions of the used materials and create new uses for them for the purpose of innovation (Davies et al., 2013). In this context, the traditional approach of learning, focusing on memorization and repetition, might impede the development of creativity in educational contexts (Kaila, 2005; Azzam, 2009). Repetition is indeed essential for memorization, the basis of learning (Krathwohl et al., 2002), but learners must also be able to combine academic and general knowledge and challenge themselves to test new possibilities (Sun et al., 2020). These different learning approaches could also be related to the dual process models opposing two cognitive systems (Kahneman, 2011; Houdé and Borst, 2014): a fast and automatic processing, mainly based on prior knowledge (the "conservative" one), and a more effortful, controlled processing system (here the "creative" one).

For several years, researchers and practitioners have placed an emphasis on the need to develop these transversal competences, but the integration of creativity in pedagogical programs is not yet well-defined and differs depending on countries (Shaheen, 2010). For a successful integration, teachers must have the proper training to teach creativity and create learning activities allowing their learners to develop their creativity. In the short term, including creative learning activities into the classroom can reduce drop out rates and lack of interest in certain school subjects, such as science and mathematics (Falls, 2020). In the long term, creative learning activities can develop transversal competencies aiming to increase employment opportunities and inclusivity in STEM careers (Daker et al., 2020).

Based on these factors, it becomes essential to address several gaps. Firstly, some teachers may be very creative in their daily lives and hobbies but remain rooted in a traditional vision of teaching that focuses on learning approaches based on memorization and repetition (Runco et al., 2017). In fact, despite the importance of creativity in today's citizenship, teacher education's instructions on teacher creativity are applied in different ways depending on the teacher competency frameworks worldwide. As Kaufman et al. (2017) noted, creativity is domain dependent. Thus, the traditional teaching approaches based on memorization and repetition does not support a creative pedagogy context in which the learners can develop transversal competencies (Dorier and García, 2013).

To support learners' creativity skills, as a form of problem solving (Treffinger and Isaksen, 2005), different learning activities have been introduced under the umbrella of STEAM. The recent integration of the "A" (Arts) in Science, Technology, Engineering, Arts, and Mathematics (STEAM) education highlighted the need for developing arts and humanities, as well as creativity, in school programs. In fact, the arts incorporate different competencies that improve learners' motivation, heighten their interests in the sciences, and develop their critical thinking and innovation (Conradty et al., 2020). Moreover, Card and Payne (2020) support the integration of the creative and humanistic side of the A in STEAM to develop girls' interests in technological domains and attempting to limit the disproportionate gender distribution in scientific and digital professions. Furthermore, we should consider socioeconomic gaps in digital literacy. To address these educational challenges, STEAM learning activities could support the creativity competency while developing the digital literacy in creative learning activities (Romero et al., 2017).

In Malaysia, creative mathematics teaching aims to contribute to the objectives of the Program for International Student Assessment and Trends in Mathematics and Science Study but requires establishing a new approach to develop teachers' creative behaviors (Mariani and Ismail, 2015). In France, the 2018 competency frameworks of the primary and secondary education curricula integrated problem-solving skills and creativity, as transversal competencies. To guide learners in this process and regulate their own creativity, teachers should develop an awareness of this competence by combining existing knowledge to foster thought and create new learning and regulatory activities to support the learning objectives (Reilly et al., 2011; Cassone et al., 2020). They can support creativity and teach ways to creatively solve problems using digital technologies to increase the potential affordances and alternative uses for the available tools (Harris and de Bruin, 2018). However, most tests created to evaluate creativity are based on the individual measure of divergent thinking using familiar objects, but creativity also involves convergent thinking processes, especially when creating a physical artefact, as seen in maker education activities, such as educational robotics (Riikonen et al., 2020). Thus, to support the development of creativity competency through STEAM education, we must guide learners' divergent and convergent thinking processes, establish strategies to create solutions using technological materials, and develop students' critical thinking to help them understand how to not only use a certain technology, but also create something new with it.

As such, our study analyzes the cognitive modes in teacher education and identify the required factors that would effectively help teachers develop their creative competency, beyond unitary interventions (Romero et al., 2019). Specifically, we examined teachers in continuing education, who voluntarily enrolled in a creativity course, and analyzed their divergent thinking through the Alternative Uses Test (AUT) and their convergent thinking with CreaCube (problem-solving task that was identically repeated twice). We hypothesize that, despite the course's focus

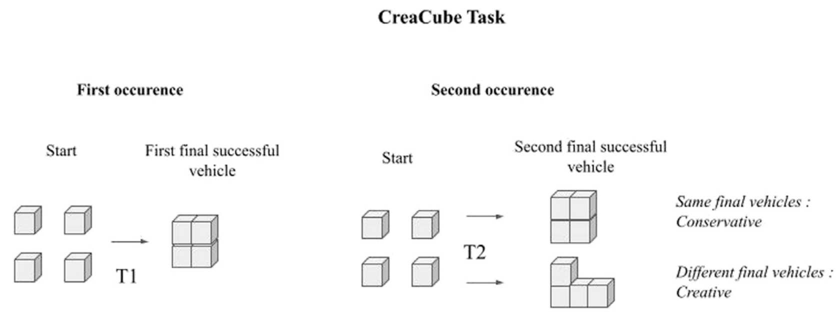

FIGURE 1 | The two stages of the CreaCube task.

on creativity and the study's initial divergent thinking test, most of the participating teachers will offer the same solution for the repeated CreaCube tasks, regardless of their AUT accomplishments. Thus, we believe that the default cognitive mode is conservative, as our teaching and learning habits are to repeat the same memorized solution to solve a task. Inhibiting this default mode is difficult, and teachers must have a certain awareness of this tendency to think and teach differently (i.e., corresponding to meta-cognitive knowledge in the Revised Taxonomy of Krathwol, 2002). As such, we first evaluate the teachers' behavioral profiles, termed conservative if they repeat the same solution or creative if they try to find a new one. Then, we explore if their behavioral profiles are linked to their creative profiles (AUT), the time required to complete the CreaCube tasks, or their cognitive profiles (their understanding of the second instruction).

MATERIALS AND METHODS

Participants

Our final sample included 37 primary education teachers in their third year of teaching who were participating in a continuous education training course on the creative uses of digital technologies. They all provided informed consent and voluntarily participated in this study (Mean age = 33.1; SD = 6.8; 32 females). This study was approved by the Comité d'Éthique pour les Recherches non-Interventionnelles (ethics committee) of the Université Côte d'Azur in France.

Materials

Alternative Use Test

In this divergent creativity test, the participants had to write multiple ideas for using three familiar objects (a box, can, and chair) and we allocated 2 min for each object (total duration = 6 min). This task allowed us to assess creativity in terms of fluency (total number of differing ideas), flexibility (number of different categories), and originality (responses given by less than 5% of all participants, determined through answer comparisons). For example, with regards to using a box, if a participant responded with "I can use it to store clothes and shoes, and to create a robot costume," he/she will receive three points for fluency (three different answers) and two points for flexibility ("storing" clothes and shoes are the same category). Finally, as in other study (Radel et al., 2015) we scored one point for each answer, and then summed and averaged the scores for each of the three components and each participant.

The CreaCube Task: Modular Robotics

The CreaCube task (Romero et al., 2018) is a problem-solving task that uses a manipulative robotic cube from the Cubelets Modular Robotic set (https://www.modrobotics.com/cubelets/). It requires participants to create a vehicle that could move by itself from one point to another with the use of four cubes, chosen for their different affordances (technological and material). Before starting the activity, the examiner explained that the participants' hands would be filmed (informed consent provided). There were no time constraints and although the participants did not receive any help, they were free to listen to the recorded instructions as much as they wished: "build an autonomous vehicle that moves from a starting red point to the finishing black point." As these cubes are generally unfamiliar objects, the participants must explore them and try different associations to resolve the task. Each cube has its own characteristics (i.e., wheels, sensor, battery, or inverter) and the way the cubes are connected can help or impede the task's resolution. The different associations create different "configurations," meaning different global forms (**Figure 1**), and some are successful, while others are not, due to, for example, imbalances or poor technological connections. A total of 12 successful configurations are possible, the number of functional combinations is thus limited, which makes it possible to study their frequency of occurrence but remains large enough to allow participants to explore different solutions. We asked the participants to resolve this CreaCube task twice: once the first endeavor was finished (A1), we situated the cubes in the same position as in the beginning of the first activity and with we gave the same instructions, without commenting or disclosing any further information. Therefore, participants were free to decide if they wanted to be creative and attempt a new solution (find a new successful configuration for resolving the task), or be conservative and resolve the task with the same configuration. Then, we noted if the second final successful vehicle was the same as or different from the first, and recorded the time needed to resolve the first and second CreaCube tasks. Notice that they were no timer, the time was recorded during the viewing of the videos in order not to put any time pressure on the task. If a time pressure can be observed in the participants, it comes from the time felt, perceived by the participants themselves without any external reference.

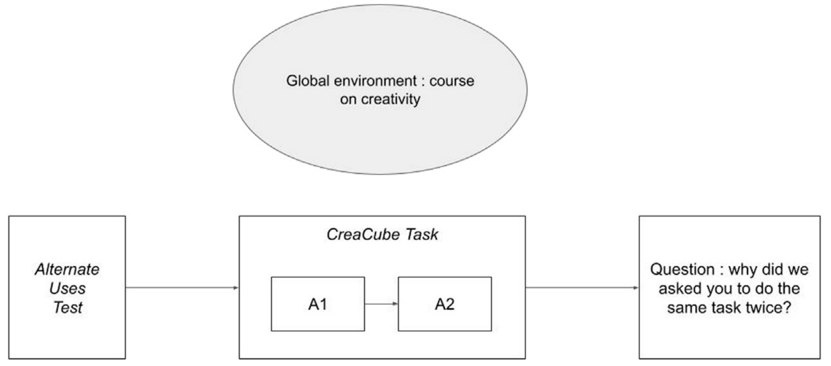

FIGURE 2 | Protocol progress.

TABLE 1 | Correlation scores between the AUT task component, behavioral profiles (CreaCube task-creative or conservative), and cognitive profiles (answers to why the CreaCube activity was repeated).

		AUT_Fluidity	AUT_Flexibility	AUT_Originality	Behavioral profile
AUT_Fluidity	Pearson's r	—			
	p-value	—			
AUT_Flexibility	Pearson's r	0.777	—		
	p-value	< .001***	—		
AUT_Originality	Pearson's r	0.484	0.400	—	
	p-value	0.002**	0.014*	—	
Behavioral Profile	Pearson's r	0.042	0.078	0.001	—
	p-value	0.805	0.647	0.996	—
Cognitive Profile	Pearson's r	-0.012	0.127	0.102	0.379
	p-value	0.945	0.452	0.549	0.021

Procedure

The tests had taken place during a course on the creative uses of digital technology. The participants of this course were proposed to participate in a study on creativity without explaining further at this stage the objectives of this research. the participants were free to refuse to participate in the study and have the possibility to refuse to have their data recorded and used in the study. We proposed the first task, the AUT (**Figure 2**), to all the participants at the same time and in the same space, but they had to complete it individually. Once the AUT was finished, each participant individually resolved the CreaCube problem-solving task outside the classroom. Participants can do the task without any time restriction and are not aware of the time they engage in the task. Once the two CreaCube activities were finished, the experimenter asked verbally to the participants to answer the following questions: "in your opinion, why did we ask you to complete the same task twice?" and "what were your main difficulties to resolve the task?". The experimenter transcribed the participants answers. It is important to keep in mind that we conducted the study during a training course on digital creativity, therefore the participants were in a context directly related to creativity and thus to the test task.

Data Analysis

In order to test our hypothesis, we analyzed different data: 1) the scores for the different AUT components, examining fluidity, flexibility, and originality (creative profile); 2) CreaCube task repetition comprehension (cognitive profile), 3) the time required to finish the first and second CreaCube tasks, establishing the "time optimization" variable (the second activity's duration minus the first activity's duration); and 4) the creative or conservative categorizations, based on the differences or similarities between the two CreaCube vehicles (behavioral profile). Then, we determined if the behavioral profiles were linked to the creative profiles, to the time optimization variable, and/or to the cognitive profiles.

RESULTS

We conducted all statistical and graphical analyses with an open source statistical analysis program: Jamovi (version 1.1.9).

Realization of the CreaCube Tasks

Most participants had the same configurations for the first and second CreaCube task vehicles (27 participants), with only 10 proposing a new solution. We found correlations between the CreaCube solution methods (behavioral profiles-creative or conservative), the AUT scores, and the final question answers (cognitive profiles) (**Table 1**). However, there was no relationship between the AUT's creativity

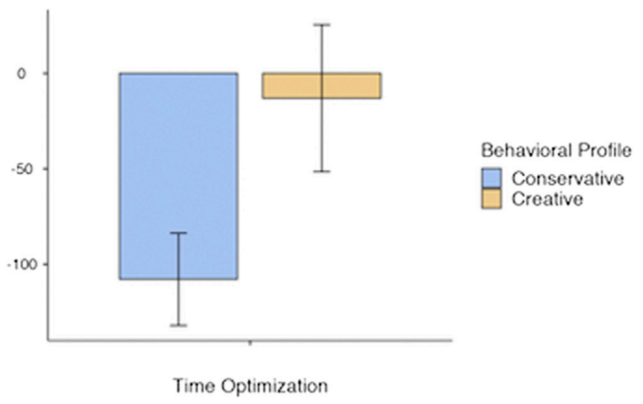

FIGURE 3 | Mean average score of time optimization considering participants' behavior profiles.

evaluations and the CreaCube's creative behaviors (all $r < 0.1$; all $p \geq 0.647$).

Differences in the Duration of the Second CreaCube Task Compared to the First

We verified that the time optimization variable was normally distributed (Shapiro-Wilk test), and as this was not the case ($p < 0.001$), we used non-parametric tests. We ran a Kruskal-Wallis test with behavioral profile as the fixed factor and time optimization as the dependent variable, finding a significant time difference between the two CreaCube activities, χ^2 (1,36) = 5,57; p = 0.018. As expected, the conservative participants needed less time to successfully complete the second activity, compared to the first (108 s on average +/−24; **Figure 3**), while the creative participants' time variations between the two tasks were minimal (−13 s on average, SE: 35). We also found a similar exerted effort when the participants were creative during the second activity.

Answers Regarding the CreaCube Activity's Repetition

The participants proposed two general answers: the second activity serves to determine if participants have correctly memorized how to resolve the task (15 participants) or to explore if they can find a new way to resolve problem (22 participants). These answers match the conservative and creative cognitive profiles, respectively. As seen in **Table 1**, we found a significant correlation between the cognitive and behavioral profiles. Indeed, all the participants showing conservative behaviors answered that the reason for the repetition was to test their memorization. Within those who answered that the repetition was to show if they could find a new solution, almost half created a new vehicle (10 participants), but the other 12 participants offered the same solution a second time (**Figure 4**), suggesting that in addition to creative intentions, creative execution requires other competencies.

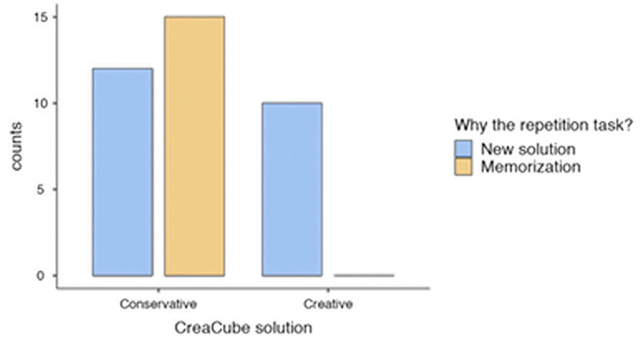

FIGURE 4 | Proportion of participants with regards to CreaCube task solutions and why the task was repeated.

DISCUSSION

Initial Conservative Bias and Hindrances to Creativity

Overall, the results of this study show that only one quarter of the participants, approximately, solved the second identical task in a creative way by proposing a new solution, and most simply replicated the first solution. The results also reveal that the attitude with which an activity is approached influences its realization. Although the course the participants were taking focused on creativity, more than 40% believed that asking them to resolve the task a second time was meant to test their memorization. Despite being on a creativity course, the memorization hypothesis for the task repetition shows an important number of participants to lack a creative opportunity for the task repetition. This conservative cognitive profile is linked to traditional visions of teaching (i.e., learning by repetition, memory), but trying new solutions allows for more exploration, expands understandings of the used materials, and promotes critical thinking. The results of this study also show that the conservative's participants spend less time for the repetition of the CreaCube task although the creative ones need approximatively the same time to resolve the task with a new solution. Therefore, it's seems that to be creative, one must go further than simply remembering and reproducing the initial steps or the effortless way to address a problem. In the context of this study, it is necessary to really understand the features of the robotic cubes, how their relative positions affect the configuration, and what aspects (e.g., balance, direction of the wheels, etc.) must be considered to successfully complete the task. It is important to remember that the teachers chose to attend a course on creativity, among the various training topics offered by the in-service training program including other domain-specific courses in mathematics and language. Thus, we can assume that they already understood the importance of developing creativity competency among their learners. The in-service teachers were engaged in a full day of creative learning activities engaging different uses of technologies. Despite the in-service teachers selected the creative pedagogy course, the majority repeated the same solution, highlighting the creative hindrance issues.

The teachers' feedback at the end of the study revealed that those who tried to reproduce the first vehicle from memory were indeed performance oriented, but they also described an initial fear of not being able to find a new solution, because they did not feel confident in their logical thinking abilities or competent in manual activities. Some of the teachers also reported that the social pressure of under-performing in terms of problem-solving speed and overall failure inhibited their creativity when repeating the task. Finally, the participants who answered that the repetition of the task was made to observe if they managed to build a new vehicle but who proposed in the end the same solution as in the first occurrence of the task, tried to find a new solution, they spent time on it and after a while decided to come back on their first solution. The pressure of being too slow and not succeeding rapidly to solve in a new way the second repetition of the task, made them abandon their creative will to return to a more conservative, simpler, already known behaviour.

This brings us to an important point: even when teachers see a task repetition as an opportunity to be creative, we need to encourage them to persevere. There is a need to encourage and strengthen teachers' creativity to support learners' creativity. Creative competence requires one to take the time to test other solutions, instead of quickly repeating the known solution, and to overcome the fear of failure and the self-efficacy threats that some teachers experience when facing problem-solving tasks with unknown technologies.

To go further than the direct applications of this study, another important point involves the link between creativity and different disciplines, especially in interdisciplinary projects. To remove creativity's previous restriction to the artistic domains, we must also develop creative approaches in science and technology activities, or even in interdisciplinary STEAM activities. In other words, to overcome the traditional dichotomy between the scientific and artistic domains, we must underline the creative processes, engaging divergent and convergent thinking, that appear in different domains. In this study, the participants proposed many different ideas (divergent thinking) when writing about the different uses of familiar objects (AUT), but when solving the same problem twice, the majority repeated the same solution. This result suggests a restrictive view of task or domain specific for creativity, means that in this particular task the participant could give lot of different and non-usual answers but in a more logical, technological or more "academic" domain I stay in a classical, repetitive solution. Indeed, this highlight the need to change this mindset of speed and repetition that emerges in classical teaching. Only by overcoming this mindset can we be able to engage in creative activities with a perspective that will contribute to developing more creative competencies in the different disciplines required for citizens and professionals living in today's society (European Commission, 2017).

How to Teach Creativity

It seems that to teach creativity, teachers must overcome their performance orientation to engage in task repetitions as an opportunity to be creative. Instead, repetition with an intentional focus on novel solutions and creative exploration is needed to overcome performance orientation. Thus, it is necessary to guide them in this transformative professional development and help them first develop their own creative competencies. Supporting teachers in overcoming their temporal performance orientations and their fears related to technology can contribute to the development of new approaches that would support teachers' acquisitions of creative competency through long-term mindset adjustments. In this sense, the results of our study are aligned with (Beghetto and Kaufman, 2014) practical insights, including the need to integrate creativity in all learning activities during the entire year, instead of only teaching it as a specific activity. In other words, creativity competence development for learners of all ages, including pre-service and in-service teachers, should be developed through long term interventions that embrace a creative pedagogy, instead of specific creativity tasks. Ironically, it is by repeating creative activities, but crucially with an intentional focus on the research of novelty, creativity, that we will be able to overcome the conservative perspective of repetition for memorization and learning that is still predominant in worldwide educational practices (Sawyer, 2019). Additionally, teachers can design STEAM activities to support the development of learners' creativity in different disciplinary domains (Craft, 2005). They can create interdisciplinary learning activities that would help students improve their capacities to solve complex problems that require an integrative interdisciplinary approach, such as sustainable development goals or other societal challenges in today's society.

To conclude, our objective was to focus on the effects of an short and easy to implement (few materials needed) training session that allows teachers to increase their awareness of the necessary prerequisites for the creative process. Therefore, one of the strengths of this study is that the participants directly experienced the difficulties in acquiring a creative mindset, and this direct experience can not only enhance the learning process (Stull et al., 2018; Castro-Alonso et al., 2019; Kubik et al., 2020), but also improve creativity itself (for a review; Frith et al., 2019). By directly engaging in the CreaCube activity, teachers' awareness on the conservative behavior bias will increase and allow them to make changes in their teaching, especially with regards to improving divergent thinking, testing new solutions (Beghetto, 2010; Beghetto and Kaufman, 2014), and going beyond memorization through exact repetition. Future studies should aim to advance in the confirmation of these results within different modalities of the CreaCube task but also with other STEAM tasks aiming to engage participants in the development of their creativity.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Comité d'Ethique pour les Recherches Non

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AUTHOR CONTRIBUTIONS

AL and MR conceived the study, the theoretical framework and methodology. MR directed the project and task protocol. AL carried out the data collection and performed the data analysis.

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The Effects of Emotional Design on Multimedia Learning and Appreciation of Chinese Poetry

Yi Wang[1,2], Zhijin Zhou[1,2], Shaoying Gong[1,2]*, Dandan Jia[1,2] and Jing Lei[3]*

[1] Key Laboratory of Adolescent Cyberpsychology and Behavior (Central China Normal University), Ministry of Education, Wuhan, China, [2] School of Psychology, Central China Normal University, Wuhan, China, [3] Dengzhou No. 1 Middle School, Dengzhou, China

Painting, music, literature, and other art forms embody the essence of human wisdom and induce esthetic experience, among which poetry is inherently creative, because it contains a wealth of symbols, imageries, insights, and so forth. The appreciation and learning of Chinese poetry is an important part of the curriculum in secondary schools. However, studies have mainly focused on textual characters of poetry, with little literature focusing on esthetic appreciation and in-depth learning of poetry. In this vein, we ask whether emotional designs will promote the appreciation and learning of Chinese poetry. To answer this question, we explored the influence of the combination of external emotion induction (positive and neutral movie clips) and internal colorful design (chromatic and achromatic) on esthetic preference and learning of poetry. One hundred and sixty-six participants (14–15 years old) were randomly assigned to one of four conditions created by two factors (external emotion induction and internal colorful design). The results showed that the combination of external emotion induction and internal colorful design promoted positive emotions, retention, and transfer performances of learners. Furthermore, perceived difficulty of learners decreased significantly when external emotional induction and internal colorful design were both positive. Consequently, these findings indicated that emotional designs in multimedia facilitated the learning performance of middle school students in Chinese poetry, and supported the cognitive-affective theory of learning with media. This research was a preliminary exploration of emotional design in humanities.

Keywords: emotional design, emotion induction, appreciation of chinese poetry, positive emotions, cognitive affective theory of learning with media (CATLM)

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Edited by:
Weiping Hu,
Shaanxi Normal University, China

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Linshu Zhou,
Shanghai Normal University, China
Jiumin Yang,
Central China Normal University, China
Vanessa Era,
Sapienza University of Rome, Italy

****Correspondence:***
Zhijin Zhou
zhouzj@mail.ccnu.edu.cn
Shaoying Gong
gongsy@mail.ccnu.edu.cn

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INTRODUCTION

The crystallization of human wisdom, paintings, music, literature, and other art forms can induce esthetic experiences in people. Poetry, which contains abundant symbols, icons, and imageries, is a creative language and an indispensable form of literature. In the current literature, studies have focused more on the superficial textual characters of poetry, such as rhyme (Jacobs, 2015), and its influence on poetry appreciation. Rhyme of poems in different languages, such as Chinese (Chen et al., 2016; Chen and Yang, 2017), English (Xue et al., 2019), German (Obermeier et al., 2013; Lüdtke et al., 2014), and Spanish (Navarro-Colorado, 2018), has received extensive attention from researchers. However, less attention has been directed to the esthetic appreciation and in-depth learning of poetry in multimedia learning classrooms. To fill this gap, we investigated the impact of emotional designs in the multimedia environment on the appreciation and learning of Chinese poetry, which belongs to liberal education.

The Rhythm of Chinese Poetry and Its Impacts on Appreciation

The current empirical research on Chinese poetry mainly focuses on the congruency of rhyme and its expectation effect, and indicates that the rhyming effect works throughout the reading process of Chinese poetry. Specifically, top-down expectations about the rhyme scheme modulated early phonological coding of Chinese characters and semantic access thereafter (Chen et al., 2016; Chen and Yang, 2017). In addition, the perception of rhyme does not seem to be influenced by relevant experiences: poetry is the spoken form of music songs. Although subjects who have been trained in music for years can process rhyme in Chinese poetry more quickly (Zhang et al., 2020), pupils in primary schools have acquired rhythm information on a Chinese poem (e.g., coherent repetition, stress pattern) implicitly (Li et al., 2009).

Moreover, rhyming and regular metered poetry can promote the esthetic appreciation of Chinese poetry (Gao and Guo, 2018). Gao and Guo (2018) employed *QiJue*, which is characterized by strict rhyme schemes and constitutes a well-structured prosodic hierarchy in accordance with the features of ancient Chinese poetry, and examined the mechanism of appreciation of beauty of Chinese poetry. They found that, compared with reading prose, appreciating *QiJue* promoted the activation of the bilateral insula and the left inferior orbitofrontal cortex, which plays a significant role in the neural basis of esthetic appreciation.

Impacts of Other Factors on Poetry Appreciation

Rhythm may only be one of the influential factors affecting the esthetic appreciation of poetry. Besides rhythm, other features in poetry, such as e key emotional tonality and motifs (or themes), can impact esthetics as well. To illustrate, Kraxenberger and Menninghaus (2017) asked adult participants to respond to two self-reported items ("How beautifully is the poem written?" and "How much do you like this poem?") to evaluate the esthetic appreciation of poems with different emotional tonalities. They found that, compared with happy poems, the subjects had higher esthetic appreciation toward sad poems. Regarding the influence of motifs on poetic esthetic appreciation, Lüdtke et al. (2014) investigated the esthetic appreciation of four different themes (morning, space, stillness, and city). Three self-reported items were completed by readers to evaluate poems from three different aspects: beauty, affection (liking), and attractiveness (wanting). The results indicated that the stillness-themed poems [Tieck's "Im Windsgeräusch, in stiller Nacht," 1796 (The Sound of Wind in the Silent Night)] evoked significantly higher esthetic appreciation than other themes.

In sum, the current literature mainly examines influences of surface features of poetry, such as rhythm, emotional tonality, and motif, on the appreciation of poetry. However, few studies have focused on the deep comprehension of poetry texts and their transfer applications (Xue et al., 2020), especially in the study of Chinese poetry. For example, existing studies focus more on whether there is a violation of the rhyme on the level of phonology (Chen et al., 2016), and whether they are esthetically beautiful merely by subjective evaluation (Gao and Guo, 2018). Less focus is placed on semantics, such as meanings of poetry beyond its literary meaning [Seyed-Gohrab (2012) in certain cultural context]. This may be attributed to the following reasons: the language of poetry, by its very nature, tends to compress, inclining toward the condensation of metaphorical language without syntax or connectives, resulting in subjective and open-ended poetry comprehension and appreciation (Peskin, 1998). Thus, the obscurity of language, reflected by imageries, insights, and icons of poets, leads to greater demands on cognitive resources of readers, and the interpretation is tightly bound up to prior knowledge of poetry of readers (Peskin, 1998; Piirto, 2011). In addition, the role of culture in the comprehension of figurative language, which might be referred to a general relationship between the language and the body, can be another reason. For example, differences in Italian and Persian abstract languages were revealed when it comes to the comprehension of the embodied language (Ghandhari et al., 2020). There are similar examples in Chinese classical poetry, e.g., the action of "折柳," with the literary meaning of "pick willow branches," usually means to persuade one's friends to stay and expresses the feelings of missing, which may exist in context of Chinese culture exclusively. Therefore, to enhance the deep comprehension of learners of poetry, we presented the imageries and scenes depicted in a rhyming and regular metered, idyllic Chinese poem in a Chinese culture context (a middle school in Chinese mainland). A Chinese poem was presented to learners visually and intuitively via an instructional flash animation in a multimedia environment to complement the compressed language, reducing demands on readers' cognitive resources, the obscurity of language, and fostering an in-depth understanding of the poem.

Theoretical Framework

Multimedia technologies are increasingly used in educational settings. Furthermore, emotional designs, instructional designs that use different design elements (e.g., pleasant colors and anthropomorphisms) to influence emotions of learners in the process of learning to improve academic performance of learners (Plass and Kaplan, 2016), have been widely employed across natural science disciplines (Um et al., 2012; Plass et al., 2014; Uzun and Yildirim, 2018; Shangguan et al., 2020a).

Regarding the influence of emotions on learning performance, the emotions-as-facilitator-of-learning hypothesis (Um et al., 2012; Park et al., 2015; Knörzer et al., 2016) assumes that cognitive and learning processes, such as information processing, category sorting tasks, and creative problem-solving (Erez and Isen, 2002), can be enhanced *via* positive emotions. An influential extended framework, the cognitive-affective theory of learning with media (CATLM) (Moreno and Mayer, 2007) further proposes that affective and motivational factors are mediating factors between emotional designs and learning effects in multimedia learning. Therefore, emotion was integrated into the CATLM, and Moreno and Mayer (2007) put forward the emotional design hypothesis, which holds that in the process of learning, making basic elements visually attractive (e.g., pleasant colors or presenting them with shapes similar to human faces) within a learning material will initiate cognitive processing (Mayer and Estrella, 2014). That is, cognitive processing during learning can be improved through the emotional design of elements in the multimedia learning material; thus, improving the learning effect. Therefore, the emotional design hypothesis has been confirmed in research (Mayer and Estrella, 2014; Gao, 2016).

In addition to the effect of internal emotional designs on learning material, external emotion-inducing methods, such as reading emotional text (Um et al., 2012; Park et al., 2015), viewing pictures and videos (Plass et al., 2014; Gong et al., 2017, Exp. 1), and recalling emotional autobiographical memories (Knörzer et al., 2016), are also effective ways to induce emotions of learners in education and also impact learning processes (Brose et al., 2012; Beege et al., 2018). The measurement of external emotion induction generally takes place after emotion induction and before multimedia learning. Although external emotion induction cannot run through the whole learning process continuously, researchers have consistently confirmed that external emotion induction can successfully induce positive emotions in learners (Um et al., 2012; Plass et al., 2014; Park et al., 2015; Knörzer et al., 2016; Schneider et al., 2016; Gong et al., 2017). The CATLM successfully explains some research on positive emotional designs in multimedia learning. For instance, Plass et al. (2014) reported that positive emotions induced by internal emotional design enhanced intrinsic motivation and comprehension performance. In addition, Um et al. (2012) found that positive emotions induced by external and internal emotional designs boosted intrinsic motivation and transfer performance of learners. However, some studies have suggested no differences in motivations (Kumar et al., 2016) or learning outcomes (Park et al., 2015; Kumar et al., 2016) between positive emotional design conditions and neutral ones, inconsistent with the proposals of the CATLM.

Meanwhile, the emotions-as-suppressor-of-learning hypothesis postulates that emotions may impair learning (Um et al., 2012). Consistent with this, cognitive load theory (Paas et al., 2003; Paas and Sweller, 2014; Kalyuga and Singh, 2016) predicts the opposite regarding learning outcomes where the positive emotions induced, compared with neutral emotions, may increase the extraneous cognitive load in learners (Rey, 2012), which is adverse to learning performance. Therefore, cognitive load theory is partially supported by previous studies (Schneider et al., 2018; Starkova et al., 2019).

The inconsistent findings in the literature may be due to the following reasons: first, the subjects of the learning material varied across studies. Most of existing research focuses on STEM (science, technology, engineering, and mathematics) subjects, such as the formation of lightning (Gong et al., 2017; Shangguan et al., 2020a), ATP structure and synthesis (Park et al., 2015; Knörzer et al., 2016; Stark et al., 2018), mechanics, and efficacy (Uzun and Yildirim, 2018), with limited focus on humanities. Second, learning in a multimedia environment involves a relatively complicated cognitive process. Therefore, in addition to induced emotions and motivation, other factors specific to the attributes of disciplines that affect learning outcomes may be present. For example, understanding and appreciation of readers of poetic texts are influenced by surface psycholinguistic features (Xue et al., 2020). Third, the internal emotional design elements of the learning material used vary in different studies. That is, some employed a combination of multiple design elements (Gong et al., 2017; Shangguan et al., 2020a), while others distinguished between different elements, such as anthropomorph or color (Heidig et al., 2015; Gong et al., 2017, Exp. 2). It has been proven that colors affect emotions, and that warm colors are deemed as stimulating and active (Kaya and Epps, 1998). Instructional designers also recruit warm colors to draw the attention of learners (Lohr, 2007). Color should be considered when manipulating emotional designs as posited by the ecological valence theory of human color preference (Palmer and Schloss, 2010), which believes that color contains useful information about an object that leads to approach-avoidance behavior of people. For example, people usually prefer red apples to green ones because the former may represent maturity and delicacy. In addition, approach-avoidance behavior is context-specific in which red in the orchard means maturity, while red signifies stopping on roads. Research on visual esthetics has also verified that people prefer color hue, saturation, brightness, and so forth, with people generally preferring harmonious color combinations (Palmer et al., 2013). Research has also confirmed the role of color in emotional design. To illustrate, Münchow et al. (2017) applied warm color designs to learning material on neuroanatomical topics and indicated that, compared with gray-scaled designs, warm color designs improved comprehension and transfer performance of learners. Plass et al. (2019) further verified that warm colors in teaching games were related to the positive emotions of participants. In addition, Wong and Adesope (2021) conducted a meta-analysis on emotional designs and found that pleasant colors were indeed an effective design principle.

Chinese poetry, which is a concentrated expression of Chinese art and culture, is loved by many literati and people at home and abroad. The terms used in Chinese poetry are appreciated esthetically. When writing poems, poets usually create connections between their inner feelings and objective external images in a metaphorical way, which is a creative process. The poet also experiences an insight, which involves restructuring the problem in a different way and enables him to experience an "Aha" moment. Poetry also provides "Aha" moments for its readers who are moved by the creative works of the poet whose insight provides insight to readers (Piirto, 2011). Only when the historical spiritual meanings of symbols, imageries, and icons in poetry are remotely associated with the esthetic creation of poets would readers understand the specific meanings of these symbols, imageries, and icons; and they would then resonate more with poets (Piirto, 2011).

Accordingly, appreciation and learning of poetry could be a creative process in itself, which can boost creativity of readers (Osowiecka and Kolańczyk, 2018). That is, emotionally designed learning materials where colorful scenes in Chinese poetry are visually presented may help learners gain perception of the poetry intuitively by assisting learners in establishing remote associations between imageries in ancient Chinese poetry and objective matters, thus, achieving insight into personal creations of the poet and fostering esthetic appreciation and deeper learning of poetry.

Problem Statement, Research Question, and Hypotheses

Existing studies on emotional designs are almost entirely concerned with natural sciences. Therefore, whether the general principles of emotional designs in STEM subjects are applicable to humanities is in question. That is, can the combination of internal colorful design of poetry learning materials and external emotion induction induce positive emotions of learners? Furthermore, what are the effects of this combination on appreciation and learning of poetry? These were the main concerns addressed in this study.

According to Leder and Nadal (2014), information processed in an esthetic episode involves perceptual, cognitive, and emotional components. That is, the appreciation of poetry could be broadly reflected in esthetic appreciation whether the poem is beautiful and fascinating, and whether one likes it. Lüdtke et al. (2014), which may include beauty (beauty) and preference ratings (wanting, liking) (Chatterjee and Vartanian, 2014; Leder and Nadal, 2014). Esthetic preference, which was separated from beauty and was a major achievement in post-Kantian esthetics, (Kraxenberger and Menninghaus, 2017), mainly follows preferences of individuals and is more closely related to emotional components. Neurasthenics confirmed that several brain regions associated with esthetic experience are implicated in emotion-valuation systems, such as the orbitofrontal and medial frontal cortices and insula (Blood and Zatorre, 2001; Chatterjee and Vartanian, 2014). Furthermore, affect could modulate the encoding and retrieval of information to form evaluations and judgments, especially when constructive processing is required (Forgas, 1995). When it comes to esthetic evaluations, artworks were more liked when they were preceded by positive primes compared with negative ones (Flexas et al., 2013), possibly because of a valence-congruency effect that indicates the transfer of affective reaction from primes to targets (Payne et al., 2005; Boukarras et al., 2020). Thus, we were curious whether emotionally designed poetry learning materials would foster the following esthetic preference of poetry.

In sum, this study aimed to investigate the influence of emotional designs on emotions of learners and esthetic preferences as well as the cognitive and learning outcomes when learning Chinese poetry in a multimedia environment with the CATLM. Specifically, the impact of the combination of external emotion induction (emotional films) and internal colorful design on positive emotions, esthetic preferences, and learning performances of learners of Chinese poetry was investigated.

Based on findings from previous studies, the following hypotheses were postulated: in the preliminary experiment, compared with internal neutral design (achromatic), internal colorful design would induce more positive emotions (H1) and esthetic preference (H2), and the positive film would evoke more positive emotions than neutral one (H3). In the following formal experiment, the combination of internal colorful design and external positive emotion induction could induce more positive emotions (H4) and esthetic preference (H5) in learners, leading to higher learning motivation, lower perceived difficulty (H6), and better learning performance (higher retention and transfer scores) (H7) compared with neutral conditions.

PRELIMINARY EXPERIMENT

A preliminary experiment was conducted to verify the emotional charges of the experimental materials. Specifically, the preliminary experiment was employed to determine whether the internal colorful design condition would induce more positive emotions and higher esthetic preference of the poem than those in the neutral condition, and whether the positive film evoked more positive emotions in learners than the neutral film.

Verification of Learning Materials

Participants and Design

G∗Power analysis (G∗Power 3.1.9.2) was conducted to estimate the sample size (Faul et al., 2007) with an effect size (Cohen's d) of 0.8 and power of 0.9, as described by Cohen (1988). We aimed for a sample size of a minimum of 36 subjects in each condition. Eighty students (42 females, age: $M = 14.91$, $SD = 0.86$) with normal or corrected-to-normal vision in a middle school in Henan Province participated in the preliminary experiment. They were randomly assigned to two conditions: internal colorful design ($n = 42$) or internal neutral design ($n = 38$). Written informed consent was obtained from both the school principal and the parents before the experiment. The research protocol was approved by the Ethical Committee of the School of Psychology of Central China Normal University.

Selection and Design of Learning Materials

Six experienced Chinese teachers with an average teaching experience of 9 ± 2.67 years in a middle school rated the eight poems proposed by researchers on three aspects: difficulty, concreteness, and dynamics of poetic scenes, as well as emotions involved in the poem on a 7-point rating scale (rater reliability: Cronbach's $\alpha = 0.9$). One poem that was not included in the existing syllabus and that had a difficulty level matching the syllabus at middle school level ($M = 6.59 \pm 0.32$) was selected. It was a rhymed poem of the Tang Dynasty with highly concrete and dynamic scenes ($M = 6.01 \pm 0.52$) and a relatively neutral emotional tone ($M = 3.69 \pm 0.72$). The poem was Meng Haoran's 《夏日浮舟过陈大水亭》(Boating to the Chen Pavilion on the Lake in Summer Evening). The relatively neutral poem content ensured that the perceived emotional involvement of the learning material was due to the manipulation of emotional design and not due to the poem itself (Beege et al., 2018).

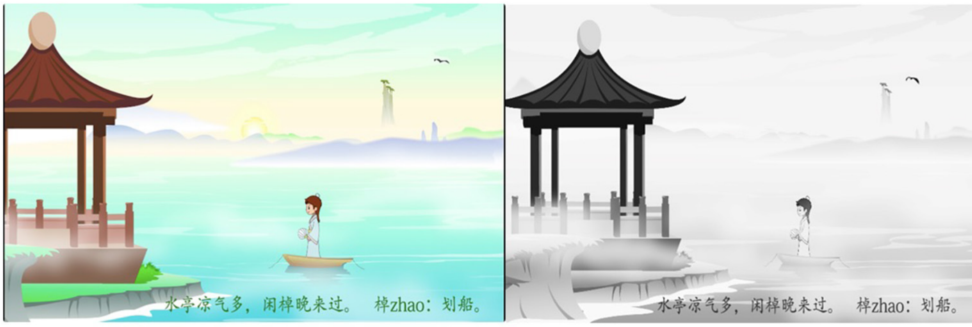

FIGURE 1 | Screenshots of multimedia learning materials in the preliminary experiment: internal colorful design (IC) on the left and internal neutral design (IN) on the right.

The learning material of the poem was jointly compiled, according to the teaching syllabus and teaching experience, by two of the six teachers (Uzun and Yildirim, 2018). It contained 650 explanatory characters, of which 130 (including the title, author, phonetic annotation, and explanation of rare characters) were visually presented as captions. The material was presented in a flash animation with a length of 5 min and 16 s, and its production was completed under the guidance of teaching experts. It was designed in two versions, which were identical to each other, except for the colors. In the positive chromatic version, cold and warm colors were included (Um et al., 2012) according to the original colors of the objects; whereas, in the neutral version, the color was gray scale. Each version contained six dynamic pictures. Please see creenshots of the learning materials in **Figure 1**.

The learning material was presented at a fixed paced in three consecutive stages: first, the poem was recited with pronunciations and annotations of rarely used Chinese characters presented at the bottom of the corresponding pictures; second, the meanings of the poem were briefly explained; and finally, the overall thoughts and feelings in the poem were sublimated.

Emotional Measures

According to previous studies (Chaffar and Frasson, 2004; Gong et al., 2017), to check the manipulation of the mood induction, six items concerning positive emotions in a positive emotion self-report inventory (Gross and Levenson, 1995) were used (happy, excited, content, active, interested, and relaxed). The subjects were required to respond by indicating the extent to which they felt these six positive emotions in response to the learning material using a 9-point rating scale ranging from 1 (not at all) to 9 (very much). The positive emotion score was calculated by averaging the scores from the six responses above. This scale showed high internal consistency in the preliminary experiment (coefficient $a = 0.89$).

Esthetic Preference

The esthetic preference of the poem included two 7-point rating items (1 = strongly disagree, 7 = strongly agree) (Lüdtke et al., 2014; Kraxenberger and Menninghaus, 2017): "I like the poem" and "The poem is fascinating (attractive) to me." The final score was calculated by averaging the scores of the two items. The internal consistency coefficients of the two items were 0.9.

Control Measure: Prior Knowledge of Chinese Poetry

The prior knowledge questionnaire on Chinese poetry was compiled by Chinese teaching experts in a middle school based on literature by Xu (2020) and Bao (2012). There were 12 items with a maximum total score of 26. The questionnaire contained a self-report item: "What do you think of your knowledge of Chinese poetry?" ranging from 1(extremely low) to 7 (extremely high), five gap fillings (five points in total), five multiple-choice questions (10 points in total), and one subjective question ("Please write as much as you can about your understanding on the pastoral poetry") which counted a total of four points. Two trained raters rated the prior knowledge test, and the inter-rater reliability was 0.89.

Procedure

The participants were first informed of the procedure by the experimenter who was familiar with the procedure. Then, they completed the prior knowledge questionnaire, positive emotion questionnaire for the first time (PE1), and a demographic survey. They then learned the material under chromatic or achromatic conditions *via* a computer. Immediately after, the participants completed the positive emotion measure again (PE2) and then completed the esthetic preference judgment. This experiment lasted for ∼40 min for each subject.

Analysis

First, independent sample *t*-tests were performed to check for differences between the two conditions regarding prior knowledge (PE1). Then, we performed a 2 × 2 ANOVA with the colorful design in the learning material as a between-subject factor and emotion measures (PE1 and PE2) as the within-subject factors to test H1. Then, H2 was tested using an independent sample *t*-test with the internal colorful design of the learning material as the independent variable.

TABLE 1 | Means and standard deviations of all variables for the two groups in the preliminary experiment.

Variables	IC ($n = 38$) *M* (*SD*)	IN ($n = 42$) *M* (*SD*)
Prior knowledge	11.05 (2.52)	10.95 (3.13)
Positive emotion (1)	5.58 (2.00)	5.15 (1.79)
Positive emotion (2)	5.64 (2.01)	5.15 (2.21)
Esthetic preference	11.53 (2.26)	10.10 (3.63)

IN, internal neutral design; IC, internal colorful design.

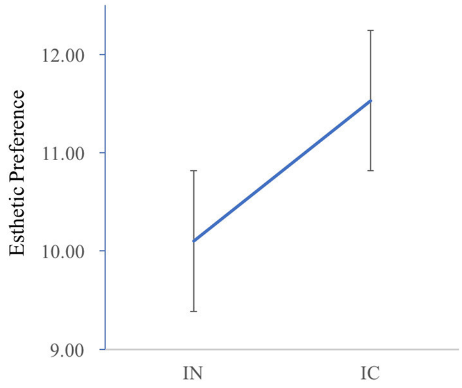

FIGURE 2 | Esthetic preference in the preliminary experiment.

Results

Table 1 shows the descriptive statistics of the control and dependent variables. The results of independent samples *t*-tests revealed no group differences between the two conditions regarding PE1, $t_{(78)} = 1.43$, $p = 0.16$, or in prior knowledge, $t_{(78)} = 0.19$, $p = 0.85$.

Positive Emotions

Regarding the effects of positive emotional design on emotions, the results revealed no significant main effects of emotional design in the learning material, $F_{(1,78)} = 1.19$, $p = 0.28$, or positive emotion measures, $F_{(1,78)} = 0.04$, $p = 0.85$, with no significant interaction effect, $F_{(1,78)} = 0.03$, $p = 0.85$.

Esthetic Preference

Regarding the effect of colorful design on esthetic preference of learners, the result revealed a significant difference, $t_{(78)} = 2.09$, $p = 0.04$, $d = 0.47$, with the colorful design inducing higher esthetic preference than the neutral design and the difference was displayed in **Figure 2**.

The Verification of the Emotional Films

Selection of Emotional Films

Regarding the external emotion induction videos, we employed *Mr. Bean* and *March of the Penguins* as the positive and neutral condition (Gong et al., 2017) with a total length of 346 and 330 s, respectively. The films were clips selected from the corresponding movies and edited with Photoshop.

Measurement and Subjects

Both clips were rated on a 7-point scale (1 = very negative, 7 = very positive) by 31 subjects (14 males, age: $M = 14.37$, $SD = 0.67$) who did not participate in multimedia learning.

Analysis

A paired sample *t*-test was employed to test H3.

Result

The paired sample *t*-test suggested that emotions induced by *Mr. Bean* were more positive than those by the *March of the Penguins* [$M = 6.15$, $SD = 1.79$; $M = 3.95$, $SD = 1.98$; $t_{(30)} = 5.86$, $p < 0.01$, $d = 0.72$].

Brief Discussion

A preliminary experiment was conducted to verify the emotional charge of the experimental materials, such as internal colorful designed learning material and external emotion induction film clips.

The results showed that the colorful learning material did not induce more positive emotions than the neutral material, suggesting a lack of support for H1. However, compared with the neutral material, the internal colorful designed learning material induced a higher esthetic evaluation of the poem than the neutral one, which supported H2. Furthermore, emotions evoked by positive external emotion videos were more positive than those by neutral ones, supporting H3.

In terms of positive emotion, there was no significant difference between the two learning materials. That is, the internal colorful design did not induce more positive emotions than the neutral one. Many studies on emotional design have used a combination of multiple elements, such as color and anthropomorphism (Plass et al., 2014; Gong et al., 2017), and positive emotions induced in learners would increase with the increase in emotional design element amount (Uzun and Yildirim, 2018). In this study, the difference between positive and neutral conditions was only in color. This use of a single element may have weakened the emotion induction effect. This was consistent with the study of Park (Park et al., 2015), who also failed to induce positive emotions by only anthropomorphism to design learning material. Moreover, we did not induce the personification design because the poetry text already contained characters (the old and the young), thus it was not possible to use the anthropomorphic emotional design element further. Even by employing a combination of colors, shapes, and anthropomorphism, Li et al. (2020) did not successfully evoke more positive emotions, which were measured by galvanic skin response and electroencephalogram instruments objectively, in internal positive conditions than the neutral ones. In line with Li et al. (2020), the learning material in this study was presented in a system-paced manner, which meant that learners did not have control over their learning process. This may have resulted in disappointment and boredom of learners according to the control-value theory of academic emotions (Pekrun, 2006).

In terms of esthetic appreciation, the colorful designed learning material induced higher esthetic preferences in learners. Consistent with prior research and compared with achromatic learning material, the colorful material based on real objects made a more harmonious impression (Palmer et al., 2013), which may suggest that preference for colorful pictures contained in learning material may promote higher esthetic appreciation in colorful condition. In addition, the higher esthetic preference in the colorful design condition could be attributed to the age characteristics of middle school students where they were in the concrete image thinking period (Hao et al., 2019); thus, they preferred learning contents involving chromatic color, which is more vivid than the grayscale ones (Prensky, 2001; Gong et al., 2017).

Regarding the inducing effect of external induction films, *Mr. Bean* induced more positive emotions than *March of the Penguins.* Inducing emotions through movie clips is more intuitive and vivid, which can attract the attention of subjects, and is widely used to induce emotions before learning (Plass et al., 2014; Gong et al., 2017). *Mr. Bean,* which delivers a clumsy and naive performance, is obviously more emotionally contagious for middle school students than *March of the Penguins*, which is a relatively objective documentary.

Findings from the preliminary experiment suggested that the internal positive emotional design in the poem learning material can improve esthetic preference, an emotional component in esthetics that is especially relevant in poetry appreciation and is appropriate for middle school teenagers. Meanwhile, the emotion induced by the positive emotion film clip was more positive than that by the neutral one; therefore, they were assumed to be suitable for subsequent formal experiments.

THE FORMAL EXPERIMENT

To investigate whether the combination of external emotion induction and internal emotional design can enhance positive emotions of middle school students, esthetics, and learning performance in Chinese poetry, a formal experiment was conducted.

Method

Participants and Design

When conducting the G*Power analysis with G*Power (version 3.1.9.2), we set the effect size (partial η^2) as 0.25, α as 0.05, and power as 0.8, and the ideal total sample size was 179 with 45 in each group. Overall, 166 participants (77 males and 89 females; age: $M = 15.05$, $SD = 0.99$) with normal or corrected-to-normal vision were recruited.

We used a 2 × 2 between-subjects design with external emotion induction (positive vs. neutral) as one factor and internal emotional design (positive vs. neutral) as the other. The participants were randomly assigned to learn the material of a Chinese poem, similarly as in the preliminary experiment, under one of the four conditions:

Group 1: External positive emotion induction and internal positive emotional design condition ($n = 44$).

Group 2: External positive emotion induction and internal neutral emotional design condition ($n = 38$).

Group 3: External neutral emotion induction and internal positive emotional design condition ($n = 41$).

Group 4: Neutral under both external and internal emotional design conditions ($n = 43$).

Materials

The experimental materials employed were the same as those utilized in the preliminary experiment.

Measures and Procedures

The emotion measures, esthetic preference, and control measures were identical to those in the preliminary experiment. The other measures are described below.

Motivation

A 7-point self-report instrument containing seven items developed by Isen and Reeve (2005) was used to measure the motivation of learners (Shangguan et al., 2020b). The participants rated their motivation of the learning experience (e.g., "The learning material aroused my curiosity") with 1 = strongly disagree to 7 = strongly agree. The final motivation score was calculated by averaging all response scores (coefficient $a = 0.89$).

Cognitive Load

Two items measured cognitive load of learners concerning different constructs (Deleeuw and Mayer, 2008). They were "How easy or difficult was the material to understand?" (Kalyuga et al., 2000) and "How much mental effort did you invest in studying the material?" (mental effort) (Paas, 1992). Both were 9-point rating scales and were included in the final cognitive load scores (Park et al., 2015).

Retention and Transfer Tests

The subjects' recognition, remembering, and reproduction of the learning material was investigated by a retention test, with a maximum score of 12, including three multiple-choice questions (For example, "What is the motif of the poem?"; six points in total) and two subjective questions [For example, "The description of '涧影见松竹, 潭香闻芰荷' (The clear water reflects pine and bamboo, and the water emits the fragrance of lotus) is exquisite, try to elaborate it"; six points in total]. Answers to these questions were presented in the learning material. The retention test was rated by two trained raters with sufficient inter-rater reliability (0.9).

A transfer test was conducted to investigate the overall comprehension and appreciation of the subjects of poetry of the same motif (pastoral poetry of the Tang Dynasty). The maximum score was 17 points with three multiple-choice questions (seven points in total; for example, "Which of the following poems is not idyllic?") and two subjective questions (10 points in total; for example, "The description of '荷风送香气, 竹露滴清响' 'The fragrance of the lotus rose far in the wind, and the dew on the bamboo leaves dropped into the water' is exquisite, try to appreciate it briefly.") The five items were compiled regarding the representatives of pastoral poetry, writing objects, writing techniques, and thought expressions. The inter-rater reliability of the transfer test by the two trained raters was 0.86.

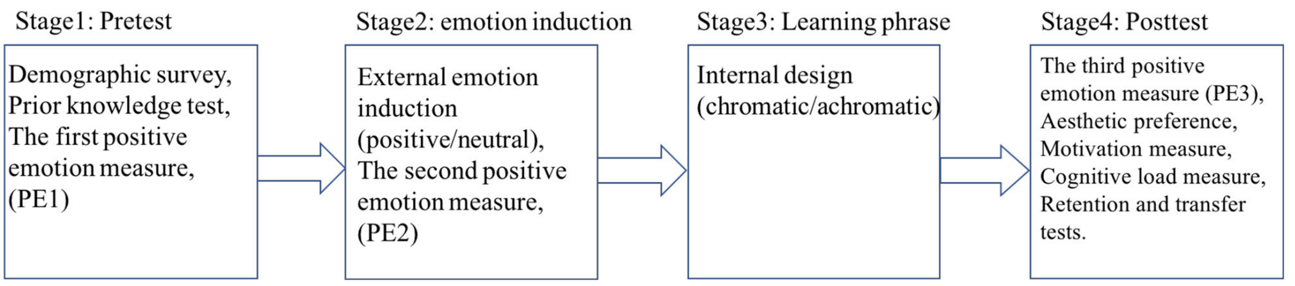

FIGURE 3 | Procedure of the formal experiment.

TABLE 2 | Means and standard deviations of all variables for the four groups in the formal experiment.

Variables	EPIC (n = 44) M (SD)	EPIN (n = 38) M (SD)	ENIC (n = 41) M (SD)	ENIN (n = 43) M (SD)
Prior knowledge	10.18 (3.11)	12.30 (2.37)	12.90 (2.37)	10.20 (2.45)
Positive emotion 1	5.57 (1.67)	5.94 (1.67)	5.61 (1.68)	5.52 (2.26)
Positive emotion 2	6.48 (1.67)	6.97 (1.75)	5.48 (1.64)	5.50 (2.34)
Positive emotion 3	5.85 (1.65)	5.93 (2.05)	5.58 (1.69)	5.57 (2.31)
Esthetic preference	10.50 (2.63)	10.92 (2.94)	10.83 (2.53)	9.21 (3.19)
Retention	6.96 (1.85)	7.16 (2.21)	6.93 (2.03)	4.74 (2.69)
Transfer	7.04 (2.69)	6.42 (2.54)	7.22 (2.26)	4.39 (2.00)
Perceived difficulty	4.68 (1.68)	5.29 (1.86)	5.22 (1.72)	5.13 (2.07)
Mental effort	5.96 (1.68)	6.24 (1.90)	6.02 (1.70)	6.09 (1.98)
Motivation	4.52 (1.66)	4.94 (1.70)	4.84 (1.57)	3.93 (1.47)

EPIC, external positive induction and internal colorful design; EPIN, external positive induction and internal neutral design; ENIC, external neutral induction and internal colorful design; ENIN, external neutral induction and internal neutral design.

Procedure

The participants were first informed of the procedure by the experimenter who was familiar with the procedure. Then, they completed the prior knowledge questionnaire, positive emotion questionnaire for the first time (PE1), and a demographic survey. Next, the participants watched one of the two external emotion induction films and responded to the positive emotion measures (PE2) before the learning stage. Thereafter, they learned the poem material under the colorful or achromatic condition. Immediately after learning the poem, the participants completed the positive emotion measure again (PE3), and then the esthetic preference judgment, cognitive load questionnaire, motivation questionnaire, and retention and transfer tests. The complete procedure is illustrated in **Figure 3**.

Analyses

First, a one-way ANOVA was performed to explore the differences between conditions of PE1 and prior knowledge, and an independent samples t-test was performed to check the manipulation of external emotion induction. Then, repeated measures analysis of covariance (a 2 × 4 RM-ANCOVA) was conducted with the positive emotion measures (PE2 and PE3) as the within-subject factors and the four conditions as the between-subject factors to check for manipulation. Paired sample t-tests were performed to examine the changes in positive emotions in the four conditions during the learning process. In addition, we performed an independent samples t-test to further examine the esthetic preference of Groups 3 and 4, whose external induction was the neutral film and which may have been regarded as emotionally homogeneous to the two conditions in the preliminary experiment, to examine the consistency of the esthetic emotional charge of the poem videos. Thereafter, we performed 2 × 2 ANCOVAs with internal colorful design and external emotion induction as between-subject factors; prior knowledge as covariates; and positive emotions scores, esthetic preference, motivation and cognitive load, and learning performance as dependent variables to test H4, H5, H6, and H7.

Results

Table 2 shows the descriptive statistics of all control and dependent variables. Preliminary analyses were conducted to examine the possible differences in baseline mood (indicated by PE1) and prior knowledge. The PE1 scores were compared between the four groups [$F_{(3,162)} = 0.42$, $p = 0.74$]. The differences in prior knowledge between the four conditions were significant, $F_{(3,162)} = 12.34$, $p < 0.001$, $\eta^2{}_p = 0.19$; follow-up analysis indicated that scores of Group 1 on prior knowledge were comparable with those of Group 4 ($p = 0.99$) and prior knowledge scores of Group 2 were comparable to those of Group 3 ($p = 0.36$). However, prior knowledge scores of Group 1 were significantly lower than those of Groups 2 and 3, $p < 0.001$ and $p < 0.001$, respectively; prior knowledge of Group 4 was significantly lower than those of Groups 2 and 3 ($p < 0.001$ and $p < 0.001$, respectively). Thus, prior knowledge was treated as a control variable in the following analyses. In addition, one way ANOVA revealed that the positive video (*Mr. Bean*) induced more positive emotion than the neutral video (*March of the Penguins*) before the learning of the Chinese poem, $F_{(3,162)} = 6.93$, $p < 0.001$, and further post-testing (LSD) found that the PE2 of Groups 1 and 2 were comparable ($p = 0.71$). In addition, the PE2 of Group 3 was comparable to that of Group 4 ($p = 0.24$), while that of Group 1 was significantly higher than that of Groups 3 and 4 ($p < 0.01$, $p < 0.01$). Furthermore, the PE2 of Group 2 was also significantly higher than that of Groups 3 and 4 ($p < 0.01$, $p < 0.001$).

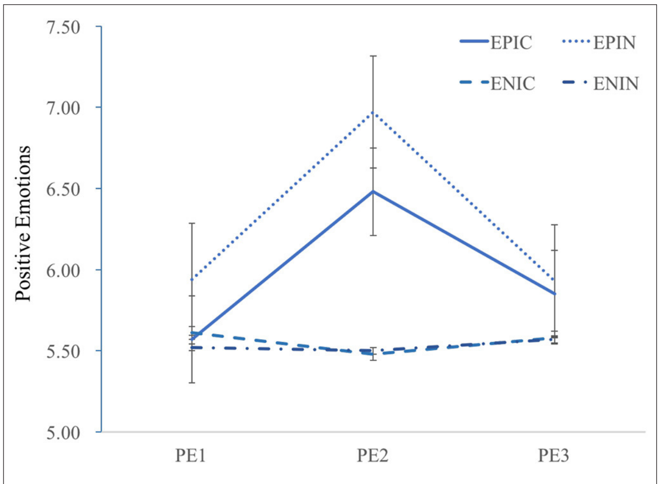

FIGURE 4 | Positive emotions (PE1, PE2, and PE3) in the formal experiment.

Positive Emotions

First, the 2 × 4 RM-ANCOVA with the four conditions as the between-subject factors and positive emotion measures (PE2 and PE3) as repeated measures revealed a significant main effect of the conditions, $F_{(3,161)} = 3.15$, $p = 0.03$, $\eta^2_p = 0.06$, and an insignificant main effect of positive emotion measures, $F_{(3,161)} = 0.44$, $p = 0.51$. The interaction effect was significant, $F_{(3,161)} = 5.82$, $p < 0.001$, $\eta^2_p = 0.1$. Concerning whether the positive emotion (from PE2 to PE3) changed significantly during the learning process, the results of paired sample t-tests indicated that for Group 1, the scores on positive emotion reduced significantly from PE2 to PE3, $t_{(43)} = 3.02$, $p < 0.01$, $d = 0.68$; for Group 2, positive emotions decreased significantly from PE2 to PE3, $t_{(37)} = 4.7$, $p < 0.001$, $d = 0.76$; and for Groups 3 and 4, the positive emotions remained comparable from PE2 to PE3, $t_{(40)} = -0.7$, $p = 0.49$; $t_{(42)} = -0.37$, $p = 0.72$.

Regarding the effects of external emotion induction and internal colorful design on positive emotions (PE3), the results of the 2 × 2 ANCOVA showed no main effect of external emotion induction, $F_{(1,161)} = 1.2$, $p = 0.28$, or a main effect of internal colorful design, $F_{(1,161)} = 0.3$, $p = 0.86$. Furthermore, no interaction effect was found, $F_{(1,161)} = 0.05$, $p = 0.83$.

The results of PE1, PE2, and PE3 are presented in **Figure 4** to enable readers to have an intuitive understanding of emotional changes during the experiment.

Esthetic Preference

Concerning esthetic preference of learners as a dependent measure, the results of 2 × 2 ANCOVAs showed no significant main effects of external emotion induction or internal colorful design, $F_{(1,161)} = 2.68$, $p = 0.1$; $F_{(1,161)} = 1.68$, $p = 0.2$. Furthermore, no interaction effect was observed, $F_{(1,161)} = 2.46$, $p = 0.12$. However, an interesting and consistent result was revealed by the independent t-test, where the esthetic preference of Group 3 was significantly higher than that of Group 4, $t_{(82)} = 2.57$, $p < 0.012$, $d = 0.56$.

Cognitive and Motivation Outcomes

The effects of external emotion induction and internal colorful design on learning outcomes were examined by 2 × 2 ANCOVAs, with prior knowledge as a control variable and retention and the transfer test scores as dependent measures.

The main effects of external emotion induction and internal colorful design on retention were both significant, $F_{(1,161)} = 12.45$, $p < 0.01$, $\eta^2_p = 0.07$; $F_{(1,161)} = 7.05$, $p < 0.01$, $\eta^2_p = 0.04$. The retention scores under the external positive emotion induction condition were significantly higher than those under the external neutral emotion induction condition. Performance on retention showed the same pattern as the internal colorful design. Furthermore, the interaction between the two factors was not significant, $F_{(1,161)} = 2.72$, $p = 0.1$.

Significant main effects of external emotion induction and internal colorful design on transfer scores were also revealed, $F_{(1,161)} = 5.62$, $p = 0.02$, $\eta^2_p = 0.03$; $F_{(1,161)} = 17.53$, $p < 0.001$, $\eta^2_p = 0.1$. The transfer scores for positive external emotion induction conditions were significantly higher than those for neutral external conditions. Performance on transfer tests suggested the same tendency as the internal colorful design. The interaction between the above factors did not significantly affect the transfer performance, $F_{(1,161)} = 0.33$, $p = 0.86$.

Concerning perceived difficulty, mental effort, and motivation of learners as dependent measures, and prior knowledge as control variables, the results of the 2 × 2 ANCOVA showed no significant main effects, $Fs < 0.76$, $p > 0.05$. However, the interaction on perceived difficulty was significant, $F_{(1,161)} = 9.55$, $p < 0.05$, $\eta^2_p = 0.06$, and LSD-corrected *post-hoc* tests revealed that when positive emotion was induced before learning, the perceived difficulty of internal colorful design was significantly lower than the internal neutral condition, $F_{(1,161)} = 4.62$, $p = 0.03$, $\eta^2_p = 0.03$. While the neutral video was presented before learning, perceived difficulty showed a reversal pattern where the perceived difficulty was significantly lower in the achromatic condition than in the chromatic condition, $F_{(1,161)} = 5.9$, $p =$

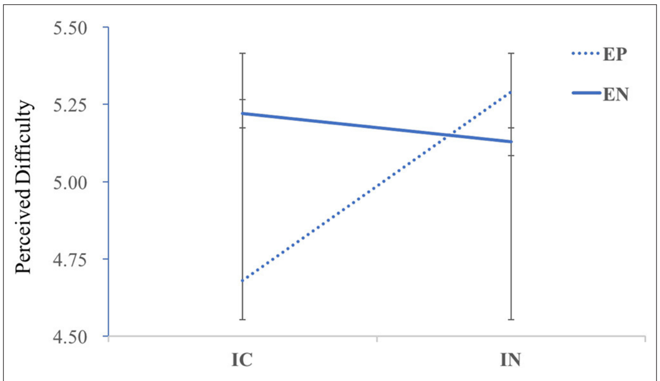

FIGURE 5 | Perceived difficulty by condition in the formal experiment.

0.02, $\eta^2_p = 0.04$ (see in **Figure 5**). No other interaction effects were revealed, $Fs < 0.57, p > 0.05$.

Brief Discussion

The formal experiment examined whether the combination of external emotion induction and internal colorful design would promote the appreciation and learning of Chinese poems. The results showed that external emotion induction significantly improved positive emotions of learners when they entered the learning situation, thus, partially supporting H4. The combination of external emotion induction and internal colorful design did not improve the esthetic evaluation of poems; however, the color learning material boosted appreciation of learners of the poem compared with the gray scale one when the external film clip was neutral, therefore, partially supporting H5. Moreover, the combination reduced perceived difficulty (partially supporting H6) and enhanced retention and transfer performance of learners (supporting H7).

Regarding positive emotions, consistent with previous research (Plass et al., 2014; Gong et al., 2017), the external positive emotional video successfully induced more positive emotions in learners than the neutral one (indicated by PE2). According to the CATLM (Moreno, 2006; Moreno and Mayer, 2007), the positive emotions induced by external manipulation may influence the learning process by activating the topic-related prior knowledge of a learner and driving learners to recruit cognitive resources in subsequent similar situations, thus, promoting comprehension of learners and retention of the poem, and boosting their transfer performance. Furthermore, positive emotion fosters more holistic processing of information, which coincides with more creative thinking (Isen, 1999; Bless and Fiedler, 2006; Knörzer et al., 2016; Beege et al., 2018) and, therefore, may promote deeper learning of Chinese poetry, which is also a creative process.

Concerning esthetic preference judgment, no main effect or interaction effect of external emotion induction and internal colorful design was found. Compared with the preliminary experiment in which internal colorful design promoted esthetic preference of learners for the poem using a chromatic design element, the formal experiment introduced external emotion induction by employing emotional films, with *Mr. Bean* being used in the external positive condition. The clumsy and naive performance of *Mr. Bean* successfully evoked more positive emotions. Although poetry always possesses an emotional component that facilitates esthetic preference in readers, the emotion of poetry is usually captured through referential linguistic conventions, such as metaphors and imagery (Piirto, 2011). This may be less emotionally contagious for middle school students than *Mr. Bean*, which has been famous for its amusement for over 30 years worldwide. The positive emotions evoked by external induction videos may mask emotional involvement of the poem perceived by learners, thus, resulting in a null effect on esthetic preference judgment. Moreover, esthetic preference is primarily driven by high affective arousal (Kraxenberger and Menninghaus, 2017), and the arousal of *Mr. Bean* was much higher than the poem containing neutral key emotional tonality; thus, the film showed higher esthetic preference. However, it should not be ignored that when the external emotion induction is neutral (Groups 3 and 4), which we may regard as emotionally homogeneous to the preliminary experiment, the internal colorful design made the poem more appealing to learners. This was consistent with the preliminary experiment, indicating that the internal colorful design successfully induced emotional esthetics of teenagers in poetry appreciation.

Regarding the cognitive load outcomes, it was found that when the external video successfully induced positive emotions, perception difficulty of the learners was significantly lower in the internal colorful design condition than in the internal neutral condition; when the external induced video was neutral, the perception difficulty of the internal neutral condition was significantly lower than that of the internal colorful condition. That is, the congruency of external and internal emotions reduces perceived difficulty. The mood-affect congruency (Kim and Pekrun, 2014; Beege et al., 2018; Schneider et al., 2019) facilitated the access and retrieval of topic-related experiences through stronger activation, thus, reducing perceived difficulty. Concerning motivation, no effects of external emotion induction or internal colorful design were revealed, which was in line with previous research (Kumar et al., 2016; Navratil et al., 2018), suggesting that the learning material was designed in a way that promotes positive emotions rather than motivation (Knörzer et al., 2016; Stark et al., 2018; Shangguan et al., 2020a). More explorations need to be implemented to motivate teenagers in multimedia learning.

GENERAL DISCUSSION

This study investigated the influence of emotional designs on Chinese poetry esthetics and learning in multimedia learning. The results showed that the use of color in the internal colorful design in the learning material of Chinese poetry did not induce more positive emotions than the neutral one (lack of support for H1) and could significantly improve esthetic preference of learners (in support of H2). The external positive films evoked more positive emotions than the neutral film (in support of

H3) in the preliminary experiment. In the formal experiment, positive external emotion induction improved positive emotions when entering instructional situations (in partial support of H4). When the external induction was neutral, the colorfully designed learning material achieved a higher appreciation of the poem in learners than the gray scale one (partially supporting H5). Mood (induced by external induction)-affect (internal colorful design) congruency reduced perceived difficulty of learners (in partial support of H6), and the combination of external emotion induction and internal colorful design boosted retention and transfer performance (supporting H7). Overall, the findings partly replicated the results in natural science disciplines and supported the CATLM theory. This study extended the discipline fields of existing emotional designs in multimedia learning to humanities by examining the effects of emotional designs on learning and appreciation, which may reflect the unique disciplinary attributes of Chinese poetry.

Regarding the positive emotion outcomes, the single internal colorful design element did not successfully evoke positive emotions (Park et al., 2015), and the external emotion induction induced short-lived positive emotions (Gong et al., 2017). Consistent with previous literature, these results suggest that the means of inducing emotions have inherent characteristics; one-dimensional manipulation of internal colorful design may have limited effects in accumulating enough positive emotions captured by scales, while the external mood induction effect was unsustainable throughout the learning process. Further research should be conducted to explore more design variations, such as design elements at the behavioral level implied in the control-value theory of academic emotions (Pekrun, 2006), to evoke positive emotions effectively and efficiently. Moreover, esthetic preference of learners, an emotional indicator in poetry appreciation, for the poem was higher in the positive condition than in the neutral one in the preliminary experiment, which may indirectly verify the effectiveness of the internal colorful design.

Regarding cognitive outcomes, mood-affect congruency reduced perceived difficulty. The effect of mood-affect congruency on cognitive load could be explained by an associative network (Kim and Pekrun, 2014) where emotions are inextricably linked to events in daily life; hence, objective knowledge is stored emotionally in memories. Mood-related knowledge would be more easily available if the mood is experienced before retrial (Levine and Pizarro, 2004), following which the combination of positive external emotion induction and internal colorful design would decrease perceived difficulty and is conducive to deeper processing of the poem. Furthermore, learning outcomes in positive conditions were better than those in neutral conditions. This is not surprising as emotion always interacts with other cognitive processes (Knörzer et al., 2016) and is a crucial factor that influences learning of individuals in educational settings (Pekrun, 2006). It also affects creativity (Hu and Wang, 2010). Positive emotions are associated with a wider attention span, global information processing (Fredrickson, 2004), and improved creativity implicated in the appreciation of poetry, which may explain the better learning performance in positive conditions regardless of internal colorful design or external emotion induction.

Although science, committed to revealing the truth of nature, and art (humanities), committed to create beauty and to express inner desires and emotions, are two different aspects of human activities and inquiries, the findings replicated the results of multimedia learning in natural science disciplines. This supports the statement, "In education, the perfect combination of science and humanities is the hope of cultivating talents who can meet the development needs of the new century" made by Li Zhengdao, a Chinese physicist.

Implications and Limitations

Two theoretical implications can be derived from this study. First, according to the purposes of prior studies, results from emotional design studies on natural sciences, such as biology (Park et al., 2015; Knörzer et al., 2016), physics (Mayer, 2005; Gong et al., 2017; Uzun and Yildirim, 2018), and astronautics (Kühl et al., 2018) can be transferred to humanities. Meanwhile, humanities, such as story reading (Takacs and Bus, 2016) and appreciation of poetry, seems to require learners to actively and creatively construct and have a closer bond with the relevant knowledge and experience of recipients. This suggests that the measures of learning effect may not be limited to conventional measures of retention, comprehension, and transfer. Therefore, it is necessary to seek other indicators that fit the attributes of the subject, such as esthetic evaluations. In practice, when implementing emotional designs in multimedia learning, not only is the emotional design of the learning material necessary but also the influence of existing emotions of learners when entering educational situations on subsequent learning should be considered.

Some limitations that should be considered: first, the topics of poems ranged throughout inspiration by love and desire, nature, social injustice, dreams, and many other situations (Piirto, 2011). Only one pastoral poem was studied in this research; thus, whether the results could be extended to other themes remain unanswered. In addition, the number of participants in different conditions in the preliminary and formal experiments was not the same, which may have resulted in experimental deviations. Future research should pay more attention to the choice of the number of participants to avoid possible errors. Moreover, as for the measurement of emotion, we used self-reported items before and after learning instead of an objective, continuous measurement. Finally, demographic variables, such as gender (Castroalonso et al., 2019) and age (Shangguan et al., 2020a), which may also have impact multimedia learning, need to be further investigated.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethical Committee of the School of Psychology at

Central China Normal University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

YW: conceptualization, acquisition, collection, analysis, interpretation, and drafting. ZZ: conceptualization, supervision, and validation. SG: conceptualization, interpretation, revision of the study, and validation. DJ: revision of the draft. JL: design of the learning materials and tests. All authors contributed to the article and approved the submitted version.

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Teacher Suggestion Feedback Facilitates Creativity of Students in STEAM Education

Sha Shen[1], Saidi Wang[2], Yun Qi[1], Yanli Wang[1] and Xiangdong Yan[3]*

[1] College of Educational Science and Technology, Northwest Minzu University, Lanzhou, China, [2] Gansu 24 Refractive New Media Technology Co., Ltd., Lanzhou, China, [3] Shanghai Hui Ye (Lan Zhou) Law Office, Lanzhou, China

This study examined the influence of the formative feedback types of teachers on creativity in Science, Technology, Engineering, Art, Mathematics (STEAM) education. Participants were 90 undergraduate students who were randomly assigned to the teacher opinions feedback group, the teacher suggestion feedback group, or the non-feedback group, and took part in three courses of STEAM education of 3D-printing technology. Before and after each course, they were asked to fill out the Eugene Creativity Test. The results showed that compare with the teacher opinions feedback group and the non-feedback group, the participants in the teacher suggestion feedback group showed a higher score on the creativity scale. This suggests that the teacher suggestion feedback can be useful for improving the creativity in STEAM education.

Keywords: creativity, STEAM education, teachers' formative feedback, active learning, science skills

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****Correspondence:***
Saidi Wang
sforcld@163.com

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INTRODUCTION

Creativity is considered to be one of the core skills of the 21st century (e.g., Gajda et al., 2017; Shin and Jang, 2017), and has been noted to be a crucial human asset necessary to deal with complex reality effectively (Corazza, 2017). Creativity is generally defined as the ability to generate new and appropriate ideas (Feist and Barron, 2003; Boden, 2004). Creativity is particularly important for college students, which is considered to be one of the necessary skills for them (e.g., Lai and Viering, 2012; Podolsky and Pogozhina, 2017; Tirri et al., 2017).

Science, Technology, Engineering, Art, Mathematics (STEAM) education, as a popular pedagogical approach to teaching, seems to have the potential to improve the creativity of students (Liliawati et al., 2018). STEAM education can be defined as "education for increasing students' interest and understanding in scientific technology and for growing STEAM literacy based on scientific technology and the ability to solve problems in the real world" (Kofac, 2017, p. 3). STEAM education combines the arts with the STEAM subjects to increase engagement, creativity, innovation, and problem-solving skills of students (e.g., Liao, 2016; National Art Education Association [NAEA], 2016), which was able to inspire learners to become more different and to be creative thinkers (Liliawati et al., 2018). Furthermore, STEAM education can make students feel at ease, can help them understand the subject and apply it to daily life (Yakman and Lee, 2012).

Some studies indicated that STEAM education enhances the creativity of students (e.g., Root-Bernstein, 2015; Liao, 2016; Oner et al., 2016; Karaca, 2017; Khamhaengpol et al., 2021). For example, Khamhaengpol et al. (2021) developed a STEAM course on nanotechnology for high school students and took 180 high school students as participants. After finishing all the courses, they measured their basic science skills, engineering design process, and creativity. The results show that the basic science skills, engineering design process, and creativity of the participants have been significantly improved.

Though researchers agree that STEAM education enhances creativity, this skill is rarely measured in studies of STEAM education (Perignat and Katz-Buonincontro, 2019). More empirical studies need to conduct for providing more evidence of the enhancing effect of STEAM education on creativity. This is an urgent question because determining whether STEAM education can enhance the creativity of students is an early and critical step for conducting STEAM education on a large scale.

One of the vital factors that appear to have the potential to influence creativity is the formative feedback of teachers (Calavia et al., 2021). "Feedback" was first applied in the fields of electronic technology and machine control, and later gradually promoted in the social sciences such as psychology and biology. In the mid-20th century, the American psychologist Skinner first proposed "procedural teaching" and pointed out that the core of procedural teaching is immediate feedback, that is after students answer questions, they should be told whether the result is correct or not in time (Rinvolucri, 1994). In the field of teaching, feedback means that in the process of teaching, teachers compare the current behavior and performance of students with the set teaching objectives and then provide students with the feedback information, so that students can improve, change, or rebuild their knowledge system according to the feedback information received (Winne and Butler, 1994). The reinforcement theory holds that reinforcement is an important reason for the change of individual behavior (Skinner, 1957; Soh, 2017). For students, the feedback received in the teaching process is the most important influencing factor in the learning process and is also the core of effective learning (Hattie and Timperley, 2007; Hattie, 2008).

The formative feedback of teachers can be divided into opinions and suggestions according to the types of feedback (Gielen et al., 2010). The opinions feedback of the teacher refers to the feedback of the teacher of the quality of the answers of students in the previous test, such as your idea is good. The suggestion feedback of the teacher refers to the further and complete suggestions of the teacher of the answers given by the students in the previous test. For example, your idea is good and innovative, and you can find relevant information online to supplement your idea. Accumulative studies have shown that formative feedback of teachers can improve the critical thinking of students (e.g., Pedrosadejesus et al., 2014; Liwen and Liu, 2018). Furthermore, there is a significant and positive relationship between critical thinking and creativity of students (e.g., Fahim and Zaker, 2014; Nosratinia and Zaker, 2014). Does this imply that the formative feedback type of teachers influences the creativity in STEAM education?

The present study used the experimental method to investigate whether the formative feedback types of teachers (teacher opinions feedback group, teacher suggestion feedback, and nonfeedback) influence the creativity of students in STEAM education. Based on previous studies, these study hypotheses that the formative feedback types of teachers influence the creativity of students in STEAM education. Specifically, the creativity of the participants in the teacher suggestion feedback group was higher than the ones in the teacher opinions feedback group and non-feedback group.

METHOD

Participants

Freshmen from a Chinese university participated in the study ($N = 90$; 48 females). They were aged 16–20 years ($M = 17.74$ SD $= 0.83$). According to the interviews before the formal experiment, none of the participants had participated in a similar experiment. After the experiments, all the participants received a small gift worth 50 RMB. The study protocol was approved by the local academic committee.

Measures

Creativity

We used the Eugene Creativity Scale, which was compiled by Princeton Innovation Talent Research Company and has verified have good reliability and validity by domestic scholars in practice (e.g., Zhu et al., 2011; Wang, 2016). The scale includes 50 items, the first 49 items (e.g., "I do not do blind things, that is, I always have a target in mind, with the right steps to solve every problem.") were single-choice questions of the three choices (e.g., "yes," "no," and "I am not sure"). The 50th is a multiple-choice question, with a total of 54 alternative words, of which only 23 words have positive weight and the rest are selected with a weight value of 0.

Procedure

This experiment was a mixed experimental design of 3 (feedback type: teacher opinions feedback, teacher suggestion feedback, and non-feedback) × 3 (course time: the first course, the second course, and after the third course). Feedback type was the between-subjects variable, the participants were randomly assigned to the teacher opinions feedback group, the teacher suggestions feedback group, or the non-feedback group. The dependent variable was the creativity of participants which was measured by the total score on the Eugene Creativity Test.

Before the study, all the participants filled out the demographic questionnaire (gender and age) and the Eugene Creativity Test. Then, all the participants were randomly assigned to the teacher opinions feedback group, the teacher suggestions feedback group, or the non-feedback group. All the participants were given three courses of STEAM education (**Table 1**). In the opinions feedback situation of the teacher, the teacher only gave opinions feedback during the teaching process, such as your idea is good. In the situation of the teacher suggestion feedback, the teacher gave suggestions in the teaching process, such as your idea is good and innovative, you can find relevant materials on the Internet to supplement your idea. In the situation of the non-feedback feedback, the non-feedback is given to the students throughout the process. At the end of each course, all the participants filled out the Eugene Creativity Test.

RESULTS

Analysis of Variance for Pretests of Three Different Feedback Groups

First, ANOVA was used to calculate the differences in the creativity pretest scores of different feedback groups. The results

TABLE 1 | The procedure of the proposed STEAM activity.

Week	Timing (minutes)	STEAM activity content
1	60	Activity 1: What is 3D printing technology? In order to prepare students for this course, the teacher encourages students to think about 3D printed objects found in everyday life. After that, the teacher encouraged the students to go online and find the difference between the 3D printed objects and the traditional manufactured ones. In this activity, the students realized the important role of 3D printing technology in daily life, and knew that 3D printing is different from ordinary printing.
2	90	Activity 2: Different properties of 3D printed materials This activity is aimed at improving students' BBSP (Observation Skill proposed by the American Association for the Advancement of Science (AAAS, 1993).Students in each group were provided with materials commonly used in 3D printing, such as ABS plastic, PLA plastic, engineering plastic, industrial ABS material, PC material and nylon material. They observed the characteristics of different materials and discussed the uses of different materials. After that, show students how to use 3D technology and PC plastic to print a water and introduce the principle of 3D printing technology.
3	90	Activity 3: Design a 3-D item Each group of students had a period to brainstorm and share ideas among group members to design an object that could serve the public using concrete materials and 3D technology.

showed that there were no significant differences in creativity between the participants in the teacher opinions feedback group (M = 15.47, SD = 5.09), the ones in the teacher suggestion feedback group (M = 16.83, SD = 6.66), and the ones in the nonfeedback group (M = 15.70, SD = 4.76) before receiving STEAM education, F (89) = 0.52, p =0.60 > 0.05.

ANOVA of Teacher Feedback Type and Course Time on Creativity

The ANOVA results of 3 (teacher feedback type: opinions type, suggestion type, and nonfeedback) × 2 (course time: the first course, the second course, and after the third course) showed that the main effect of course was significant, $F_{(2,174)} = 566.85$, $p = 0 < 0.001$, $\eta 2 = 0.87$. The creativity score of the participants after the third course (M = 52.07, SD = 0.68) was significantly higher than that after the first course (M = 23.83, SD = 0.72), $d = 29.23$, $p = 0 < 0.001$, and significantly higher than the creativity score after the second course (M = 35.66, SD = 0.87), $d = 16.41$, $p = 0 < 0.001$. The creativity score of the participants after the second course was significantly higher than that after the first course, $d = 12.82$, $p = 0 < 0.001$. The results showed that the creativity of participants improved significantly after receiving the STEAM course.

In addition, the main effect of teacher feedback type was significant, F (2, 87) = 171.95, $p = 0 < 0.001$, and $\eta 2 = 0.80$. The creativity score of the participants in the teacher suggestions feedback group (M = 51.82, SD = 0.99) was significantly higher than the ones in the teacher opinions feedback group (M = 30.47, D = 0.99), $d = 21.36$, $p = 0 < 0.001$. The creativity score of the participants in the teacher suggestions feedback group (M = 51.82, SD = 0.99) was significantly higher than the ones in the nonfeedback group (M = 28.27, SD = 0.99), $d = 23.56$, $p = 0 < 0.001$. However, there were no significant differences between the ones in the teacher opinions feedback group and the nonfeedback group, $d = 2.20$, $p = 0.12 > 0.05$. The results showed that compared with the nonfeedback and the teacher opinion feedback, the teacher suggestion feedback is more significant in promoting the creativity of students in the STEAM course.

Furthermore, the interaction between teacher feedback type and course was significant, F (4, 174) = 18.92, $p = 0 < 0.05$, and $\eta 2 = 0.3$ (as shown in **Figure 1**). After receiving the first STEAM education, the creativity score in the teacher suggestions feedback group (M = 32.63, SD = 1.79) was significantly higher than the ones in the teacher opinions feedback group (M = 19.13, SD = 0.93), $d = 13.50$, $p = 0 < 0.001$; and significantly higher than the ones in the nonfeedback group (M = 16.73, SD = 0.78), $d = 15.90$, $p = 0 < 0.05$. However, there were no significant differences between the ones in the teacher opinions feedback and the ones in the nonfeedback group, $d = 2.40$, $p = 0.18 > 0.05$. After receiving the second STEAM education, the creativity score in the teacher suggestions feedback group (M = 50.47, SD = 1.99) was significantly higher than the ones in the teacher opinions feedback group (M = 30.20, SD = 1.45), $d = 26.30$, $p = 0 < 0.001$; and significantly higher than the ones in the nonfeedback group (M = 26.30, SD = 0.88), $d = 24.17$, $p = 0 < 0.05$. However, there were no significant differences between the ones in the teacher opinions feedback and the ones in the nonfeedback group, $d = 3.90$, $p = 0.07 > 0.05$. After receiving the third STEAM education, the creativity score in the teacher suggestions feedback group (M = 72.37, SD = 1.31) was significantly higher than the ones in the teacher opinions feedback group (M = 42.07, SD=1.12), $d = 30.30$, $p = 0 < 0.001$; and significantly higher than the ones in the nonfeedback group (M = 41.77, SD = 1.10), $d = 30.60$, $p = 0 < 0.05$. However, there were no significant differences between the ones in the teacher opinions feedback and the ones in the nonfeedback group, $d = 0.30$, $p = 0.86 > 0.05$. The results showed that compared with the teacher opinions feedback and the nonfeedback, the teacher suggestion feedback can promote the creativity of the participants significantly even receiving the multiple STEAM education.

DISCUSSION

The present study examined whether the formative feedback types of teachers influenced the creativity of students in STEAM education. It was found that the creativity score of the participants in the teacher suggestion feedback group was significantly higher than that of the teacher opinions feedback group and the nonfeedback group. However, there were no significant differences between the ones in the teacher opinions group and the nonfeedback group. The results indicated that one of the key conditions for STEAM education to foster student creativity is to provide the students with the teacher suggestions feedback. Although researchers have admitted the

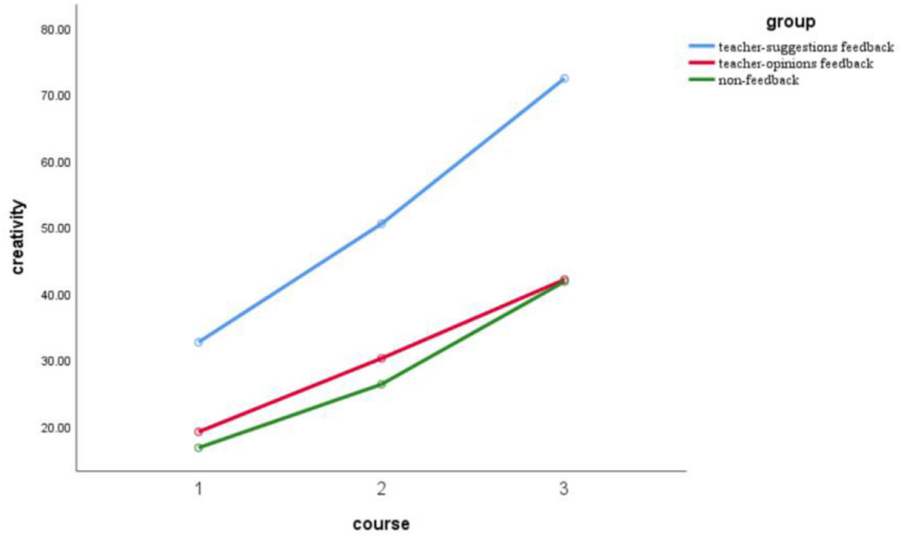

FIGURE 1 | Teacher feedback type and course time on creativity.

potential effects of the formative feedback of teachers to creativity in STEAM education, the present study was the first attempt to examine this argument.

The present study showed that in STEAM education, the suggestion feedback of teachers promoted the creativity of students, which was consistent with the opinions of the previous studies. Studies showed that creativity is learned by the practice (Root-Bernstein, 2015), and teachers should shape the creative behavior by supporting the feedback (e.g., Cropley, 1995; Sternberg and Williams, 1996; Runco, 2014). In addition, the present study was consistent with the reinforcement theory. According to the reinforcement theory of Skinner, the behavior changes because of the reinforcement and the control of reinforcement is the control of behavior (Skinner, 1957). For learners, the feedback they receive during a course is one of the most powerful influences on their learning process (Hattie and Timperley, 2007) and central to effective learning development (Sadler, 1989). Based on a meta-analysis of more than 7,000 studies on teacher feedback in real classroom situations, Hattie and Timperley (2007) showed that the most effective feedback is to provide clues or reinforcement for the learners, associated with the correct behavior or other criteria related to the task completion. In addition, the exploratory studies of the teacher feedback in online collaborative writing tasks have shown that the learners can improve their learning if the feedback includes suggestions and questions, rather than just direct corrections.

The present study has several limitations. First, using only one creativity scale as a measure of creativity may cause the results to lack ecological validity. Future research could add other creative tasks to validate this experiment (e.g., open-ended realistic problem; Pi et al., 2019). In addition, in the process of the teaching process, the feedback of the students may also affect the results of this experiment. Future studies should examine the confounding factor to expand the understanding of the effects of teacher feedback on creativity.

This study has important theoretical significance for developing the development of an effective STEAM model. For STEAM education to develop into an effective teaching method, research is needed to understand what STEAM means in practice. Though researchers posit that STEAM education is an effective pedagogy for enhancing creativity, few empirical studies were conducted to support this notion. In addition, riches of studies indicated that arts education enhances cognitive and academic ability, whether these benefits can be transferred to STEAM education remains unclear (Perignat and Katz-Buonincontro, 2019). The present study provided evidence for the view that STEAM education is a model for enhancing creativity. In addition, this study has an important practical significance for expanding the research field of teacher feedback and creativity. Studies have examined the associations between teacher feedback and critical thinking and revealed a positive relationship between them (e.g., Pedrosadejesus et al., 2014; Liwen and Liu, 2018). However, few studies have examined the relationship between teacher feedback and creativity. To date, this is the first attempt to examine the relationships between teacher feedback and creativity under the background of STEAM education. Furthermore, this study is of great practical signicance in improving the creativity of the students. For example, in the process of STEAM teaching, we need to strengthen the suggestion feedback of teachers to promote the improvement of the creativity of students.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

This research was approved by the Ethics Committee of the College of Educational Science and Technology of Northwest Minzu University. All participants were volunteers who provided written informed consent, and they were told they could quit the experiment at any time if they didn't want to go on.

AUTHOR CONTRIBUTIONS

SS, SW, and YW proposed the original thoughts and conducted the experiments. YQ and XY collected the data and completed the article revisions. All the authors were involved in the writing of the article and approved the submitted version.

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Analysis of Critical Thinking Path of College Students Under STEAM Course

Jingrong Sha[1]*, *Hong Shu*[1] *and Zhaocao Kan*[1,2]

[1] *College of Educational Science and Technology, Northwest Minzu University, Lanzhou, China,* [2] *College of Teacher Education, East China Normal University, Shanghai, China*

This study examined the differences in critical thinking levels among students with different levels of academic engagement in STEAM courses. In this study, 30 college students were selected as subjects. Before experimenting, they received the academic engagement test and were divided into high, medium, and low groups based on their performance. Then, each group received three STEAM sessions and was asked to complete a topic discussion task. The results show that there are significant differences in the critical thinking level of students with different levels of academic engagement. Specifically, the students with a medium level of academic engagement had the highest critical thinking. Research has shown that the level of academic engagement affects the critical thinking of students in STEAM courses.

Keywords: STEAM, STEAM course, critical thinking, academic engagement, science skills

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Correspondence:
Jingrong Sha
shajr818@163.com

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INTRODUCTION

Critical thinking is one of the twenty-first skills centuries for contemporary college students, ranking as the most sought-after higher-order thinking skills, along with creativity, collaboration, and problem-solving (Lai and Viering, 2012; Vasilyev et al., 2015; Podolsky and Pogozhina, 2017). Critical thinking is defined as purposeful, self-calibrated judgment. This kind of judgment manifests itself in interpretation, analysis, evaluation, inference, and the explanation of the evidence, concept, method, standard, or context on which the judgment depends (Nair and Lynnette Leeseberg, 2013).

The studies indicated that the STEAM course has the potential to improve the critical thinking of students (Allamin et al., 2018; Siregar et al., 2019). The STEAM course is an interdisciplinary and integrated course that combines science, technology, engineering, art, and mathematics (Yakman, 2008; Corbo et al., 2014; Hwang, 2017). In the STEAM course, students can focus on the specific problems rather than being confined to a single subject boundary, and they can practice their thinking from different perspectives and develop cross-border communication in the context of diversified development (Yakman, 2008; Corbo et al., 2014; Hwang, 2017; Hatlevik, 2018). The STEAM course is designed to guide learners to develop problem-solving, critical thinking, and collaboration skills (Tillinghast et al., 2015).

The previous studies results are not consistent on whether STEAM course improves the critical thinking of students. For example, Ridwan et al. (2020) implemented a STEAM course based on a smoke absorber project in a high school chemistry course. Through simple analysis of online discussion texts, the study found that STEAM courses can promote the development of the critical thinking of students (Ridwan et al., 2020). However, other researchers have found a different result. For example, Ho Sha (2019) explored the changes in the critical thinking level of students before

TABLE 1 | Steam course design and implementation plan.

STEAM course	Engineering design process	STEAM event plan	Activity content	Discussion theme	STEAM element integration
1	1. Identify the Theme/requirements	– Students identify subject-related needs	– Searching and summarizing the content of engineering thinking, ADDIE teaching thought, structure, design and so on online in groups	Combined with ADDIE's instructional design analysis and engineering ideas, this paper discusses how to do a good job in online course design	Connotation, structure, and design of engineering thinking and overall course process design—integration of science content and engineering content
	2. Gather ideas/explore information	– Students use technology to find solutions – The students did experiments related to the STEAM event			
2	3. Solution design	– Students put their heads together to come up with more possible solutions – Students design online course plans	– Searching online course design examples by myself in groups – Collect the similarities and differences of cases through group discussion – Plan the overall curriculum by myself in combination with scientific content and engineering thinking	Discuss the design of the online learning program based on the results of the demand survey and analysis	Mathematical statistics for needs analysis, learning activity design—the integration of mathematical content and engineering content
	4. Implementation and development	– Students take online courses	– Design the needs analysis questionnaire – Distribution and collation of data results – Based on the analysis results of learning rules and characteristics, online learning activities were designed in the form of group discussion		
3	5. Test, evaluate, and design improvements	– Students test and evaluate online courses – Students adapt their online courses to their needs	– Technical support and interactive interface design (graphic design, interaction design, user research, etc.) for the group's online course – Online course evaluation test was conducted for each group and improved according to the actual situation	Combined with the content of online platform technical support and interface design, how to do a good job of online learning support and service?	Online teaching and learning support, friendly interface design—the integration of art and technology content
	6. Display of works	– Students share their designs and successes with the class through demonstrations	– Students report online courses in groups, highlight the advantages and innovations, and evaluate them by their fellow teachers		

TABLE 2 | Behavior switching frequency of critical thinking process in the low engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2	Totals
R1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
R2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	0	0	0	0	0	0	1	0	0	0	0	2	0	0	0	1	0	0	0	0	0	1	0	0	0	5

TABLE 3 | Behavioral adjustment residual values of critical thinking process in the low engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2
R1	0	0	0	0	0	0	−0.72	0	0	0	0	−0.83	0	0	0	2.55*	0	0	0	0	0	−0.51	0	0	0
R2	0	0	0	0	0	0	1.45	0	0	0	0	−0.83	0	0	0	−0.51	0	0	0	0	0	−0.51	0	0	0
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	0	0	0	0	0	0	0	0	0	0	0	1.67	0	0	0	−1.02	0	0	0	0	0	−1.02	0	0	0
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	−0.72	0	0	0	0	−0.83	0	0	0	−0.51	0	0	0	0	0	2.55*	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

**Indicates that the Z-score value is significant.*

and after the implementation of the STEAM course and found that the critical thinking level of students did not improve significantly.

The cultivation of critical thinking in STEAM courses may be influenced by academic engagement. In the study, each student has a different degree of academic engagement (Curry, 1984; Nystrand, 1989; Cancelli, 1993). The research found that academic investment can affect the self-efficacy of students (Yüksel and Alci, 2012; Samareh and Kezri, 2016). Specifically, students with high education have more self-efficacy (Samareh and Kezri, 2016). In addition, the study found that self-efficacy and critical thinking were significantly correlated, specifically, the higher the self-efficacy of students, the higher the level of academic engagement (McKinnon, 2012; Dong, 2016). Then, academic engagement may affect critical thinking in the STEAM curriculum.

This study aimed to examine whether the implementation of STEAM courses had significant differences in the development of critical thinking levels of students at different levels of academic engagement (high, medium, and low). Based on previous research, this study hypothesizes that academic engagement affects the critical thinking of students in STEAM courses. Specifically, the higher the level of academic engagement, the higher is the critical thinking level of students in STEAM courses.

METHODS

Participants

The participants in this study were 30 college students (14 male students and 16 female students). The average age of the participants was 20.43 (SD = 0.89). All participants received a small gift worth 30 RMB after the completion of the experiment. The study protocol was approved by the local Academic Committee.

This experiment was an in-subject experiment design, and all subjects received three STEAM courses. The subjects were asked to fill out the questionnaire before receiving the experimental treatment, and according to the results, the subjects were divided into groups with high, medium, and low academic involvement.

Measures

Academic Engagement Scale

The Academic Engagement Scale (Awang-Hashim and Sani, 2008) is used to measure the academic engagement of students in school learning activities. The scale is divided into three dimensions: "behavioral engagement," "cognitive engagement," and "emotional engagement." The scale has a total of 29 items, which consist of eight items of behavioral engagement, 10 items of cognitive engagement, and 11 items of affective engagement. The scale uses Likert-five assessment, with 1 representing "completely inconsistent" and 5 representing "completely consistent." The higher the score, the higher is the degree of academic engagement. The internal consistency coefficient of the scale was 0.851, among which the behavioral engagement dimension coefficient was 0.782, the cognitive engagement dimension coefficient was 0.835, and the affective engagement dimension coefficient was measured to 0.742.

Critical Thinking Coding Tool

The study adopted the critical thinking coding tool proposed by Murphy (2004) and added the "Null" dimension (encoding topics unrelated to the course and opinions purely expressing emotions) in this study. The critical thinking coding tool is divided into six dimensions: recognition, understanding, analysis, evaluation, creation, and null value, including a total of 25 specific indicators.

Online Collaboration Platform

Each group establishes a group online cooperative learning community through QQ. It is a widely used instant messaging software in China, which can realize voice and text communication, file transfer, and other functions. Before the experiment, the participants were informed that the teacher would post the course tasks that needed to be solved in each class on the QQ group and asked them to discuss according to the task requirements proposed by the teacher, and finally put forward a group plan.

Procedure

Before the formal experiment, each participant was required to complete the Academic Engagement Scale. Then, the experimenter divided the participants into three groups according to the academic engagement questionnaire: high, medium, and low. After that, all participants were given three STEAM sessions. Each course lasts 90 min, and the contents of the three courses are shown in **Table 1**.

At the end of the three sessions, the online discussion texts were collated for coding and lag sequence analysis (LSA). First, the two researchers coded the code together. They are familiar with coding tools for critical thinking and have discussions before coding. In the coding process, the two researchers separately encoded the text of the online discussion. After the formal coding was completed, 154 texts were randomly checked by the two coders to verify the consistency of the coding results of the two researchers. The results show that the Kappa consistency coefficient is 0.75, which indicates that the data encoding has good reliability and can be used for LSA. Second, GSEQ software

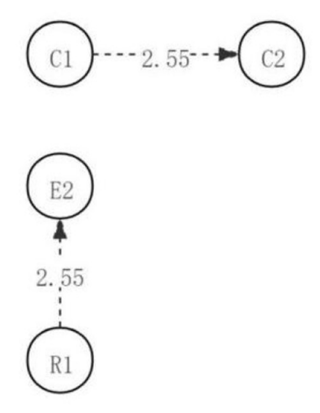

FIGURE 1 | The critical thinking discussion activity path diagram of the low engagement group.

TABLE 4 | Behavioral adjustment residual values of critical thinking process in the medium engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2	Totals
R1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
R2	0	0	0	1	0	0	0	0	1	0	0	3	0	0	0	0	0	0	1	0	0	0	0	0	0	6
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	2	0	0	0	0	0	0	8
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	0	0	0	0	0	0	0	0	4
A2	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	3
A3	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
A4	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	3	0	0	0	0	0	0	11
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	2
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3	0	0	0	0	0	0	4
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	3
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	0	1	0	1	0	0	0	0	1	0	1	13	9	0	1	1	2	0	10	3	0	3	0	0	0	46

TABLE 5 | Behavioral adjustment residual values of critical thinking process in the medium engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2
R1	0	6.9*	0	−0.14	0	0	0	0	−0.15	0	−0.14	−0.71	−0.47	0	−0.14	−0.15	−0.2	0	−0.51	−0.25	0	−0.25	0	0	0
R2	0	0	0	2.84*	0	0	0	0	2.7*	0	−0.37	0.7	−1.24	0	−0.37	−0.38	−0.53	0	−0.25	−0.65	0	−0.65	0	0	0
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	0	−0.46	0	−0.43	0	0	0	0	−0.45	0	−0.43	2.43*	−1.45	0	−0.43	−0.45	−0.62	0	0.39	−0.76	0	−0.76	0	0	0
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	−0.31	0	−0.29	0	0	0	0	0	0	−0.29	−0.46	0.39	0	3.5*	−0.3	2.29*	0	−1.07	−0.52	0	−0.52	0	0	0
A2	0	−0.26	0	−0.25	0	0	0	0	−0.26	0	4.13*	1.1	−0.84	0	−0.25	−0.26	−0.36	0	−0.91	−0.44	0	−0.44	0	0	0
A3	0	−0.15	0	−0.14	0	0	0	0	−0.15	0	0	1.26	−0.48	0	−0.14	−0.15	−0.2	0	−0.52	−0.25	0	−0.25	0	0	0
A4	0	−0.69	0	−0.65	0	0	0	0	−0.68	0	−0.66	0	3.69*	0	−0.66	−0.68	−0.94	0	−0.3	−1.16	0	−1.16	0	0	0
A5	0	−0.23	0	−0.22	0	0	0	0	−0.23	0	−0.22	−1.12	0	0	−0.22	−0.23	−0.32	0	0.85	−0.39	0	2.48*	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	−0.15	0	−0.14	0	0	0	0	−0.15	0	−0.14	−0.72	−0.48	0	0	6.98*	−0.2	0	−0.52	−0.25	0	−0.25	0	0	0
E2	0	−0.31	0	−0.29	0	0	0	0	−0.3	0	−0.29	−1.49	−0.99	0	−0.29	0	2.29*	0	2.85*	−0.52	0	−0.52	0	0	0
E3	0	−0.15	0	−0.14	0	0	0	0	−0.15	0	−0.14	−0.73	−0.48	0	−0.14	−0.15	0	0	−0.52	4.08*	0	−0.25	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	−0.29	0	−0.28	0	0	0	0	−0.29	0	−0.28	−1.41	−0.94	0	−0.28	−0.29	−0.4	0	0	4.18*	0	1.84	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	−0.15	0	−0.14	0	0	0	0	−0.15	0	−0.14	−0.71	−0.47	0	−0.14	−0.15	−0.2	0	−0.51	−0.25	0	4.17*	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Indicates that the Z–score value is significant.

is used to analyze the lag sequence. Lagging sequence analysis produces two important tables, namely, behavior conversion frequency table and adjustment residual table. According to the theory of LSA, the Z-score >1.96 indicates that this behavior path is significant (Sjalander et al., 1996). Finally, the behavior transformation diagram is drawn according to the important behavior sequence. The result is research on critical thinking levels.

RESULTS

The Critical Thinking Pathways of Participants With Different Levels of Academic Engagement After the First STEAM Course

According to the coding results, the characteristics of critical thinking pathways of the low, medium, and high academic engagement group students after the first course were analyzed. The specific results are analyzed as follows.

The results showed that, for students with low academic engagement, there are four kinds and five effective single sequences in this stage, such as R2→U5, U5→A4, R1→E1, and C1→C2, as shown in **Table 2**. For the first time to talk about the single sequence including identification agree with to understand answer questions (R2→U5), understanding to answer the question—analysis explanation view (U52→A4), preliminary identification problem to determine the effectiveness of the current information and value point (R12→E1), project implementation plan to create design new ideas (C12→C2) sequence, respectively 1, 2, 1, 1.

The adjusted residual was calculated by GSEQ software (as shown in **Table 3**). Among them, there are two significant sequences with residual values >1.96, namely, preliminary identification of problems → judgment of the validity and value points of current information (R1→E1), application of implementation plan → creation of new ideas (C1→C2). In addition, according to the adjusted sequence of significant behavioral residuals, a complete directed path diagram of learning activities is generated, as shown in **Figure 1**. As can be seen from the visual path diagram discussed in the first discussion, students in the low engagement group initially identified the problem and then judged the validity and value of the information provided. Students will be inspired to put forward new ideas, strategies, and methods based on applying new ideas and plans.

The results showed that for students with medium academic engagement, U5→A4, A4→A5 are generated in this stage, with a total of 25 kinds and 46 effective single sequences, as shown in **Table 4**. The single sequence generated in the first discussion includes understanding and answering questions → analyzing and explaining viewpoints (U5→A4), analyzing and explaining viewpoints → decomposition of problem viewpoints (A4→A5). There are six and eight sequences, respectively, and there are relatively few process sequences from creating (C).

As can be seen from the visual path diagram of the first discussion, after the students understand and answer the questions, they then analyze and explain the questions, and further decompose the views of the current problems, to

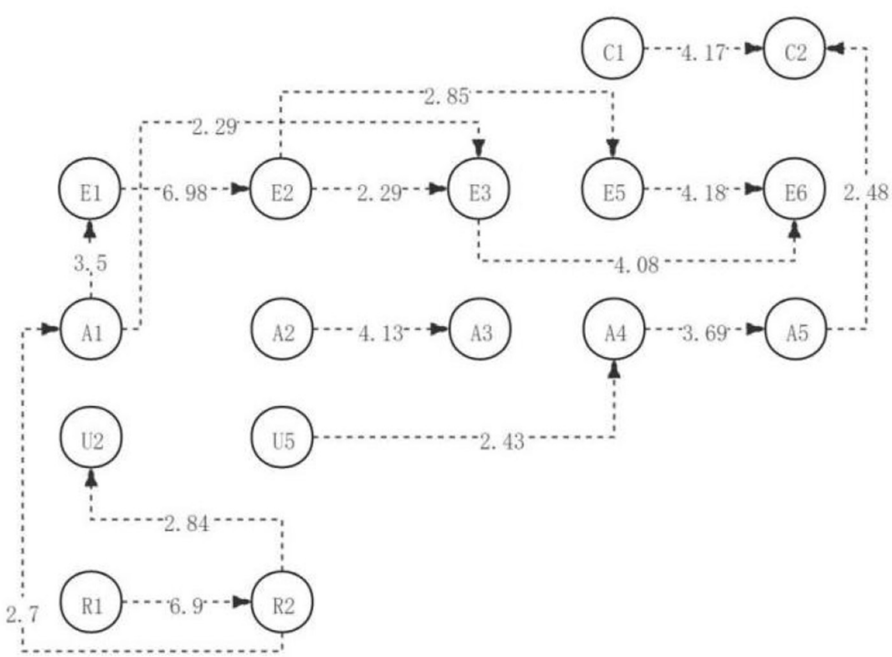

FIGURE 2 | The critical thinking discussion activity path diagram of the medium engagement group.

TABLE 6 | Behavioral adjustment residual values of critical thinking process in the high engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2	Totals
R1	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3
R2	1	0	0	0	0	1	0	0	0	0	0	4	0	0	0	0	0	0	1	0	0	0	0	0	0	7
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
U3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	1	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	4
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2
A2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	2	2	0	0	0	1	1	0	0	3	1	8	1	0	0	1	0	0	1	0	0	0	0	0	0	21

TABLE 7 | Behavioral adjustment residual values of critical thinking process in the high engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2
R1	0	−0.75	0	0	0	−0.42	2.19*	0	0	−0.78	2.51*	−0.28	−0.42	0	0	−0.43	0	0	−0.42	0	0	0	0	0	0
R2	0.28	0	0	0	0	1.4	−0.81	0	0	−1.38	−0.74	0.95	−0.74	0	0	−0.75	0	0	1.4	0	0	0	0	0	0
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	−0.34	−0.39	0	0	0	−0.22	−0.24	0	0	−0.41	−0.22	−0.79	−0.22	0	0	4.74*	0	0	−0.22	0	0	0	0	0	0
U3	−0.34	−0.39	0	0	0	−0.22	−0.24	0	0	2.61*	−0.22	−0.79	−0.22	0	0	−0.22	0	0	−0.22	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	1.04	0.71	0	0	0	−0.48	0	0	0	0.68	−0.48	−0.62	−0.48	0	0	−0.5	0	0	−0.48	0	0	0	0	0	0
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	−0.49	−0.56	0	0	0	−0.32	−0.35	0	0	1.6	−0.32	0.42	−0.32	0	0	−0.32	0	0	−0.32	0	0	0	0	0	0
A2	−0.37	−0.42	0	0	0	−0.23	−0.26	0	0	0	−0.23	1.15	−0.23	0	0	−0.24	0	0	−0.23	0	0	0	0	0	0
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	−0.43	−0.49	0	0	0	−0.27	−0.3	0	0	−0.51	−0.27	0	3.77*	0	0	−0.28	0	0	−0.27	0	0	0	0	0	0
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	−0.35	2.52*	0	0	0	−0.22	−0.25	0	0	−0.42	−0.22	−0.81	−0.22	0	0	0	0	0	−0.22	0	0	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

**Indicates that the Z-score value is significant.*

create new views for the current problems to be solved (U5→A4→A5→C2). During the discussion, students usually create new ideas (C1→C2) based on creating and implementing new ideas, new conclusions, or new plans. The next step in the classification of evidence is usually to further analyze the similarities and differences between opinions (A2→A3). After the preliminary identification of repeated problems, most students responded to agree with the current specific problems. Then, they will join themselves to solve the current problems of new or new ways of thinking, next, the difference in the behavior way, part of the society, and to detect the current point of view of the consistency and inconsistency. Finally, the students will show their acceptance or refutation of the views and explain why and list the arguments (R1→R2→A1→E3→E6). The other students will first judge the validity of the information sources and the value of the information itself, and then, they further criticize the views themselves, and then put forward their views and find relevant arguments to support the arguments. Finally, we will summarize and state the acceptance or refutation and explain the reasons for the argument (R1→R2→A1→E1→E2→E5→E6). In this process, some students will first test the consistency and inconsistency after criticizing the opinions. Then, directly discuss the acceptance or refutation and explain the reasons for the argument (R1→R2→A1→E1→E2→E3→E6). The common points presented by the visualization path chart are: students will first identify and clarify the existing views, problems, and contradictions, then, explain in-depth, organize the known information, clarify the unknown information, decompose the basic elements of the opinions or problems, and finally clearly criticize and judge the information or opinions. In addition, according to the adjusted sequence of significant behavioral residuals, a complete directed path diagram of learning activities is generated, as shown in **Figure 2**.

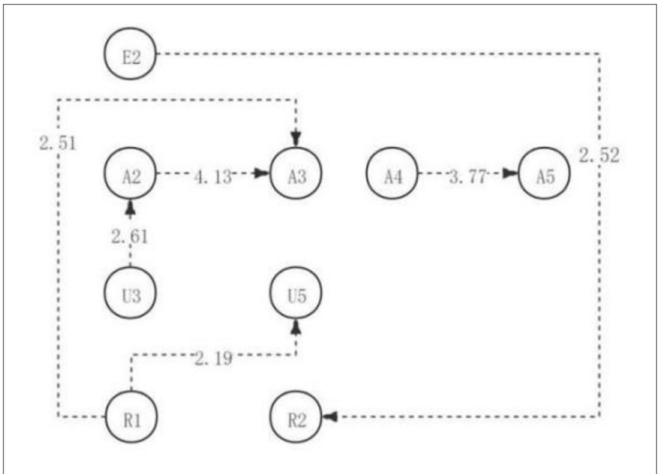

FIGURE 3 | The critical thinking discussion activity path diagram of the high engagement group.

Among them, there were 15 significant sequences with residual values greater than 1.96 (as shown in **Table 5**).In other words, identify the restatement question→identify the agreement question (R1→R2), identify the agreement opinion→understand and answer the question (R2→U2), identify the agreement question→add new thinking behavior (R2→A1), understand and answer the question→analyze and explain the opinion (U5→A4), add new thinking behavior→judge the validity of information (A1→E1), add new thinking behavior→test 1Causes and inconsistencies (A1→E3), evidence classification→analysis of opinion similarities and differences (A2→A3), analysis and interpretation of opinion→decomposition of problem opinion (A4→A5), decomposition of problem opinion→creation of new opinion (A5→C2), judgment of information validity→critical opinion hypothesis (E1→E2), critical opinion hypothesis→detection of consistency and inconsistencies (E2→E3), critical opinion hypothesis→evidence supporting the argument (E2→E5), detection of consistency and inconsistency→refute acceptance and evidence (E3→E6), evidence supporting the argument→refute acceptance and evidence (E5→E6), evidence supporting the argument→create a new idea (E5→C2), application of implementation plan→create a new idea (C1→C2).

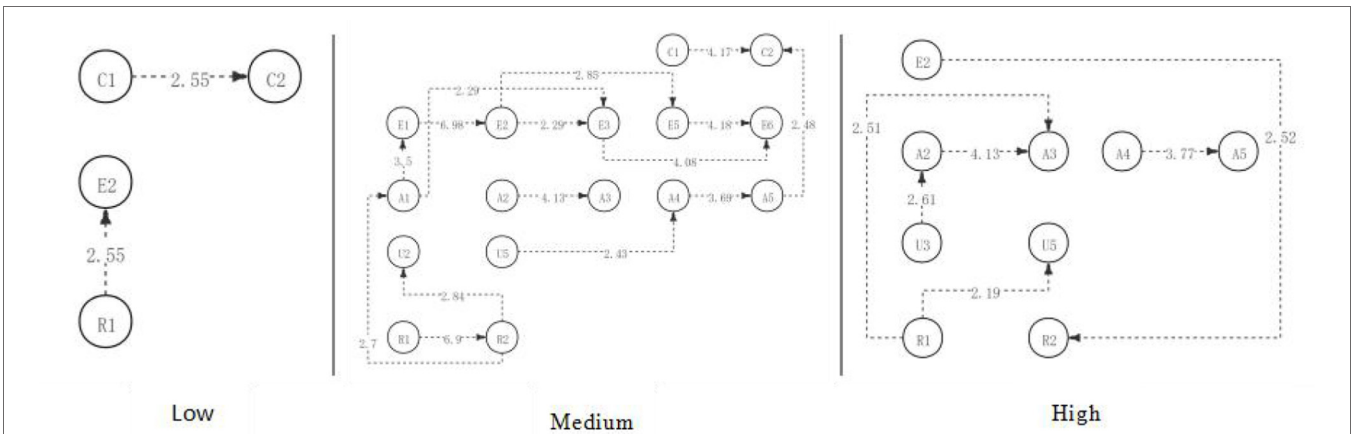

FIGURE 4 | The critical thinking discussion activity path diagram of the different engagement group.

The results showed that for students with high academic engagement, this stage mainly produces 18 kinds of R2→A4 and 21 effective single sequences, as shown in **Table 6**. The single sequences generated in the first discussion mainly include identification and approval point → analysis and explanation point (A4→A5), and there are four sequences in total.

Among them, there are five significant sequences with a residual value >1.96 (as shown in **Table 7**). Identifying and reiterating questions → understanding and answering questions (R1→U5), identifying and reiterating questions → analyzing similarities and differences of viewpoints (R1→A3), searching for different evidence → classification and classification of evidence (U3→A2), analyzing and explaining viewpoints → decomposition of viewpoints (A4→A5), and criticizing assumptions → identifying and approving questions (E2→R2). In addition, according to the adjusted sequence of significant behavioral residuals, a complete directed path diagram of learning activities is generated, as shown in **Figure 3**. As can be seen from the visual path diagram of the first discussion, after the initial identification of the problem, some students in the high engagement group proceeded to evaluate and clarify the problem to explore its essence (R1→U5), while some students proceeded to analyze the similarities and differences of various viewpoints (R1→A3). After looking for different pieces of evidence, students will further classify the collected evidence (U3→A2). After analyzing and explaining ideas, students will further decompose their ideas (A4→A5). Students criticize the opinion, but at the same time, they put forward the part that they agree with (E2→R2).

The results above indicated that, to sum up, in the first discussion, students with high, medium, and low academic engagement showed significant differences in the visualized critical thinking activity path diagrams in the discussion activities (as shown in **Figure 4**). However, contrary to the expectations, students in both the low and medium engagement groups reached the highest level of critical thinking—creativity; students in the high engagement group only reached the evaluation level. In contrast to the previous hypothesis, there were more significant behavioral sequences in the medium engagement group than in the high engagement group. The significant behavior sequence of critical thinking activities of students in the high and medium engagement groups was more than that in the low engagement group, which was consistent with the hypothesis of the study.

Critical Thinking Pathways of Participants With Different Levels of Academic Engagement After the Second STEAM Course

According to the coding results, the characteristics of critical thinking pathways of students in low, medium, and high academic engagement groups were analyzed. The specific results are analyzed as follows.

For students with low academic engagement, only one effective single sequence U5→A4 is generated at this stage, as shown in **Table 8**. However, there was no significant behavioral residual (as shown in **Table 9**).

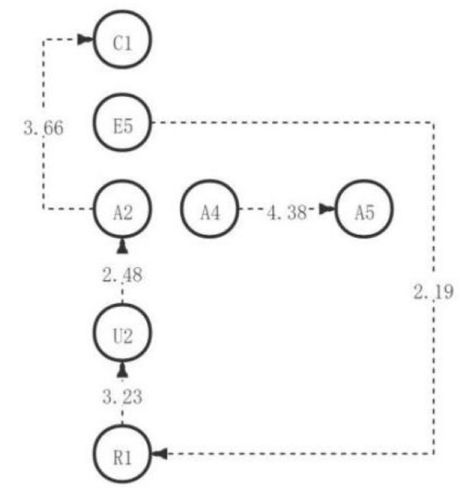

FIGURE 5 | The critical thinking discussion activity path diagram of the medium engagement group.

For students with medium academic engagement, 12 kinds and 18 effective single sequences are generated in this stage, such as U2→A2, R1→U2, R2→R1, A2→C1, as shown in **Table 10**. The second discussion produced more single sequences mainly for understanding and seeking relevant content → evidence classification and classification (U2→A2). There were four sequences in total and relatively few sequences from the process of creating (C).

Among them, there are five significant sequences with a residual value >1.96 (as shown in **Table 11**). That is, to identify and reiterate the problem → understand and search for relevant content (R1→U2), understand and search for relevant content → classification and classification of evidence (U2→A2), classification and classification of evidence → application and implementation plan (A2→C1), analysis and explanation of viewpoints → decomposition of problem viewpoints (A4→A5), and supporting arguments → identification and reiterate the problem (E5→R1). According to the adjusted sequence of significant behavioral residuals, a complete directed path diagram of learning activities is generated, as shown in **Figure 5**. As can be seen from the visual path diagram of the second discussion, students in the input group initially identified the problem, then searched for some contents related to the problem, and then classified these contents. Finally, based on this, they implemented the new plans and ideas according to the requirements of the problem (R1→U2→A2→C1). After analyzing the current opinion, students will usually further break down the current opinion or the problem (A4→A5). After using evidence to support the argument, students will further reiterate the problem to be solved (E5→R1).

For students with high academic engagement, there are altogether eight kinds and 12 effective single sequences,

TABLE 8 | Behavioral adjustment residual values of critical thinking process in the low engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2	Totals
R1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1

TABLE 9 | Behavioral adjustment residual values of critical thinking process in the low engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2
R1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 10 | Behavioral adjustment residual values of critical thinking process in the medium engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2	Totals
R1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
R2	2	0	0	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	7
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	0	0	0	0	0	0	0	0	0	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	3	0	0	2	0	0	1	0	1	5	1	1	1	0	0	0	0	0	1	0	2	0	0	0	0	18

TABLE 11 | Behavioral adjustment residual values of critical thinking process in the medium engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2
R1	0	0	0	3.23*	0	0	−0.38	0	−0.38	−1.04	−0.38	−0.39	−0.38	0	0	0	0	0	−0.39	0	−0.55	0	0	0	0
R2	1.05	0	0	−1.34	0	0	1.46	0	1.46	−1.08	−0.78	1.38	−0.78	0	0	0	0	0	1.38	0	−1.13	0	0	0	0
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	−1.28	0	0	0	0	0	−0.65	0	−0.65	2.48*	1.6	−0.67	−0.65	0	0	0	0	0	−0.67	0	−0.95	0	0	0	0
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	−0.8	0	0	−0.7	0	0	−0.41	0	−0.41	0	−0.41	−0.42	−0.41	0	0	0	0	0	−0.42	0	3.66*	0	0	0	0
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	−0.48	0	0	−0.42	0	0	−0.24	0	−0.24	−0.67	−0.24	0	4.38*	0	0	0	0	0	−0.25	0	−0.35	0	0	0	0
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	2.19*	0	0	−0.42	0	0	−0.24	0	−0.24	−0.67	−0.24	−0.25	−0.24	0	0	0	0	0	0	0	−0.35	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

**Indicates that the Z–score value is significant.*

TABLE 12 | Behavioral adjustment residual values of critical thinking process in the high engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2	Totals
R1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
R2	0	0	0	1	0	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	4
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	1	0	0	1	0	0	1	0	2	1	0	0	1	0	0	1	0	0	0	0	4	0	0	0	0	12

TABLE 13 | Behavioral adjustment residual values of critical thinking process in the high engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2
R1	0	0	0	−0.33	0	0	−0.33	0	−0.47	2.61	0	0	−0.32	0	0	−0.32	0	0	0	0	−0.75	0	0	0	0
R2	−0.75	0	0	1.44	0	0	1.44	0	2.34	−0.89	0	0	−0.71	0	0	−0.71	0	0	0	0	−1.68	0	0	0	0
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	3.24*	0	0	0	0	0	−0.33	0	−0.47	−0.4	0	0	−0.32	0	0	−0.32	0	0	0	0	−0.75	0	0	0	0
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	−0.33	0	0	−0.33	0	0	0	0	−0.47	−0.4	0	0	−0.32	0	0	3.42*	0	0	0	0	−0.75	0	0	0	0
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	−0.8	0	0	−0.8	0	0	−0.8	0	−1.13	0	0	0	−0.76	0	0	−0.76	0	0	0	0	3.25*	0	0	0	0
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	−0.32	0	0	−0.32	0	0	−0.32	0	−0.45	−0.38	0	0	3.6*	0	0	−0.3	0	0	0	0	−0.71	0	0	0	0
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

**Indicates that the Z-score value is significant.*

such as R2→A1, A2→C1, in this stage, as shown in **Table 12**. In the second discussion, more single sequences were generated, mainly from the evidence classification → application implementation plan (A2→C1), with a total of four sequences, and relatively fewer from process sequences to creation (C).

Among them, there are six significant sequences with a residual value >1.96 (as shown in **Table 13**). That is, to identify and restate the problem → evidence classification and classification (R1→A2), identify and approve the problem → add new thinking behavior (R2→A1), understand and find relevant content → identify and restate the problem (U2→R1), understand and answer the problem → critical hypothesis (U5→E2), evidence classification and classification → application implementation plan (A2→C1), analyze and explain the point of view → problem view decompose (A4→A5). According to the adjusted sequence of significant behavioral residuals, a complete directed path diagram of learning activities is generated, as shown in **Figure 6**. As can be seen from the visual path diagram of the second discussion, students in the high engagement group initially identified the problem, then classified the evidence related to the problem, and directly put the new plan and new idea into practice on this basis (R1→A2→C1). Based on identifying the approval problem, students add new thinking or new behavior mode (R2→A1). After students understand the problem and look for relevant content, they further identify and reiterate the problem (U2→R1). After the students understand and answer the questions, they further criticize the current opinions (U5→E2). During the discussion, students usually breakdown the problem further (A4→A5) after explaining the current problem.

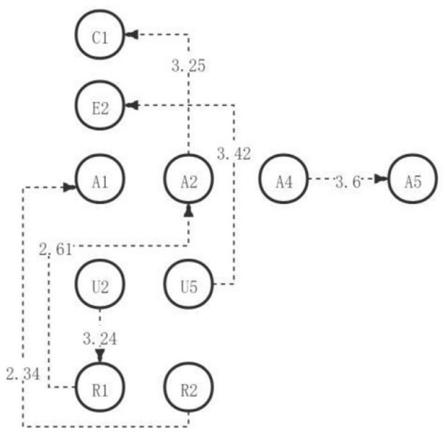

FIGURE 6 | The critical thinking discussion activity path diagram of the high engagement group.

Based on the above results, in the second discussion, students with high, medium, and low academic engagement showed significant differences in the visualized critical thinking activity path diagrams in the discussion activities (as shown in **Figure 7**). The low engagement group did not produce a significant behavior sequence in this discussion, which is consistent with the hypothesis. What is inconsistent with the hypothesis is that although both the medium engagement group and the high engagement group have reached the highest level of critical thinking—creation, the significant behavior path of the medium engagement group is significantly better than that of the high engagement group.

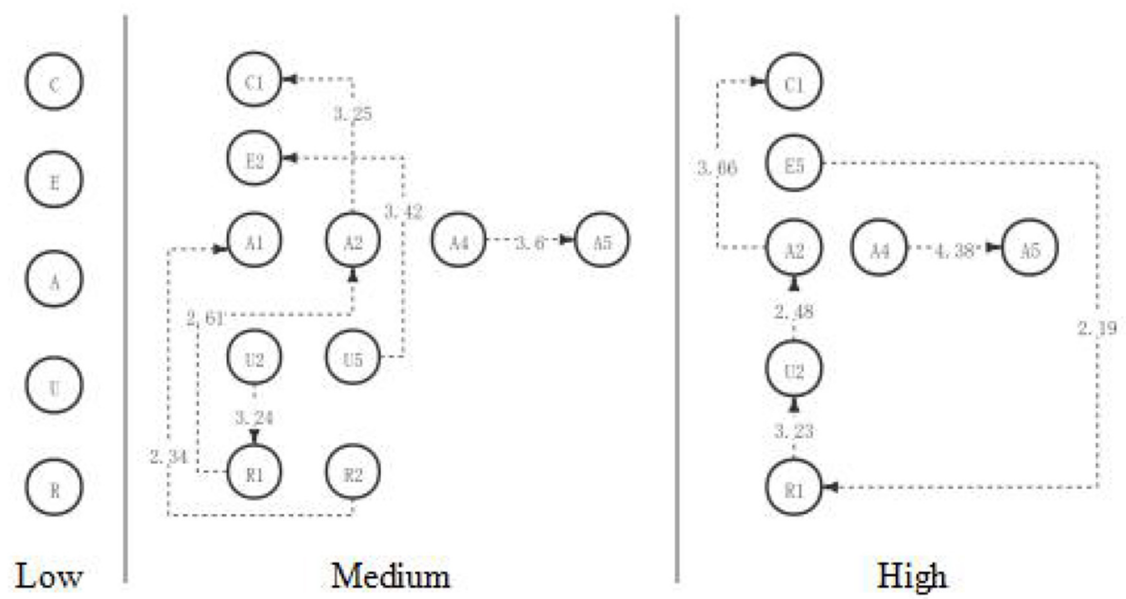

FIGURE 7 | The critical thinking discussion activity path diagram of the different engagement group.

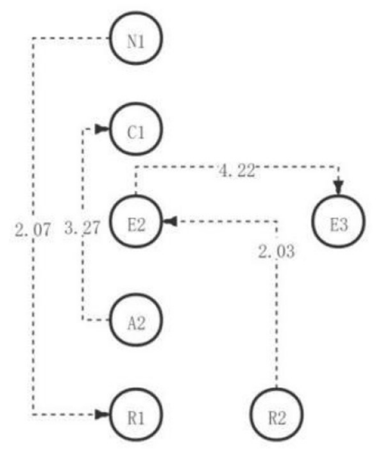

FIGURE 8 | The critical thinking discussion activity path diagram of the medium engagement group.

Critical Thinking Pathways of Participants With Different Levels of Academic Engagement After the Third STEAM Course

According to the coding results, the characteristics of critical thinking pathways of students in low, medium, and high academic engagement groups were analyzed. The specific results are analyzed as follows.

In the third discussion, there were two effective sequences, U2→A4 and C1→R1, in the low academic engagement group (**Table 14**). There is no sequence of behaviors with significant residuals between behaviors (**Table 15**).

In the third course, there were 12 kinds and 19 effective single sequences, such as U2→A4, R2→A4, and R2→A4, in the medium school engagement group, as shown in **Table 16**. The third discussion produced more sequences, mainly for understanding and seeking relevant content → analyzing and explaining viewpoints (U2→A4), with a total of four sequences, and relatively few sequences for the process of creating (C).

Among them, there were four significant sequences with residual values >1.96 (**Table 17**), that is, identification approval problem → critical hypothesis (R2→E2), evidence classification → application implementation plan (A2→C1), critical hypothesis → detection consistency and inconsistency (E2→E3), and unrelated topic → identification restatement problem (N1→R1). After identifying the approval problem (as shown in **Figure 8**), medium school students in the academic engagement group would be making critical recognition of the current view (R2→E2). Based on classifying the collected evidence, students will directly implement the new ideas and plans (A2→C1). After criticizing the hypothesis, students will further test the consistency and inconsistency of the current opinion (E2→E3). After presenting some irrelevant content, some students will further clarify the problem to be solved, to refocus their thoughts on the topic (N1→R1).

In the third discussion, there were seven kinds and 12 effective single sequences, such as U2→R1 and U2→A2, R2→E5, in the medium and high school academic engagement group, as shown in **Table 18**. In the third discussion, more single sequences were generated, mainly identifying the approval question → supporting argument (R2→E5). There were four sequences in total.

Among them, there is one significant sequence with a residual value >1.96 (as shown in **Table 19**), that is, understanding and searching for relevant content → evidence classification and classification (U2→A2). As shown in **Figure 9**, students in the medium and high engagement group in the third discussion would further categorize or classify the current evidence (U2→A2) based on understanding the problem and searching for relevant content.

Based on the above results, in the third discussion, students with high, medium, and low academic engagement showed significant differences in their critical thinking activity path diagrams in the discussion activities (as shown in **Figure 10**). Consistent with the hypothesis, the low engagement group had the worst significant behavior path of critical thinking among the three groups and did not produce a significant behavior sequence. Contrary to the hypothesis, the medium engagement group had a significantly better sequence of behaviors than the high engagement group and reached the highest level of critical thinking—creativity. The high engagement group only reached the analytical level.

Comparison of Critical Thinking Levels of Participants With Different Academic Engagement Levels in Three STEAM Courses

With the longitudinal comparison of the three-course discussions, it is found that students in the low engagement group show a low level of critical thinking behavior sequence in the three discussions (as shown in **Figure 11**). With the implementation of the STEAM course, there is no influence on the critical thinking behavior sequence of students. Under the implementation of the STEAM course, all the students in the engagement group showed more significant behavior sequences of critical thinking, and their critical thinking level reached the highest level—creation; students in the high engagement group also showed significant critical thinking behavior sequence, but their critical thinking level did not reach the level of creativity.

DISCUSSION

This study examined the differences in critical thinking among students with different levels of academic engagement in STEAM courses. The results show that there are significant differences in critical thinking levels among students with different levels of academic engagement in STEAM courses. Moreover, students with medium academic engagement have the highest level of critical thinking in the STEAM course, which is superior to those in the high academic engagement group, while students with low academic engagement have the lowest level of critical thinking. Although the researchers have done some studies on the relationship among STEAM education methods, academic

TABLE 14 | Behavioral adjustment residual values of critical thinking process in the low engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2	Totals
R1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2

TABLE 15 | Behavioral adjustment residual values of critical thinking process in the low engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2
R1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	−1.41	0	0	0	0	0	0	0	0	0	0	1.41	0	0	0	0	0	0	0	0	0	0	0	0	0
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	1.41	0	0	0	0	0	0	0	0	0	0	−1.41	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 16 | Behavioral adjustment residual values of critical thinking process in the medium engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2	Totals
R1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R2	0	0	0	0	0	0	0	0	1	1	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	6
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	2	1	0	0	0	0	0	0	0	1	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	8
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	3
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	4	1	0	0	0	0	0	0	1	2	0	6	0	0	0	2	1	0	0	0	2	0	0	0	0	19

TABLE 17 | Behavioral adjustment residual values of critical thinking process in the medium engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2
R1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R2	−1.55	0	0	0	0	0	0	0	1.48	0.32	0	0.06	0	0	0	2.03*	−0.71	0	0	0	−1.03	0	0	0	0
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	0.47	0.72	0	0	0	0	0	0	−0.85	0.05	0	1.64	0	0	0	−1.28	−0.85	0	0	0	−1.24	0	0	0	0
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	0.47	−0.56	0	0	0	0	0	0	−0.46	0	0	−1.33	0	0	0	−0.69	−0.46	0	0	0	3.27*	0	0	0	0
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	−0.55	−0.3	0	0	0	0	0	0	−0.25	−0.4	0	−0.72	0	0	0	0	4.22*	0	0	0	−0.36	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	2.07*	−0.29	0	0	0	0	0	0	−0.24	−0.38	0	−0.68	0	0	0	−0.35	−0.24	0	0	0	−0.34	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

**Indicates that the Z-score value is significant.*

TABLE 18 | Behavioral adjustment residual values of critical thinking process in the high engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2	Totals
R1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R2	1	0	0	0	0	0	1	0	0	0	0	2	0	0	0	0	0	0	3	0	0	0	0	0	0	7
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	3	0	0	0	0	0	1	0	0	2	1	2	0	0	0	0	0	0	3	0	0	0	0	0	0	12

TABLE 19 | Behavioral adjustment residual values of critical thinking process in the high engagement group.

Given:	R1	R2	U1	U2	U3	U4	U5	U6	A1	A2	A3	A4	A5	A6	E1	E2	E3	E4	E5	E6	C1	C2	C3	N1	N2
R1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R2	−1	0	0	0	0	0	0.74	0	0	−1.83	−1.23	1.33	0	0	0	0	0	0	1.72	0	0	0	0	0	0
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	1.43	0	0	0	0	0	−0.77	0	0	2.21*	−0.74	−1.09	0	0	0	0	0	0	−1.41	0	0	0	0	0	0
U3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U5	−0.63	0	0	0	0	0	0	0	0	−0.49	3.29*	−0.49	0	0	0	0	0	0	−0.63	0	0	0	0	0	0
U6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

**Indicates that the Z-score value is significant.*

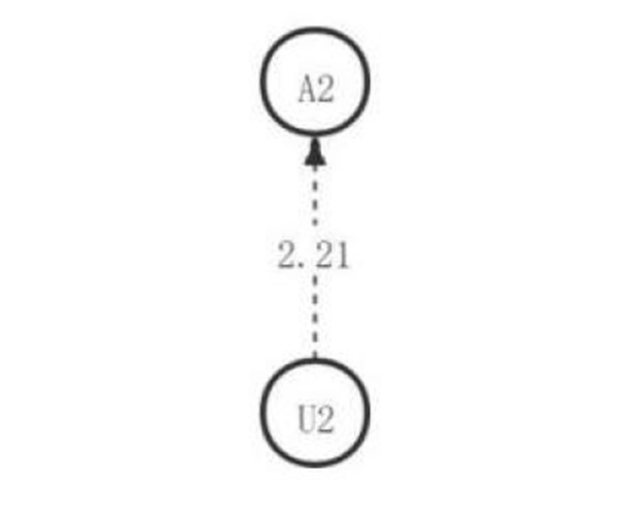

FIGURE 9 | The critical thinking discussion activity path diagram of the high engagement group.

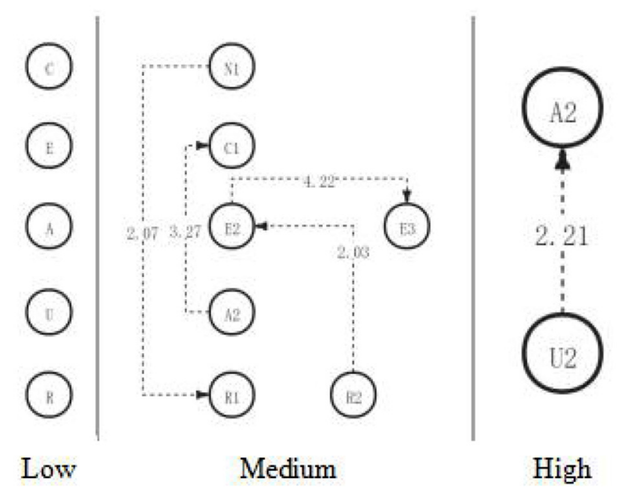

FIGURE 10 | The critical thinking discussion activity path diagram of the different engagement group.

engagement, and critical thinking level, this study found the moderating effect of academic engagement on the development of critical thinking level in STEAM courses.

Different levels of academic engagement also reflect different characteristics in the five levels of critical thinking from low to high. Among the students having a low engagement, there were few effective sequences and significant behavior sequences in the discussions of three STEAM courses. In the few significant behavior sequences, the level of critical thinking reached the level of creation, but such a situation did not continue to appear in the three discussions, and no effective single sequence or significant behavior sequence appeared in the two discussions. This may be due to a variety of reasons, such as students in the low academic engagement group did not actively participate in the discussion, did not fully understand the task topic, or did not focus on the discussion task. The students with a medium level of academic engagement showed good critical thinking levels in the three discussions, and there were more effective behavior sequences and significant behavior sequences in the three discussions. However, the effective behavior sequence and significant behavior sequence of the high academic engagement group were less than those of the medium academic engagement group. This seems to be different from the views mentioned in the existing studies that students with high engagement are energetic and not tired in learning activities, have a high degree of study concentration, and can actively participate in class discussions (Fredricks et al., 2004). The reasons for this situation need further research to determine the influence of other factors on the critical thinking level of students.

This research has made some theoretical contributions to the cultivation of critical thinking of students by a STEAM education method. First, compared with previous studies, this study considered the moderating effect of academic engagement on the STEAM curriculum and critical thinking level. Future research needs to explore the synergistic effects of academic interest of students (Pan, 2017), learning motivation (Liang and Lu, 2019), etc. Second, the measurement of the critical thinking level of students in this study is based on the content analysis of the online discussion texts in the STEAM course. Compared with the previous measurement method of self-report, this study makes full use of the process data to dig deeply into the changes in the critical thinking level of students in the learning process.

The study also provides some practical guidance for promoting critical thinking in STEAM education: first, to guide students to participate more actively in course discussions, such as designing thematic tasks to attract students; second, timely guidance should be provided to students with low academic engagement to improve their learning participation.

OPEN DATA

The data has not yet loaded online. However, we will send the data by request. The request should be sent to Jingrong Sha: shajr818@163.com.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

This research was approved by the Ethics Committee of the College of Educational Science and Technology at Northwest Minzu University. Participants were volunteers who provided written informed consent.

AUTHOR CONTRIBUTIONS

JS designed and implemented the experiments. HS is responsible for collecting data and analyzed the data. All the authors

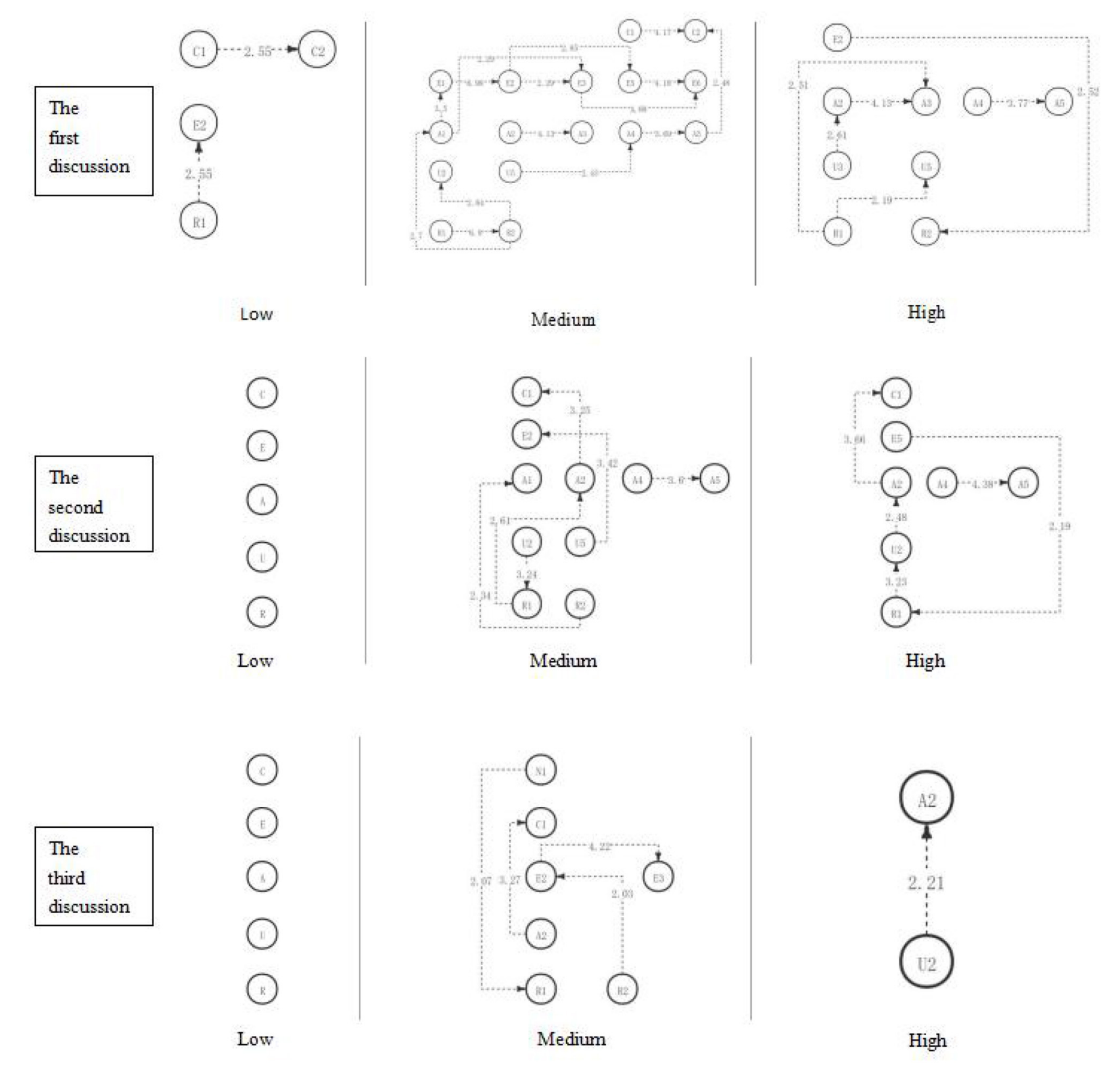

FIGURE 11 | The critical thinking discussion activity path diagram of the different engagement group.

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A Curriculum Integrating STEAM and Maker Education Promotes Pupils' Learning Motivation, Self-Efficacy, and Interdisciplinary Knowledge Acquisition

*Yangyang Jia, Bing Zhou and Xudong Zheng**

School of Educational Information Technology, Faculty of Artificial Intelligence in Education, Central China Normal University, Wuhan, China

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Weiping H. U.,
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Reviewed by:
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Shaanxi Normal University, China
Yizhou Qian,
Jiangnan University, China

****Correspondence:***
Xudong Zheng
xudong@mail.ccnu.edu.cn

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Contemporary society expects learners to synthesize large amounts of available information and take advantage of interdisciplinary knowledge to tackle complex, real-world issues. STEAM education aims to cultivate students' ability to solve such problems through interdisciplinary thinking but is often represented by courses that are merely disjointed arrays of school subjects. On the other hand, Maker education harnesses society's enthusiasm for technological innovation and creativity but overlooks the scientific principles that underpin these processes. This research presents a novel elementary school course informed by the interdisciplinary principles of STEAM, integrated with Maker's focus on technology and creativity. The course design also utilized engineering design as a meta-thematic framework. A total of 164 third-grade pupils participated in the research, with responses analyzed using descriptive statistical methods. The findings indicated that the integrated design of the course promoted pupils' learning motivation, self-efficacy, and acquisition of interdisciplinary knowledge. These effects were not gender-specific and demonstrate the potential applicability of a STEAM/Maker integrated approach to curriculum design in other settings.

Keywords: engineering design, STEAM education, Maker education, STEAM and maker integrated curriculum, learning motivation, self-efficacy, interdisciplinary knowledge

INTRODUCTION

As the information age gives way to the comprehensive age (Cai, 2011), learners are increasingly required to synthesize large amounts of information and employ interdisciplinary knowledge to solve complex real-world problems (Nadelson and Seifert, 2017). Complex Problem Solving (CPS) is deemed to be a key cross-curricular skill of the 21st century (Herde et al., 2016). However, much formal education has traditionally been premised on the division of knowledge into discrete subject areas. Although the division of knowledge into disciplines is conducive to scientific research (Morrison et al., 2009), it detaches formal education from the real world, meaning learners may fail to apply the knowledge they have learned to resolve practical issues. This, in turn, leads to the emergence of the phenomenon of "useless knowledge" (Linn and Hsi, 2000).

STEM education, guided by interdisciplinary thinking, has received extensive attention due to its focus on cultivating students' ability to solve complex and realistic problems (National Academy of Engineering and National Research Council, 2014). Scholars have increasingly realized that arts and humanities subjects help students understand the connections between different disciplines from a more comprehensive perspective (Watson and Watson, 2013; Kant et al., 2018), and STEM education has evolved into a new "STEAM Age." While acknowledging the distinction between STEM and STEAM, this is not a central concern of the present study.

In essence, STEM education entails an interdisciplinary approach oriented toward science and engineering education, guided by the concept of knowledge integration. However, in practice, it often results in "patchwork" curricula stitched together from several different subjects, which runs counter to its stated aim of achieving greater disciplinary integration (Thuneberg et al., 2017). STEM education eradicates the barriers between themes and prioritizes current tools and technical design to resolve complex contextual problems (Kennedy and Odell, 2014). Formerly, science and mathematics were approached as isolated subjects (Breiner et al., 2012; Quigley and Herro, 2016), with almost no consideration of technology or engineering (Hoachlander and Yanofsky, 2011; Timms et al., 2018). Indeed, an atomized curriculum structure and the insufficiency of teachers' skills are the two critical reasons for STEM education's lack of success in practice, explaining its repeated and ongoing failure to achieve its intended goals (Blackley and Howell, 2015). Moreover, many curricula are not designed or delivered in ways that improve students' capacity to innovate (Taylor, 2016). School STEM programs are frequently characterized by fragmented courses whose focus is narrow (Kim and Park, 2012; Park, 2012) and whose effectiveness has not been adequately verified (Wang et al., 2018).

Maker education is a new type of educational practice which aims to foster creativity. It views learning as a shared, social process based on the design and production of physical objects (Halverson and Sheridan, 2014). It assumes that the joy of creation can stimulate students' curiosity (Anderson, 2012). Maker education focuses on the use of technical tools and equipment but is less concerned with developing knowledge of scientific concepts and principles (Dougherty, 2012).

Research indicates that STEAM education with Maker is potentially well-suited to classroom learning in the era of the Fourth Industrial Revolution (Kim and Kim, 2018). This raises the question of how to overcome the issues of disparate multidisciplinarity in STEM education and the neglect of scientific principles in Maker education to integrate the strengths of both approaches into classroom teaching. Maker education prioritizes design above processing (Jacobs and Buechley, 2013; Halverson and Sheridan, 2014) and includes the application of digital technology (Martin, 2015). These digital tools have greatly reduced experimental errors (Snyder et al., 2014), while at the same time improving the efficiency of hands-on practice (Lipson and Kurman, 2013), enabling student learning to proceed via a varied process of trial and error. However, the potential of Maker education is impacted by the current lack of genuinely interdisciplinary, unified approaches to teaching. As a result, learners' skills in and knowledge of the use of technical tools and equipment remain shallow and unintegrated. This contributes to an excessive emphasis on the value of manufactured products in what Chachra (2015) refers to as a deformed technological culture.

A complete engineering design is an emergent and highly iterative process that can facilitate meaningful learning (Roehrig et al., 2012; English, 2016). It provides a framework enabling the establishment of links between the various disciplines of STEM education (Fan and Yu, 2017) which can then be more closely integrated (Kelley and Knowles, 2016). It is well-suited to Maker's focus on the creative use of technology. Moreover, engineering-oriented STEM courses are best placed to instill the key concepts of STEM education and promote students' acquisition of content (Christensen and Knezek, 2017). However, the key task that remains is to develop syllabi that integrate STEM and Maker into classroom practice. The following account of an interdisciplinary STEM- and Maker- integrated curriculum in the field of engineering design addresses this task.

Engineering design is a creative, knowledge-driven process, in which the concepts of devices, systems or processes are generated, specified, and evaluated (Dym, 1994). During this process, specific constraints are balanced with the achievement of customers' goals and requirements (Dym et al., 2005). Engineering design includes but is not limited to the processes of questioning, imagination, creation, testing, and improvement (Dieter and Schmidt, 2009; Shahali et al., 2016). Its realization requires the use of scientific and mathematical concepts (Moore and Smith, 2014), so it can be used as the basis for establishing such concepts and practical connections in STEM education (Sanders, 2008; Donna, 2012). This also aligns it with the goal of disciplinary integration in K-12 STEM education (Moore et al., 2014). The considerable utility of engineering design as a meta-thematic concept (Fan and Yu, 2017) helps explain its considerable influence on STEM education (Katehi et al., 2009). Finally, engineering design is regarded as an essential ability for STEM students (Atman et al., 2007).

Moreover, engineering design overlaps with Maker's focus on transformative innovation in the field of technology. Maker education emphasizes the use of software and hardware to transform creativity into entities (Halverson and Sheridan, 2014). It enables students to transform the potential of their subjective initiative into real subjective creativity. At the same time, they can apprehend the potential power of scientific rationality to remold nature into concrete material power. Maker's interest in fostering technological innovation can be focused on specific learning projects by utilizing the concepts of engineering design. As a bridge between STEM and Maker, engineering design provides students with an opportunity to work on technological innovation while transforming abstract science and mathematics concepts into concrete practical processes, establishing links to real life, and improving students' familiarity with and interest in the disciplinary content (Clapp and Jimenez, 2016).

Interest is a prerequisite for students to participate in STEAM learning (Maltese and Tai, 2011; Maltese et al., 2014). And interest is closely related to intrinsic motivation, when individuals are intrinsically motivated, they do activities out of interest in the activity (Wigfield et al., 2012). Therefore, testing students ' learning motivation is an important indicator of curriculum quality. Self-efficacy is an element of intrinsic motivation (Deci et al., 1981), which defined as judgment or assessment of one's capabilities to perform a particular given task successfully (Bandura et al., 1999). Self-efficacy is regarded as a major trigger for purposeful behavior and the perseverance to achieve set goals (Özcan and Eren Gümüş, 2019), which has been highlighted as an essential predictor of general academic performance (Ferla et al., 2009). For the above reasons, while testing interdisciplinary knowledge acquisition, this research will focus on the students' learning motivation and self-efficacy to reflect learning quality.

We are currently developing a series of curriculum with the integration of STEAM and Maker, aimed at the comprehensive training of students' knowledge, abilities, and literacy in K-12 stage. This paper reports the results of our first round of development, which including the following questions: (a) How can we design curriculum framework with the integration of STEAM and Maker based on the idea of engineering design? (b) How can we develop a curriculum based on the framework? (c) How to evaluate the effectiveness of the development curriculum?

FRAMEWORK FOR DEVELOPING AN STEAM AND MAKER INTEGRATED CURRICULUM

The framework for the course content of *Soaring in the air* is shown in **Figure 1**. The syllabus is closely tied to the national curriculum standards for K-12 in China. The selection of themes draws on real-world scenarios and the content setting helps to ensure that students establish connections between disciplines. The purpose of the design activity is to allow students to use their brains in the hands-on process. The course's overarching aim is to allow students to turn the objects of their imaginations into real artifacts through practical, experiential learning. Key to this process is the students' ability to use their minds, rather than simple hands-on skills.

The curriculum design includes eight main steps of engineering design. First, clarify the problems to be solved in this course which is how to make a propeller aircraft with 33 m. Second, confirming the learning requirements. The reasons why an aircraft does not fall in the air is that it is affected by the force and following the Bernoulli principle. On this basis, the conditions required for the propeller rotation are explored through propeller rotation experiments. Third, providing solutions and plans to the problems and needs. Using the concept of scale to draw propeller aircraft drawings in prescribed area. Fourth, selecting the optimal solution. The team members will negotiate and determine the final propeller aircraft design drawings for their group based on aircraft model materials. Fifth, building the aircraft model according to the design drawings and take field tests. The team members will build the aircraft model by cooperation according to the experimental precautions. After the model is completed, the test flight will be conducted under the guidance of the teachers. Sixth, estimating the design. To explore the flight test results, optimize the aircraft model, and complete the model flight competition. Seventh, improving the design. Team members conduct brainstorming to further optimize the aircraft design drawings. Eighth, sharing the design. Each team shared the concept, role and value of their team ' s aircraft design drawings.

DEVELOPING A CURRICULUM BASED ON THE FRAMEWORK

Course manuals for teachers and students are provided. The teacher's manual presents a wealth of resources and guides which provide sets of flexible options for teaching. The students' handbook offers multiple question frames and worksheets which encourage the habit of recording and reflecting on experimental processes.

The course takes aircraft as the theme and addresses the core topic of constructing an airplane. Areas covered include the invention of airplanes, the principles of aircraft flight, aircraft design, assembling aircraft, flying aircraft, intelligent aircraft systems, and new progress in aerospace. The process by which students worked out practical problems to problems in engineering design drew on the modules presented in **Table 1**.

METHODS

Participants

This study was conducted as part of the "STEAM Plus" curriculum project carried out in the Huairou District of Beijing between December 28, 2020 to January 15, 2021. A total of 164 third-grade pupils were randomly selected to participate. Boys accounted for 52.4% ($n = 86$), while girls constituted 47.6% of the sample ($n = 78$). No participant had any previous experience of a course informed by the STEAM/Maker integrated curriculum. The research team spent 2 weeks teaching students on the self-developed STEAM and Maker integrated course *Soaring in the Air*.

Students study *Soaring in the Air* course at the Maker Lab. The desks of students in the Maker Lab are assembled and placed in groups. The Maker Lab is equipped with different kinds of experimental materials and tools that students need in the course learning, such as materials needed for Bernoulli principle proof experiments, aircraft model kits, etc.

Instruments

The learning motivation scale used in this study was adapted from the ARCS motivation model proposed by Keller (2009). The model has demonstrably excellent levels of reliability and validity in evaluating students' learning motivation. The strong factor structure of the entire toolset allows for this reduction in the item count. So it contains a total of 33 items, 17 of which were used for the study, in accordance with the developmental ages of the participants. These included six items on the dimension of attention, four each on relevance and confidence, and three items on satisfaction. Responses are graded on a 5-level Likert scale, with "1" indicating complete disagreement and

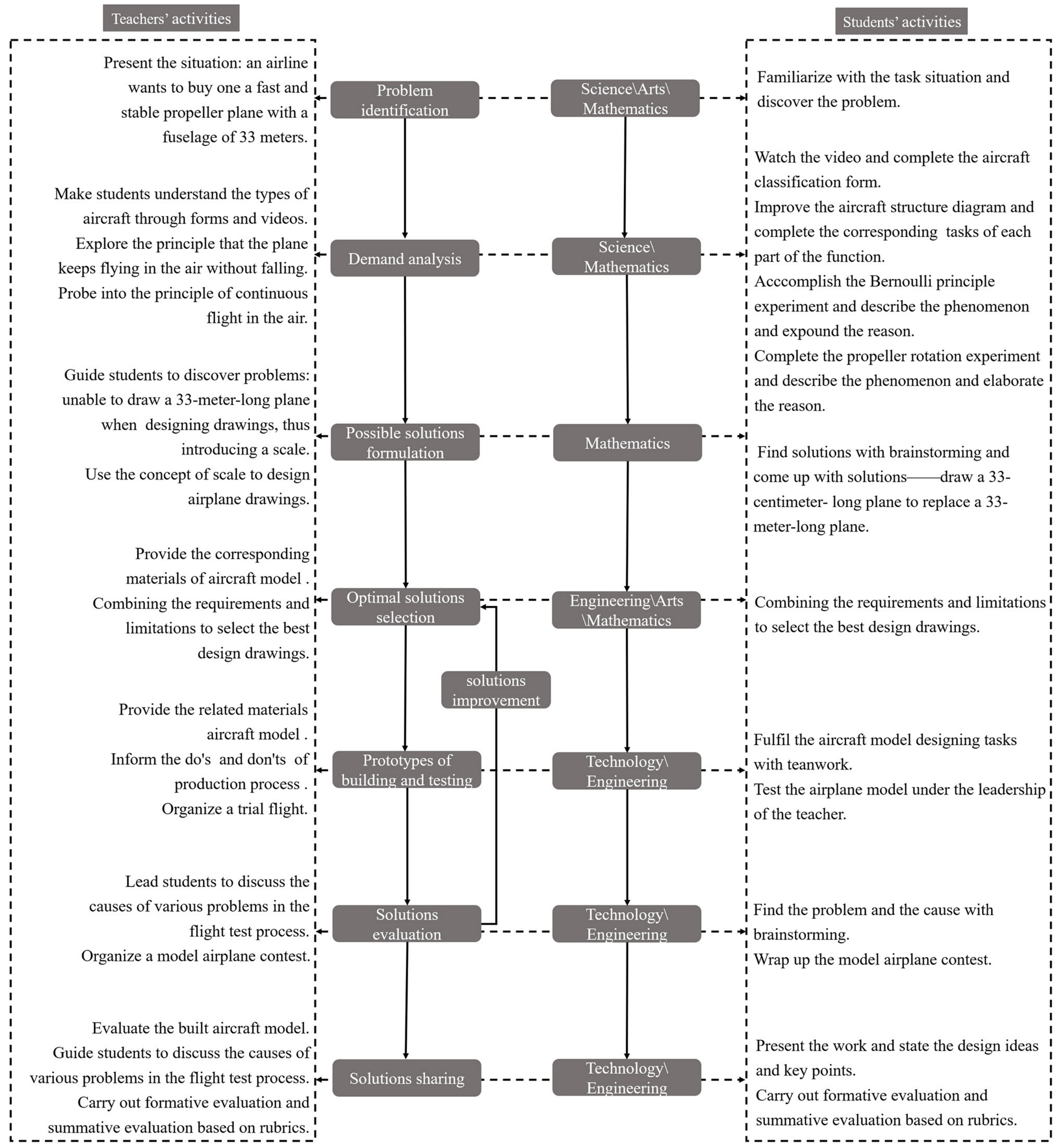

FIGURE 1 | Framework for developing a STEAM and maker integrated curriculum.

the remaining numbers signifying increasingly full agreement with each statement. Findings from a small pilot study confirmed the scale's strong reliability and validity ($\alpha = 0.891$, $KMO = 0.789$).

Measurement of self-efficacy used an adapted version of the General Self-efficacy Scale (GSES) developed by Zhang and Schwarzer (1995). It consists of a total of 10 items with single-dimensional scales. Responses to each question are recorded on a 4-level Likert scale, from completely incorrect (1), to "somewhat," "mostly," and "completely" correct (2–4). The pre-experimental results demonstrated high levels of reliability and validity ($\alpha = 0.793$; $KMO = 0.709$).

TABLE 1 | Course content of *Soaring in the Air*.

Modules	Class time	Disciplinary themes	Aims and content of modules	Related disciplines
Module 1	2 h	The history of invention	Compare the speed of different vehicles and learn the formula "Velocity=Acceleration/Time" and its conversion formula.	Science Humanities Mathematics
			Understand aircraft types and emphasize the similarities and differences between propeller and jet aircraft.	
			Understand the history of the birth of airplanes; cultivate scientific thinking and the scientific spirit of persistence.	
			Learn the process of manufacturing aircraft and the work of aircraft manufacturing engineers; cultivate the spirit of scientific exploration.	
Module 2	2 h	The principles of aircraft	Learn the concept of force; understand the components and functions of the aircraft.	Science Mathematics
			Analyze the force of aircraft and distinguish between universal gravitation and gravity.	
			Grasp Bernoulli's principle and thoroughly understand its connotations by conducting small experiments.	
			Make a paper airplane that flies steadily and far; understand the force of the airplane and Bernoulli's principle.	
			Probe the factors affecting the flight distance of aircraft and improve scientific quality.	
Module 3	2 h	The design of aircraft	Identify and analyze tasks to stimulate interest in learning.	Mathematics Engineering
			Understand the spiral and jet power system and formulate the design plan.	
			Grasp the concept of measuring scale and determine the design plan according to the engineering design process.	
			Evaluate the design plan and develop a scientific and rigorous engineering attitude.	
Module 4	2 h	Assembling and test	Deepen the understanding of each part of the aircraft and its functions by assembling the aircraft.	Technology Engineering
			Discover the problems during flight test activities and find solutions.	
			Motivate the awareness of competition through model airplane contests; cultivate class unity and cooperation with peers.	
			Clarify the design plan and explain the existing problems of the aircraft; suggest solutions to these; develop skills in personal expression and cooperation in group activities.	
Module 5	2 h	Aircraft	Understand the meaning and layered structure of the atmosphere, distinguish between aircraft and spacecraft, and select aircraft suited to each layer of the atmosphere.	Science Humanities
			Design future aircraft according to the research steps of bionics.	
			Check mastery of the course content through the "you draw and I guess" game.	
Module 6	2 h	Aerospace	Learn about international and national achievements in aerospace and aviation.	Humanities
			Draw the theme of "Flying Dream", cultivate imagination, stimulate aerospace dreams, and interest in aerospace exploration.	

The STEAM test questions were adapted from a multi-disciplinary test bank. The question types and scores consisted of seven multiple-choice questions, each worth five points; four gap-fill questions containing eight blanks, with five points per blank; and one link question worth 25 points.

The process task list is independently developed by the research team according to the course content, which mainly includes five dimensions: S (Science), T (Technology), E (Engineering), A (Art), M (Mathematics). Each dimension is scored 5 points, 3 points, 1 point and 0 points. Completing all tasks as required were scored 5 points. Completing half of the tasks were scored three points. Completing <20% of the tasks were scored 1 point, and no answer was 0.

Data Collection and Analysis

Two teachers were participated in teaching process. Teacher 1 was mainly responsible for completing the classroom teaching task according to the teaching design. Teacher 2, as an assistant, cooperates with the teacher 1 to complete the demonstration process of scientific inquiry experiment. Teacher 2 was mainly responsible for the distribution of experimental materials and task sheets, providing students guidance in the process of completing hands-on activities and keeping the activity in order. To ensure the students had enough thinking time and activity space, both two teachers provided well-structured learning environment and self-efficacy development situation for students to deal with problems and scientific questions.

TABLE 2 | Learning motivation of students.

	Dimensions		*M*	*SD*	*n*	*t*
Learning motivation	Attention	Whole	3.3110	0.5677	164	–
		Boy	3.3353	0.58158	86	0.574
		Girl	3.2842	0.55447	78	
	Relevance	Whole	3.9741	0.9158	164	–
		Boy	4.0610	0.94163	86	1.279
		Girl	3.8782	0.88250	78	
	Confidence	Whole	2.8979	0.7783	164	–
		Boy	2.8547	0.83646	86	–0.746
		Girl	2.9455	0.72373	78	
	Satisfaction	Whole	4.2846	0.9292	164	–
		Boy	4.2907	0.97792	86	0.089
		Girl	4.2778	0.87850	78	
	Total score	Whole	3.5416	0.5666	164	–
		Boy	3.5616	0.62218	86	0.472
		Girl	3.5196	0.50142	78	

TABLE 3 | Self-efficacy of students.

	Dimensions		*M*	*SD*	*n*	*t*
Self-efficacy	Pre-test		3.068	0.5475	164	–2.462*
		Whole	3.179	0.5854	164	
	Post-test	Boy	3.191	0.6110	86	
		Girl	3.167	0.5594	78	

*$p < 0.05$.

For statistical analyses, SPSS Statistics 22.0 was used. The first module measured the level of students' self-efficacy. During modules 2–5, students' procedural task lists were collected. In the 6 module measured students ' learning motivation, self-efficacy and the STEAM test questions. The procedural task list completed by students in the classroom was collected and manually graded by the research team according to shared criteria. The students' overall STEAM scores derived from their results for the final test and procedural task, each of which contributed 50% to their total score.

To understand whether students' learning motivation, self-efficacy, and acquisition of interdisciplinary STEAM knowledge developed as a result of the course, descriptive statistics were applied to the data. A paired-sample T-test was run to determine the self-efficacy changes before and after the course. An independent-samples T-test was run to determine the existence of any gender-specific effects.

RESULTS

Learning Motivation

Table 2 displays the results of the analysis of learning motivation, which consists of four parts: Attention\Relevance\Confidence\Satisfaction. The mean values for the dimensions of total score, attention, relevance, and satisfaction were all >3, the boys score slightly higher than girls, indicating the high level of students' learning motivation after the course had ended, and the boys were marginally more interested in such integrated courses, which also indicated that the courses' overall ability to adapt to the learning needs of boys and girls. However, the mean value of the confidence dimension ($M = 2.8979$, $SD = 0.7783$) was between 2.5 and 3, and girls score slightly higher than boys, indicating that students' self-confidence had reached the upper-middle level after the course, and girls' self-confidence was slightly stronger than boys. This slightly lower result may reflect the fact the uncertainty of students who had never previously encountered this type of course. In view of the broad sample for the sake of completeness, gender effects were also calculated. No gender impact appeared (t-test no sig). This result confirmed that the suitability of the *Soaring in the Air* course for motivating students in large-scale, gender-inclusive teaching environments.

Self-Efficacy

Table 3 presents the results of the analysis of self-efficacy. The post-test mean levels of students' self-efficacy ($M = 3.179$, $SD = 0.5854$) was higher than the pre-test score ($M = 3.068$, $SD = 0.5475$). A paired-sample t-test was performed on the pre- and post-test data, with the results showing that the difference between the two mean values was statistically significant ($p = 0.015 < 0.05$). In view of the broad sample for the sake of completeness, gender effects were also calculated. No

TABLE 4 | Analysis of STEAM scores.

	Dimensions	*M*	*SD*	*n*	*t*
STEAM scores	Whole	65.46	14.921	164	–
	Boy	65.06	14.4	86	−0.359
	Girl	65.90	15.558	78	

gender impact appeared (*t*-test no sig), which was consistent with the findings on motivation. It is tentatively suggested that the boys felt marginally more able to adapt to the integrated syllabus than the girls in this study: more conclusively, the *Soaring in the Air* course appears well-adapted to the simultaneous teaching of boys and girls.

Analysis of STEAM Scores

Table 4 indicates students' acquisition of interdisciplinary knowledge following the course. The mean value of students' STEAM scores was 65.46 points, demonstrating that students had acquired an upper-middle level of interdisciplinary knowledge. For students new to interdisciplinary integrated curriculum learning, this was an impressive achievement. Girls scored slightly higher than boys, but again, there was no obvious discrepancy in performance. In fact, the primary conclusion to be drawn is that the interdisciplinary content and pedagogic approach of the *Soaring in the Air* course benefited both male and female participants in the study.

DISCUSSION

The Effects of Curriculum on Students' Learning Motivation and Self-Efficacy and Knowledge Acquisition

The study results demonstrated positive changes to students' learning motivation and self-efficacy. These findings resonate with previous studies showing that the students offered a genuinely creative learning environment demonstrate improvements in their attitudes to learning and their persistence (Kong and In-Cheol, 2014; Engelman et al., 2017). They also confirm that STEAM education based on school-oriented science textbooks can boost students' motivation (Bae et al., 2013; Choi, 2013; Bahri et al., 2017) and support the development of self-efficacy (Kong and Huo, 2014). The *Soaring in the Air* course connects interdisciplinary concepts with life experience to create a diversified learning environment where students can experience the joy of using their hands and brains while learning knowledge and skills. Burguillo (2010) points out that the type of positive competition encouraged throughout our course can support the motivation to learn. Moreover, the competitive relationship between groups also helps students to actively construct scientific knowledge, promote their subjectivity and initiative, and further elevate their motivation and self-efficacy.

The findings also indicate that students successfully acquired the interdisciplinary knowledge integrated into the framework of engineering design by the *Soaring in the Air* course. In solving practical problems, students developed their awareness of the relationship between different disciplinary viewpoints. This process generates higher-level understandings of science (Ivanitskaya et al., 2002), ultimately building students' interdisciplinary knowledge. These findings corroborate previous studies evaluating the effects of an integrated STEAM approach on learning. For instance, it has been found that STEAM pedagogies boost students' ability to conceptualize themes (Liliawati et al., 2018), improve the acquisition of concepts (Perignat and Katz-Buonincontro, 2019; Wandari et al., 2019; Ozkan and Topsakal, 2020), enhance disciplinary knowledge (Ceylan and Ozdilek, 2015), raise test scores (Chien and Chu, 2018) and benefits overall academic performance (Kim et al., 2014). The current study aligns with these results, finding that STEAM courses supported by Maker technology within the framework of engineering design can increase students' academic motivation and self-efficacy, thereby facilitating the acquisition of interdisciplinary knowledge.

Curriculum Are Inclusive

The differences between boys and girls in this study were minor. Boys were marginally more motivated and achieved slightly higher scores in self-efficacy, with girls scoring fractionally higher on their STEAM scores. Nevertheless, the gender gap is manifested in the less positive attitudes and interests in STEM fields held by girls (Wang et al., 2019), and there are also discrepancies in the understanding of concepts between male and female students (Sagala et al., 2019). Women account for a relatively low proportion of roles in STEM professions (Beede et al., 2011; Weber, 2012; Su and Rounds, 2015; Casad et al., 2018; Rainey et al., 2018; García-Holgado et al., 2020). Thus, even the small differences recorded in this study should be taken into consideration as potential indicators that the STEM gender gap may begin early and widen with age.

Courses such as *Soaring in the Air* have prominent educational effects (Lee et al., 2013), which may reduce the academic and professional gender gap in STEM (Chachashvili-Bolotin et al., 2016). The *Soaring in the Air* syllabus stimulated the enthusiasm of male and female students alike, improving their self-efficacy, and promoting the acquisition of interdisciplinary knowledge. The course could allow female students to experience their skills and competences unbiasedly. The course content of *Soaring in the Air* is systematic, the course activities are universal, the course links are flexible, and the course itself is highly adaptable to the learning needs of every student. These findings resonate with those of MacPhee et al. (2013), who investigated the academic self-efficacy of STEM students. The authors discovered that the academic self-efficacy of female students was lower than that of male students upon enrollment in an interdisciplinary

STEM course, but this difference had disappeared by the time they graduated.

CONCLUSIONS

The goal of STEAM education is to strengthen learning in individual subjects (Blackley and Howell, 2015) to produce new understandings and achievements which transcend any single discipline (Peppler and Wohlwend, 2018). It also aims to improve students' creativity and ability to solve real-world problems (Watson and Watson, 2013; Kant et al., 2018). However, existing approaches to STEAM are often little more than an agglomeration of school subjects. Contemporary brain science has confirmed the importance of using hands in the learning process (Dougherty, 2012), which aligns with the idea of "learning by making" central to Maker education. This approach prizes creativity and innovation, but its prioritization of technology over principles is a major hindrance to cultivating such qualities in students.

This research designed an integrated STEAM and Maker approach to primary education by utilizing the framework of engineering design. The students' academic motivation, self-efficacy, and acquisition of cross-disciplinary knowledge were measured at high levels after the course. Moreover, the fact that no obvious difference between male and female students was identified testifies to the gender inclusivity of *Soaring in the Air*.

Based on the results, we recommend that further courses integrating STEAM and Maker approaches be developed using the expertise of researchers and curriculum developers. We furthermore propose that STEAM teachers focus on teaching goals that are comprehensible to students and can access a toolkit of teaching methods appropriate to the course content. Students should be confronted with real-world problems and situations which encourage them to connect their learning with the empirical world beyond the classroom. As Brooks and Brooks (1993) pointed out, it is only when learners associate prior knowledge with new experience and new skills in a real environment that meaningful learning will occur. It is also necessary to consider how to integrate Chinese, mathematics, physics, chemistry and other classes into STEAM courses, and how to cultivate students' passion for science. We believe that if resources are allocated to developing inclusive STEAM courses and the expertise of teachers in the future, the quality of STEAM education will continue to improve.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Files**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

Approval by an ethics committee was not required for this study as per applicable institutional and national guidelines and regulations. All participating students expressed their willingness to participate in this activity.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2021.725525/full#supplementary-material

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Design Training and Creativity: Students Develop Stronger Divergent but Not Convergent Thinking

*Tiansheng Xia, Mengxia Kang, Meng Chen, Jia Ouyang and Fei Hu**

School of Art and Design, Guangdong University of Technology, Guangzhou, China

Design training programs that teach creativity often emphasize divergent thinking (generation of ideas) more than convergent thinking (evaluation of ideas). We hypothesized that training would lead to more both types of creativity, but especially divergent thinking. Three groups of university students ($N=120$; $n=40$ in each group) were recruited to participate: senior design students (graduate students with at least 4 years of design training as undergraduates); junior design students (undergraduates in their first year of design training); and undergraduate students in majors unrelated to design. The students completed three tasks in a classroom setting to assess divergent thinking (Alternate Uses Task), convergent thinking (Remote Associates Task), and nonverbal abstract reasoning (Raven's Progressive Matrices Test). The results of one-way ANOVAs showed that as expected, senior design students significantly outperformed junior design students and non-design majors in divergent thinking. However, contrary to expectations, senior design students had significantly lower scores than the non-design group on convergent thinking; the junior design students' scores fell in the middle but were not significantly different from either of the other groups. There were no group differences in nonverbal abstract reasoning. These findings suggest that design training significantly improves students' ability to generate ideas but does not improve, or may even hinder, their ability to evaluate whether the ideas are useful for the task at hand. The results have implications for developing a research-based curriculum in design training programs.

Keywords: design training, creativity, divergent thinking, convergent thinking, cognitive flexibility

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****Correspondence:***
Fei Hu
hufei@gdut.edu.cn

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INTRODUCTION

Industrial designers are commonly assumed to be more creative than other people, because design requires creativity (Sarkar and Chakrabarti, 2011). Design ability is often applied to developing new products (Er Biyikli and Gulen, 2018; Lazar, 2018), which requires the innovative use of variables in the environment (physical objects, behaviors, rules, etc.) to result in favorable outcomes for the executor. There is a close relationship between creativity and design, and for a long time, creativity has been regarded as an important criterion in the evaluation of designers' proficiency (Sundström and Zika-Viktorsson, 2003). Therefore, many design programs have set up courses to improve students' creativity (Cheung et al., 2003, 2006; Wang, 2008). However, instructors in most training programs conceptualize creativity as a whole without examining its component parts, or they emphasize some components and not others (Sarkar and Chakrabarti, 2011). Research on this topic can help in developing a design curriculum that covers all areas of creativity.

As early as 1950, Guilford conceptualized creativity as a combination of two forms of thinking, namely, divergent thinking and convergent thinking (Guilford, 1950). Divergent thinking broadens the representational research space while convergent thinking is used to identify the best ideas for the task at hand (Cortes et al., 2019). These dual processes influence the overall process of creation (Barr, 2018), although there may be times when one form of creativity is more influential than the other (Sarkar and Chakrabarti, 2011; Lubart, 2016; Webb et al., 2017; Zhang et al., 2020). The designer can switch between the two forms of thinking according to the actual task requirements (Lazar, 2018). The alternating pattern of divergent thinking and convergent thinking forms the creative process (de Vries and Lubart, 2017).

The creative process can be divided into two stages, with divergent thinking being prominent early in the process and convergent thinking being prominent later in the process. First, in the idea generation stage, the designer uses mostly divergent thinking to put forward as many abstract ideas, forms, and design schemes as possible (Forthmann et al., 2019). During this first stage, distraction is beneficial and creative generation may depend on the availability of unfiltered, low-level perceptual information (Weinberger et al., 2017). Second, in the idea evaluation stage, the designer uses mostly convergent thinking to evaluate these ideas and to determine a solution, resulting in an answer that is not just novel but also useful for the purposes at hand (Guilford, 1957). In this stage, concentration is needed to evaluate the rationality and feasibility of the design scheme (Mohamed, 2016). This stage requires task-directed thoughts and the integration of semantically distant concepts (Weinberger et al., 2017).

Although both divergent and convergent thinking are thought to be important for creativity, there are two reasons to expect that design training might help in developing divergent thinking more than convergent thinking. The first reason is that training programs give more attention to divergent thinking (Rao et al., 2021). Some have asserted that a cognitive process can be judged as creative only if it causes divergent thinking (Finke et al., 1992). Therefore, some early evaluations of creativity focused on the novelty, fluency, and flexibility of ideas (Haritaipan et al., 2018).

The results of two recent studies on the creativity of first-year and senior engineering students suggest that the training emphasis on one thinking may come at the expense of improvements in another thinking. First-year students scored significantly higher on the design thinking scale, while senior students performed significantly better on the integrative thinking scale (Coleman et al., 2020). First-year students also generated significantly more solutions than seniors and showed higher activation in the brain region associated with cognitive flexibility and divergent thinking (Hu et al., 2021).

Design students may perform better on tasks of divergent than convergent thinking because divergent thinking can be taught even in a short period, but there is no corresponding evidence that convergent thinking can be taught. Tran et al. (2020) conducted a 14-week undergraduate creative methods course and found that the participants demonstrated significant promotion in divergent thinking at the post-test. Similarly, Rao et al. (2021) found that training in design thinking significantly increased ideational fluency and elaboration in a divergent thinking task. Another study documented that analogies training improved design consultants' innovations and divergent thinking (Kalogerakis et al., 2010). Finally, training in cognitive flexibility, which is correlated with divergent thinking (Benedek et al., 2012; Zabelina et al., 2012), has been shown to have direct and near transfer effects (van Bers et al., 2020).

The second reason to expect senior design students to show better divergent than convergent thinking is that the use of divergent thinking (encouraged in training programs) may inhibit convergent thinking. Research in cognitive psychology has shown that a person's cognitive style is mainly characterized by either divergent or convergent thinking, suggesting that one approach to thinking may hinder the other approach (Kuypers et al., 2016). The implication for design training is that the enhancement of divergent thinking may inhibit the development of convergent thinking (Yue and Gong, 1999; Hommel et al., 2011; Kuypers et al., 2016).

The aim of the current research was to address this question: What is the specific impact of design training on design majors' convergent and divergent thinking? Our general assumption was that design training would improve both types of creativity, but this would be especially evident in their divergent thinking. To test this assumption, we compared three groups of university students: senior design students (graduate students who already had at least 4 years of design training); junior design students (undergraduates in the first year of a design program); and students who were not majoring in design. The three groups were compared on tests of divergent thinking, convergent thinking, and nonverbal abstract reasoning.

Since divergent thinking might benefit from a minimum cognitive-control state and so that the individual can easily "jump" from one thought to the other. However, convergent thinking is likely to benefit from strong top-down cognitive-control state and so that the individual can quickly conduct subsequent performance in tasks. The training of one thinking may impair the performance of the other (Hommel et al., 2011). The specific hypotheses were (1) senior design students will perform better on divergent thinking tasks rather than convergent thinking tasks, when compared with junior design students and non-specific majors; (2) the difference in creativity between senior design students and the other two groups of students will be greater for divergent thinking than convergent thinking.

MATERIALS AND METHODS

Participants

Undergraduate and graduate students (N = 120; 61 males; mean age = 21.2 years, SD = 2.5) at Guangdong University of Technology participated in this study. They included three groups: senior design students ($n = 40$; graduate students majoring in industrial design, visual design, and interaction design with at least 4 years of design training); junior design students ($n = 40$; first-year undergraduate students majoring in industrial design who did not receive systematic design training in their pre-university studies); and non-design majors ($n = 40$; undergraduate or graduate students majoring in management, applied mathematics, or economics, with no design training). The three groups were similar in the proportion of male and female students, and in nonverbal abstract reasoning [measured by Raven's Standard Progressive Matrices (SPM)], see **Table 1**. The participants provided written informed consent and received a small payment (CNY 15) after the study. The study protocol was approved by the Ethics Committee of the first author's institution and was conducted according to the ethical standards established in the 1964 Declaration of Helsinki and its later amendments.

Procedure and Design

The study consisted of one 70-min session with one break. The participants signed the written consent form when they arrived. The Alternative Uses Task (AUT; 10 min), Remote Associates Test (RAT; 20 min), and SPM (40 min) were then administered. The participants then received a small payment to thank them for their time and effort.

Measures

AUT (Divergent Thinking)

The AUT (Guilford, 1967) is a test of divergent thinking. Participants are asked to think of, and then write down, as many possible uses as they can for a simple object, such as a brick, shoe, or newspaper. Participants could describe each use as briefly or extensively as they wanted, and the task was terminated after 10 min. The task was administered in Chinese for the purposes of this study. Two graduate students independently evaluated each response on four dimensions: originality, fluency, flexibility, and elaboration. The score for originality was given based on the frequency with which the use appeared in the set of uses generated by the full sample. A use that was the same as only 5% of all uses generated by the sample was scored as unusual (1 point) and a use that was the same as only 1% was scored as unique (2 points); otherwise, the score was 0. The fluency score was the number of uses generated. The flexibility score was the number of different categories represented by the items on the list. Elaboration was assessed based on the amount of detail in the list. The scores on the four dimensions were summed to create a total score, and the total scores were standardized.

TABLE 1 | Number of males and females in the senior design, junior design, and non-design groups, and descriptive information about the study variables in each group.

Sample	Senior design	Junior design	Non-design
N (F:M)	22:18	19:21	20:20
RPM	54.45 (5.48)	56.03 (4.16)	55.55 (2.54)
AUT***	0.71 (0.96)	−0.40 (0.89)	−0.32 (0.74)
RAT*	37.20 (6.00)	38.78 (5.81)	40.40 (6.16)

*$N = 120$. RPM, Raven's Progressive Matrices; AUT, Alternate Uses Task; and RAT, Remote Associates Task. *$p < 0.05$; ***$p < 0.001$.*

RAT (Convergent Thinking)

A modified Chinese version of the RAT (Mednick, 1962) was designed for the purposes of this study to measure convergent thinking. In the original English language version of the RAT (Mednick, 1962), participants are given three unrelated words (e.g., shelf, worm, and end) and asked to find another word that would form a compound word with each of the three unrelated words (e.g., adding the word "book" could create the compound words "bookshelf," "bookworm," and "bookend"). In English, the solution would produce three new words that are not related in meaning. The original word and the three solutions differ in both morphology and in semantics.

Because of the stark differences between the English and Chinese languages in morphology and semantics, the RAT in these two languages is analogous but not parallel tests of convergent thinking. In Chinese, adding the same character to three unrelated words generates new words that differ from each other in morphology (and in the pronunciation of the added character) but are related semantically. Presented with the characters "昼," "深," and "晚" (day, deep, and evening), the participant could add the character "夜" (night) to generate "昼夜," "深夜," and "夜晚" (day and night, late at night, and night). Depending on the word, the added character would appear either to the right or to the left of the original character and would likely be pronounced differently in the three solutions, but because the character for "night" appears in each new word, the three new words will be related semantically. That is, the three new words would differ from the original word and from each other in morphology, but the three new words and the original word would have shared meaning. There was a 20-min limit to complete the 58 items.

SPM (Nonverbal Abstract Reasoning)

Raven's Progressive Matrices Test is a widely used nonverbal assessment of fluid intelligence, including nonverbal abstract reasoning (Raven et al., 2003). The task measures the individual's ability to identify perceptual relations and to reason by nonverbal analogy. Sets of cards with drawings and symbols are presented and the examinee is asked to identify patterns within each set of cards. The SPM comprises 60 items, each scored as correct or incorrect. The final score is the number of correct responses. The test takes 40 min to administer.

Statistical Analysis

We performed a mixed-design 3 × 2 ANOVA with the between subjects factor of group (three groups: senior design students, junior design students, and non-design majors) and within subjects factors of creative tasks (AUT task and RAT tasks), and variables, such as intelligence (RPM), age, and gender, can be treated as covariance in our data analysis.

RESULTS

The ANOVA revealed a significant main effect of interaction of group × creative task, F (2, 114) = 8.47, $p < 0.001$, $\eta_p^2 = 0.129$, indicating that the participants' performances on the AUT and RAT tasks varied according to group, see **Table 1**. The interactions of creative task × intelligence, creative task × age, and creative task × gender are not significant, $p_s > 0.05$, indicating that these factors have no effect.

Two one-way ANOVAs were performed to test differences across the three groups (senior design students, junior design students, and non-design majors). On the AUT task, there was a significant difference across the three groups, F (2, 117) = 20.40, $p < 0.001$, $\eta_p^2 = 0.259$, see **Table 1**. As expected, pairwise comparisons showed that the senior design students obtained significantly higher scores than junior design students and non-design students, $p_s < 0.001$. There was no significant difference between the junior design students and non-design students, $p = 0.695$.

On the RAT task, there was a significant difference across the three groups, F (2, 117) = 3.14, $p = 0.047$, $\eta_p^2 = 0.051$, see **Table 1**. Pairwise comparisons revealed an unexpected pattern of results. The senior design students obtained significantly lower scores than the non-design students, $p = 0.014$. There was no significant difference between the junior design students and the non-design students, $p = 0.199$, or between the senior design students and the junior design students, $p = 0.227$.

In addition, correlation analysis showed that the correlations between gender and other variables were not significant. There was a significant positive correlation between age and AUT scores and a significant negative correlation between age and RPM scores. The correlation between RAT and RPM scores was significant and positive. The correlations between other variables were not significant, see **Table 2**. We further conducted regression on age within the groups, and all results were nonsignificant.

DISCUSSION

The results of the current study suggest that training in design improves divergent thinking but does not improve and may even lower convergent thinking. Students who were enrolled in a design program for several years had higher divergent thinking scores compared to students who were just beginning a design program and students who had no training in design. These findings are consistent with previous research on training received in typical design programs (Fink et al., 2006; Sun et al., 2016). They are also consistent with the results of an experiment in which, compared to controls, participants who received 20 sessions of training in divergent thinking showed greater changes in neural activity in brain areas linked to this form of creativity (Sun et al., 2016). However, contrary to our hypotheses, the non-design majors had significantly higher convergent thinking than the senior design students.

TABLE 2 | Correlations among the study variables.

	1	2	3	4	5
Gender	–				
Age	−0.08	–			
AUT	0.14	0.45**	–		
RAT	0.05	−0.09	0.03	–	
RPM	0.05	−0.21*	0.07	0.29**	–

**p < 0.05; **p < 0.01.*

Many believe that high divergent thinking represents high creativity (Finke et al., 1992; Goldschmidt, 2016) and it may be for this reason that educators who want to increase creativity tend to focus on increasing divergent thinking. In curriculum training of design, the educators emphasize the cultivation of divergent thinking and an open environment where students are encouraged to share their ideas, such as the teaching methods, instructional procedures, and teacher–student relationships (Wang et al., 2010; Wu et al., 2019). These design training is likely to be conducive to divergent thinking.

However, our evidence suggests that the focus on divergent thinking may come at the expense of convergent thinking. First, training in divergent thinking might take time away from training in convergent thinking, resulting in lower scores on convergent thinking tasks. Second, even in training programs that do teach convergent thinking, an increase in divergent thinking may inhibit the development of convergent thinking. The results of this study were consistent with these possibilities, in that senior design students had significantly lower convergent thinking scores than the non-design students. This may have been due to the non-design students having developed greater convergent thinking through training in their majors, but there was no significant difference in the level of convergent thinking between the junior design students and the non-design students, suggesting that having more design training (more than 4 years vs. none) did not improve convergent thinking, and may even have harmed it.

Interestingly, some research suggests that the ability to engage in divergent thinking relies in part on a certain level of convergent thinking (Webb et al., 2017; Zhu et al., 2019). Divergent thinking mostly helps in the early stage of design, but convergent thinking is needed to evaluate and hone these ideas in the late stage. Convergent thinking is necessary, and its criterion and skillful use are one key to creativity. The results suggest that students could benefit from design training that fosters both types of thinking without compromising one or the other. This possibility deserves the attention of researchers in education and psychology.

Cognitive flexibility is important to problem solving and is related to creativity. Martindale (2007) conceptualized this individual difference in terms of cognitive inhibition: Highly creative people can flexibly shift their attentional focus when faced with different task requirements—that is, they can inhibit or disinhibit cognition depending on the type of creativity that is needed. In the early stages of the creative process, in which the goal is to produce as many design schemes as possible, the creator is more likely to defocus, and disinhibition of cognition helps divergent thinking. However, in the late stage of the creative process, divergent thinking is less helpful because it leads to slower information processing, reducing the ability to evaluate and integrate design schemes using convergent thinking. Martindale's model has been supported by empirical research (Cheng et al., 2016). Creators need to suppress irrelevant information to enhance focus during convergent thinking, but can flexibly switch to divergent thinking according to task requirements (Zabelina and Robinson, 2010; Zabelina et al., 2012). This model is consistent with neuroimaging research showing that creative achievements are associated with over-activation of the prefrontal cortex, suggesting that cognitive flexibility promotes more creative ideas (Colombo et al., 2015).

Several limitations to this study are worth mentioning. First, the cross-sectional design does not provide information about changes over time and does not allow conclusions about causality (e.g., Coleman et al., 2020; Hu et al., 2021). A longitudinal design would be helpful in identifying which junior design students went on to complete the design program. Second, we adopted the standard RPM test as the tool to measure nonverbal abstract reasoning, and this measure appeared to be too easy for the college students in our sample. The average scores were in the top 90% based on the measure's norms, implying a possible ceiling effect for university students. Though Hommel et al.'s (2011) study also used the standard RPM test and obtained similar results, future research using the advanced RPM is likely to obtain more relevant results concerning nonverbal abstract reasoning. Third, the number of students in each group may have been too small to detect significant group differences.

Despite the limitations, the results from our study provide some meaningful suggestions. Design training programs should teach both divergent and convergent thinking to enhance students' creativity. Both are valued, although the extent to which each type of thinking should be emphasized is an open question. Ideally, research can inform the design training curriculum. Training could include not just learning divergent thinking, but also convergent thinking and cognitive flexibility. Educators could promote divergent thinking and cognitive disinhibition in the early stages of creation, and convergent thinking and cognitive inhibition in the later stages of creation. These three components of creativity could also be used in the assessment of designs in educational settings. Therefore, in future research on creativity, students' cognitive flexibility, divergent thinking, and convergent thinking are concepts that all need attention.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Academic Ethics Committee of Guangdong University of Technology. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

TX and MC designed the study. MC, MK, and JO collected and analyzed the data. TX, MK, and FH wrote the first draft of the manuscript. TX revised the manuscript. All authors contributed to the article and approved the submitted version.

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Investigation on the Influences of STEAM-Based Curriculum on Scientific Creativity of Elementary School Students

*Ngoc-Huy Tran[1], Chin-Fei Huang[1], Kuo-Hung Hsiao[2], Kuan-Li Lin[1] and Jeng-Fung Hung[1]**

[1]Graduate Institute of Science Education and Environmental Education, National Kaohsiung Normal University, Kaohsiung, Taiwan, [2]Collections and Research Division, National Science and Technology Museum, Kaohsiung, Taiwan

Up until now, there have been several different viewpoints on creativity in general and creativity in the science field in particular. Furthermore, STEAM (science, technology, engineering, arts, and mathematics) education is increasingly successful and widespread around the world; however, few studies on its impact on scientific creativity exist. As a result, research on the influence of STEAM-based curriculum on students' scientific creativity is critical. Elementary school students were chosen to be investigated in this research, and the main topic of the STEAM-based curriculum was about a house-shaped money-saving tube with the concept of lock science, which was developed and created by the authors' team. This research produced two phases of courses: Lock Science Courses (2 weeks) and STEAM-based courses (2 weeks). In this study, sixty-six elementary students from two separate courses were divided into two groups: control and experimental. This research used a counterbalanced design. The control group took Lock Science Courses first and then STEAM-based courses, while the experimental group did the opposite. As a pretest and posttest, students in both groups were asked to complete the "scientific creativity test" (Cronbach's α, 0.87). The findings of the paired t-test study indicate that both the control and experimental groups have shown significant improvement in their scientific creativity. However, only the fluency and flexibility components of scientific creativity (consisting of fluency, flexibility, and originality) showed considerable development, whereas the originality component remained unchanged. This research also found that after engaging in a STEAM-based curriculum, there was no substantial difference in scientific creativity between males and females. Further discussion is provided.

Keywords: scientific creativity, science education, steam, STEAM-based curriculum, elementary school students

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Weihua Niu,
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Olivia López Martínez,
University of Murcia, Spain
Chih Ming Chu,
National Ilan University, Taiwan

***Correspondence:**
Jeng-Fung Hung
t1873@nknucc.nknu.edu.tw

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INTRODUCTION

According to the Organization for Economic Cooperation and Development (OECD, 2019a) study on the Future of Education and Skills 2030 initiative, creativity is one of the most significant and necessary factors in generating new value and seeking solutions to difficult challenges and it is also becoming an increasingly important aspect to ensure sustainable development (Said-Metwaly et al., 2018). Furthermore, according to Meador (2003), someone who has learned to think creatively while working with scientific tasks is able to apply these skills in other ways.

Although there are several approaches to creativity, there are mainly four elements of creativity as observed in most of the prior research. They are action, production, disequilibrium, and sensitivity to a problem. In summary, creativity can be defined as a specific human capacity, an act that results from a perception of the environment that admits a certain unbalance, which results in productive activity that challenges patterned processes and norms of thought, then explores and creates something new in the form of a physical object or even an emotional structure, and solves real-world problems in a creative manner (Guilford, 1950; Huang et al., 2017; Walia, 2019). Most educators believe that creativity can be achieved through learning (Ford & Harris, 1992; Hoffman et al., 2021). Therefore, numerous scholars and educators around the world believe that creativity is one of the goals of education and that it is vital for the future (Shi et al., 2017; Suyidno et al., 2019).

PISA 2021, in keeping with this perspective, centered on the topic of creative thinking in schools (OECD, 2019b). In formal education, however, there are less standardized creativity-training courses and Newton and Newton (2010) found that teachers' conceptions of scientific creativity in elementary schools are either narrow or inappropriate. Thus, the aim of this research was to develop a systematic curriculum for elementary school students in order to increase their creativity.

As previously mentioned, the definition of creativity has a range of meanings based on the area of study, and it is presented with domain-specific interpretations. Despite the fact that cognitive structure of creativity is identical, the essence of domain-specific creativity differs significantly (Csikszentmihalyi, 1996). Hence, the diverse points of view will influence the conversation about creativity. In this research, creativity in the scientific field, also known as scientific creativity, is concerned.

Scientific creativity is a subset or form of scientific giftedness, which is a type of domain-specific creativity in which humans combine their science context expertise with domain-relevant creativity to achieve scientific vision (Amabile, 1996; Sternberg and Lubart, 1993; Hu and Adey, 2002; Ayas and Sak, 2014; Author, 2019). More specifically, according to Ayas and Sak (2014), scientific creativity is considered as a result of the convergence of several cognitive and noncognitive variables such as intelligence, skills associated with creation, scientific abilities, characteristics and motivations of personality, interest, concentration, and the search for knowledge and chance permutation of mental elements. It may be seen as a problem-solving process that involves three different stages. These stages include the interaction of hypothesis generation, the design and conduct of experiments, and the assessment of evidence. One of the most important characteristics of scientific creativity is the ability to generate a large number of hypotheses for a particular issue or circumstance. One crucial criterion for science creativity, according to Kind and Kind (2007), is that it should be focused on what "real" scientists do. In order to address scientific and environmental issues that are becoming global problems and threats (Dunlap and Jorgenson, 2012), not just scientists but also humans must use their scientific creativity. As a result, this study confirms the importance of focusing the definition of creativity on scientific creativity to a greater extent.

Many previous studies have found that people with high creativity skills have a deep sense of interest and a strong correlation between their knowledge and experiences in order to generate new ideas (Lubart, 1994; Feldhusen and Goh, 1995; Thuneberg et al., 2018; Conradty and Bogner, 2019). To put it another way, the interdisciplinary thinking skill or integrated learning will be a critical element in honing human creativity and making knowledge more holistic, long-lasting, and versatile (Newton, 2000). STEAM (science, technology, engineering, art, and mathematics) subjects, according to Conradty and Bogner (2019), are a form of interdisciplinary education strategy. Ngo and Phan (2019) also note that the multidisciplinary approach in the project-based learning strategy fits into the STEAM concept. According to some studies, students' scientific creativity improved significantly after taking STEAM courses (Kim et al., 2014; Genek and Doğança Küçük, 2020; Ozkan and Topsakal, 2021). However, Perignat and Katz-Buonincontro (2019) claimed in an integrative literature review that research is required to consider the effects of STEAM in practice in order for STEAM education to develop as an efficient pedagogy; several scholars posit that the STEAM concept is a model for enhancing creativity, but there is not much evidence to support this notion.

As a result, the aim of this research was to determine a STEAM-based curriculum design that is best suitable for helping elementary school students develop their scientific creativity. Using project-based learning methods, this study created a two-stage STEAM-based curriculum. The key focus of this STEAM-based curriculum is finishing a project—assembling a house-shaped money-saving tube and investigating the causes for varying outcomes under various conditions. "Lock Science Courses" and "STEAM-based courses" are the two stages of this curriculum. The next section will go into the basics of program design (Methods section).

To summarize, this study elicits two key research questions:

i) Which kind of sequence of the course stage design has the remarkable impact on improving scientific creativity of elementary school students, as measured by the constituent scores of scientific creativity (fluency, flexibility, and originality)?
ii) Is there a discrepancy in the effects of STEAM-based curriculum on various genders after they participated in the study?

This study has a few scientific limitations. All participants in this research will write down their responses to the scientific creativity test at the same time in class. However, if the number of responses is low, this study would be unable to determine whether this is due to the students' lack of commitment to complete the exam. Simply put, this study will count all data in the research article that includes terms. Besides, the findings of the paired t-test study indicate that both the control and experimental groups have shown improvement in their scientific creativity significantly.

TABLE 1 | Distribution of all participants.

Groups	Gender	Number of participants	Age (mean ± SD)	
Control group (*n* = *33*)	Male	20	11.7 ± 0.8	11.6 ± 0.7
	Female	13	11.6 ± 0.7	
Experimental group (*n* = *33*)	Male	17	11.4 ± 0.7	11.5 ± 0.6
	Female	16	11.6 ± 0.5	
Total (*n* = *66*)	Male	37	11.5 ± 0.8	11.6 ± 0.7
	Female	29	11.6 ± 0.6	

FIGURE 1 | Photos of the house-shaped money-saving tube and students participating in the study.

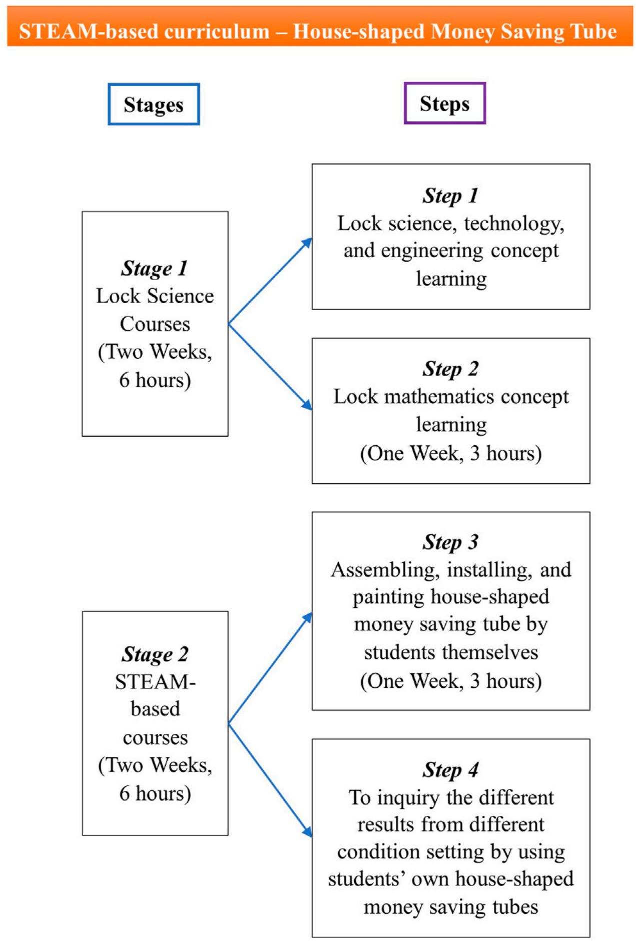

FIGURE 2 | The STEAM-based curriculum design of the house-shaped money-saving tube.

MATERIALS AND METHODS

Participants

This research was carried out in an urban elementary school in Taiwan. Sixty-six elementary school students from two elementary schools in the south of Taiwan voluntarily took part in the study, enrolled in the course, and participated in the survey. They were randomly divided into experimental and control groups. The participants' details are described in **Table 1**. Photos of students participating in the experiment are shown in (**Figure 1**). Before and after the whole course, all participants were asked to complete the scientific creativity test (Hu and Adey, 2002). The two groups of students, on the contrary, went through different stage designs. The next segment would go into the aspects of the curriculum design.

Research Design and STEAM-Based Curriculum Design

The aim of this research was to see how the STEAM-based curriculum affects scientific creativity of elementary school students. The key subject of the STEAM-based curriculum is a house-shaped money-saving tube that was designed and produced by the authors' team. In addition to serving the same role as other money-saving tubes in helping to keep coins, the house-shaped money-saving tube is also a useful tool for automatically sorting coins of various denominations into different internal storage compartments when deposited. Students must learn about the lock science, technology, engineering, and mathematics principles in order to comprehend the complexity of this. Furthermore, this study included STEAM-based courses to help students grasp the

TABLE 2 | The scientific creativity test (Hu and Adey, 2002; Huang and Wang, 2019).

Item	Contents	Scoring
Item 1: unusual uses	Please write down as many possible scientific uses as you can for a piece of glass.	Fluency, flexibility, originality
Item 2: problem finding	If you can take a spaceship to travel in outer space and go to a planet, what scientific questions do you want to research? Please list as many as you can.	Fluency, flexibility, originality
Item 3: product improvement	Please think up as many possible improvements as you can to a regular bicycle, making it more interesting, more useful, and more beautiful.	Fluency, flexibility, originality
Item 4: scientific imagination	Suppose there was no gravity, describe what the world would be like.	Fluency, flexibility, originality
Item 5: problem solving	Please use as many possible methods as you can to divide a square into four equal pieces (same shape).	Flexibility, originality
Item 6: science experiment	There are two kinds of napkin. How can you test which is better? Please write down as many possible methods as you can and the instruments, principles, and simple procedure.	Flexibility, originality
Item 7: product design	Please design an apple picking machine. Draw a picture, point out the name and function of each part.	Flexibility, originality

TABLE 3 | Definition of scoring for the originality score.

Item	Score (points)		
	The probability of a response was less than 5% of all responses	The probability of a response was from 5 to 10% of all responses	The probability of a response was greater than 10% of all responses
1–4	3	2	1
5	2	1	0
6	4	2	0
7	5	3	1

overall principles of the house-shaped money-saving tube. Both groups of students must mount, install, and paint their own house-shaped money-saving tubes and use their own tubes to investigate various outcomes from various condition settings. Hence, this research produced a STEAM-based curriculum of two stages and four steps (**Figure 2**). The curriculum design was reviewed and validated by three experts (male = 2, female = 1; all experts majored in science education).

Despite the fact that all students went through these two stages of the program, the aim of this research was to establish "the influences of the STEAM-based curriculum on students' scientific creativity" as well as "which kind of sequence of the course stage design is more successful to boost students' scientific creativity." This study used a counterbalance design to determine the potential outcomes of key research questions. Students in the control group were required to participate in stage 1 (Lock Science Courses) before going on to stage 2 (STEAM-based courses). This type of curriculum design aids students in constructing science principles first and then guiding them to incorporate these concepts through participation in STEAM courses. Students in the experimental group, on the contrary, were required to join stage 2 first and then stage 1 (**Figure 3**). This style of curriculum design assists students in self-learning of interdisciplinary expertise in STEAM courses and then leads them in generalizing their science concepts.

The control group style (stage 1 to stage 2) involves building students' science principles first and then guiding them to incorporate these concepts by participation in STEAM courses. The experimental group style (stage 2 to stage 1) allows students to learn on their own.

The research design is a kind of cross-study method. There are two reasons to use the cross-study method: 1) We did not know if the sequence of different teaching methods affected the results. 2) Students in both groups need to accept the same teaching method for better research ethics.

As can be seen in **Figure 3**, the comparison of pretest and posttest data were used to reflect about research questions "which kind of sequence of the course stage design has the remarkable impact on improving scientific creativity of elementary school students, as measured by the constituent scores of scientific creativity (fluency, flexibility, and originality)" and "is there a discrepancy in the effects of STEAM-based curriculum on various genders after they participated in the study."

Instruments and Scoring

The scientific creativity test (Hu and Adey, 2002) was used as the main instrument in this study; its details are mentioned in **Table 2**. Author (2019) retested and validated this test, and the findings showed that science performances and creativity of students in both groups correctly represented their scientific creativity.

The scientific creativity test was used in the research of Hu and Adey to investigate the scientific creativity of high school students, and reliability of Cronbach's α reached 0.89. The test was converted into Chinese and retested in middle school students (n = 82, 38 males, 44 females; mean age ±SD = 14.1 ± 1.1 years) in Taiwan, and the revised reliability of Cronbach's α reached 0.87. The test was designed for group administration with a time limit of 60 min. The examiner sought to make the students feel at ease but also wanted them to work hard to complete the tasks. **Table 2** presents each of the seven items in the test.

The definition of scoring (Author, 2019; Hu and Adey, 2002) is as follows:

i) Fluency score: to count all of the separate responses given by the subjects, regardless of the quality.
ii) Flexibility score: to count the number of approaches or areas used in the answer.

TABLE 4 | The comparison table of pretest and posttest data.

Group	Pretest (mean ± SD)	Posttest (mean ± SD)	*t*	*p*
Control group (n = 33)	55.91 ± 15.24	70.79 ± 15.11	–3.982[a]	0.000
Experimental group (n = 33)	54.70 ± 17.11	70.15 ± 17.83	–3.592[a]	0.001
Total (n = 66)	55.30 ± 16.09	70.47 ± 16.40	–8.658[a]	0.000

[a]p< *0.05.*

TABLE 5 | The comparison table of pretest and posttest data of scores of the three components of scientific creativity.

Components	Group	Pretest (mean ± SD)	Posttest (mean ± SD)	*t*	*p*
Fluency	Control group (*n* = 33)	35.58 ± 10.19	46.12 ± 9.33	–4.383[a]	0.000
	Experimental group (*n* = 33)	34.06 ± 10.83	45.55 ± 10.90	–4.293[a]	0.000
	Total (*n* = 66)	34.82 ± 10.46	45.83 ± 10.07	–7.869[a]	0.000
Flexibility	Control group (*n* = 33)	17.82 ± 4.90	22.27 ± 5.76	–3.382[a]	0.001
	Experimental group (*n* = 33)	17.42 ± 5.79	22.36 ± 6.97	–3.131[a]	0.003
	Total (*n* = 66)	17.62 ± 5.33	22.32 ± 6.34	–8.994[a]	0.000
Originality	Control group (*n* = 33)	2.52 ± 0.94	2.39 ± 3.89	0.174	0.863
	Experimental group (*n* = 33)	3.21 ± 2.18	2.24 ± 2.03	1.871	0.066
	Total (*n* = 66)	2.86 ± 1.70	2.32 ± 3.08	1.623	0.109

[a]p< *0.05.*

TABLE 6 | ANCOVA analysis to compare scientific creativity among different groups of students (*n* = 66).

Source	*SS*	*df*	*MS*	*F*	*p*	*η2*
Corrected model	6,651.260	2	3,325.630	19.326	0.000	0.380
Intercept	6,464.842	1	6,464.842	37.568	0.000	0.374
Precreativity	6,644.579	1	6,644.579	38.613	0.000	0.380
Group	0.261	1	0.261	0.002	0.969	0.000
Error	10,841.179	63	172.082			
Total	345,247.000	66				

iii) Originality score: scored based on the probability of a response among all responses, detailed in **Table 3**.

All answers by the students were read by three professional experts, and the results were the individual scores of fluency, flexibility, and originality. Each expert could then read the scores of the other two experts and make remarks or changes of their own. The three experts came to a unanimous decision after reviewing three times.

All of the data selected by the study was approved by the volunteering students, and they all had provided volunteer citation.

RESULTS AND DISCUSSION

This study aimed to explore the influences of STEAM-based curriculum on the scientific creativity of elementary school students. There are two main research questions in this study: "which kind of sequence of the course stage design has the remarkable impact on improving scientific creativity of elementary school students" and "is there a discrepancy in the effects of the STEAM-based curriculum on various genders after they participated in the study."

On the whole, the results from **Table 3** show that not only all participants but also the control group and experimental group obtained significant higher scores of scientific creativity after joining the whole STEAM-based curriculum than before. The result supports that the curriculum design in this study could improve students' scientific creativity.

The findings from **Table 4** show in general that after joining the entire STEAM-based curriculum, not only all participants but also the control and experimental groups achieved significant higher scores than before. The outcome supports that the curriculum design in this study could improve students' scientific creativity. This could be confirmed by previous studies which indicated that a multidisciplinary approach of project-based STEAM curriculum design would improve students' scientific creativity (Erdoğan et al., 2013; Knezek et al., 2013; Kim et al., 2014; Ugras, 2018; Ngo and Phan, 2019; Akhmad et al., 2019; Genek and Doğança Küçük, 2020; Ozkan and Topsakal, 2021). In addition, Ozkan and Topsakal (2021) have concluded in their research that the STEAM design curriculum will boost scientific creativity in students' verbal and figure domain-relevant skills. While using the scientific creativity test (Hu and Adey, 2002), the examiners need to clearly explain, motivate, and encourage students to try to promote their scientific creativity and problem-solving skills. That being said, in order for students to develop scientific creativity, teachers, who will be in contact with students for a long time, need to have a clear understanding of scientific creativity and STEAM courses and take active measures to create motivation and interest in students. This is consistent with the findings of Ugras (2018).

TABLE 7 | The comparison table of pretest and posttest data by gender.

Groups	Gender	Pretest (mean ± SD)	Posttest (mean ± SD)	*t*	*p*
Control group (*n = 33*)	Male (*n = 20*)	49.80 ± 12.26	69.80 ± 8.90	−5.903[a]	0.000
	Female (*n = 13*	65.31 ± 14.96	72.31 ± 21.90	−0.952	0.351
Experimental group (*n = 33*)	Male (*n = 17*)	53.41 ± 16.11	68.35 ± 18.06	−2.546[a]	0.016
	Female (*n = 16*)	56.06 ± 18.55	72.06 ± 17.98	−2.477[a]	0.019
Total (*n = 66*)	Male (*n = 37*)	51.46 ± 14.07	69.13 ± 13.68	−5.478[a]	0.000
	Female (*n = 29*)	60.21 ± 17.38	72.17 ± 19.46	−2.470[a]	0.017

[a]$p < 0.05$.

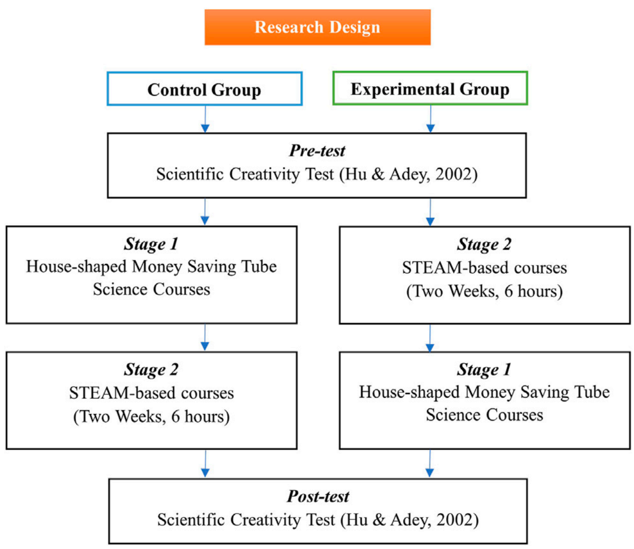

FIGURE 3 | The research design structure of this study.

Data analyses of components of scientific creativity are also conducted in order to better understand the influence of the STEAM curriculum on participating students (**Table 5**).

The findings of **Table 5** demonstrate that, after engaging in the STEAM-based program, the fluency and flexibility of students in both experimental and control groups were significantly higher. However, the originality score did not vary significantly in the pretest and posttest. This is in line with the findings by Darvishi and Pakdaman (2012). This means that, after participating in the STEAM-based curriculum, the development of elements of scientific creativity in students is different. The STEAM-based curriculum has a major impact on fluency and flexibility but does not significantly change the originality component. Many explanations can be given for this. Previous studies have shown that cultural background and students' attitudes towards science and technology courses have an influence on students' scientific creativity (Usta and Akkanat, 2015; De Vries and Lubart, 2019). In addition, other factors, such as the nature of the STEAM curriculum, the quality of the courses, the characteristics of the participating students, and cultural background can also influence students' scientific creativity. Further study is therefore essential to confirm the above concerns and find ways to enhance all the three components of scientific creativity.

Next, this study wanted to find out which kind of sequence of the course stage design has more influence on improving scientific creativity of elementary school students. There are two kinds of curriculum designs in this study (see in **Figure 3**). The first one is used in the control group; students were required to participate in stage 1 course (Lock Science Courses) before going on to stage 2 (STEAM-based courses). This type of curriculum design aids students in constructing science principles first and then guiding them to incorporate these concepts through participation in STEAM-based courses. The second one is used in the experimental group; students were required to join stage 2 first and then stage 1. This style of curriculum design assists students in self-learning of interdisciplinary expertise in STEAM courses and then leads them in generalizing their science concepts. To answer this question, ANCOVA analysis to compare scientific creativity among different groups of students was performed (**Table 6**).

Table 5 shows that, after joining all STEAM-based curriculums, there were no significant differences in the control group and the experimental group. The different course sequence of the design, in other words, has little effect on the final results of scientific creativity of the students. According to Perignat and Katz-Buonincontro (2019), despite the variety of models and pedagogical approaches for STEAM education, they almost educate students to utilize cross-disciplinary knowledge to solve real-world problems. Besides, most contents of the scientific creativity test (Hu and Adey, 2002) were concerned with real-life problems; this could be a reason to understand why the students' scientific creativity performances could be significantly improved by the STEAM-based curriculum participation no matter which stage was used first. However, these implications and hypotheses should be supported by further research.

Finally, to answer the question "is there a discrepancy in the effects of STEAM-based curriculum on various genders after they participated in the study," an analysis of scientific creativity scores by gender before and after participating in the experiment has been performed (**Table 7**).

While there was no substantial difference in scientific creativity of females in the control group for pretest and posttest scores ($p = 0.351 > 0.05$), the other findings showed substantially higher scientific creativity scores regardless of gender in the control group, the experimental group, and all of the participants. The effects of the STEAM-based curriculum on various genders are obviously similar in this study. This result is consistent with that of previous studies (Darvishi and Pakdaman, 2012; Genek and Doğança Küçük, 2020). This indicates that males and females have the same potential to improve scientific creativity after participating in STEAM education and also contributes to affirming and reinforcing the goal of equality in education between men and women in the sustainable development goals (UN, 2015), where both genders are equally capable of developing scientific creativity. It is important to create conditions for both material and learning programs so that they have the ability to perfect themselves to the fullest.

CONCLUSION AND SUGGESTION

This study aimed to investigate the influences of STEAM (science, technology, engineering, arts, and mathematics)-based curriculum on scientific creativity of elementary school students. The two core research questions are as follows:

i) Which kind of sequence of the course stage design has the remarkable impact on improving scientific creativity of elementary school students, as measured by the constituent scores of scientific creativity (fluency, flexibility, and originality)?
ii) Is there a discrepancy in the effects of STEAM-based curriculum on variousgenders after they participated in the study?

The main project of STEAM-based curriculum in this study is the house-shaped money-saving tube which was designed and produced by the authors' team. Furthermore, the main concept of house-shaped money saving-tube is about lock science. This study adopted the counterbalance design. The control group joined Lock Science Courses first and then enrolled in STEAM-based courses, and the experimental group joined in the reverse sequence.

Data analyses show that the STEAM-based curriculum could increase scientific creativity of elementary school students, regardless of the kind of sequence of the course stage design. Specifically, in the three components of scientific creativity (fluency, flexibility, and originality), students, after participating in the whole STEAM-based curriculum, showed a significant improvement in fluency and flexibility components but the same result was not observed in the originality component.

This research also found no substantial difference in science creativity between males and females following STEAM-based curriculum participation. It is indicated that the development of scientific creativity of males and females participating in STEAM education is the same.

While the findings of ANCOVA analysis demonstrate that there are no significant differences between scientific creativity performances of students in the control group and experimental group after joining the whole STEAM-based curriculum, this study does not indicate which stage supports the scientific creativity of students more actively. Further research on these two stages (Lock Science Courses stage and STEAM-based courses stage) is therefore needed to verify.

The results suggested that both the STEAM courses and traditional science courses could help students preserve or continue their scientific creativity. Furthermore, considering gender differences, the STEAM course could improve female students' scientific creativity; however, the traditional course did not show significant improvement in female students' scientific creativity. This study suggests the investigators to extend the investigation period or to do the delayed posttest to validate the statements of implications.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Written informed consent was obtained from the minors' legal guardian/next of kin for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

All authors contributed to conception and design of the study. N-HT, C-FH, K-HH, and K-LL organized the database and collected data. N-HT performed the statistical analysis and wrote the first draft of the manuscript. C-FH, K-HH, K-LL, and J-FH listed sections of the manuscript. All authors contributed to manuscript revision and read and approved the submitted version.

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BRIEF RESEARCH REPORT
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Can Priming Multiple Identities Enhance Divergent Thinking for Middle School Students?

Qian-Nan Ruan[1], Xin-Wu Ye[1], Sui-Lin Jia[1], Jing Liang[2], Wen-Jing Yan[3]* and Yao-Ju Huang[1]*

[1] Wenzhou Seventh People's Hospital, Wenzhou, China, [2] School of Educational Science, Ludong University, Yantai, China, [3] College of Teacher Education, Wenzhou University, Wenzhou, China

Previous studies have found that promoting multiple identities can improve children's creative performance (divergent thinking). The present study employed a priming paradigm to design two experiments and investigate whether promoting a sense of multiple identities in middle school students could enhance their divergent thinking, a key component of creativity. In Experiment 1, 77 junior high school students were divided into multiple identities and physical trait condition groups. They were instructed to think about a child with multiple identities or physical traits. The results showed that there were no differences in divergent thinking (DT) scores between the two groups. In Experiment 2, we modified the priming method by asking participants to think about and write a description of the various identities or physical traits and employed a subjective top-scoring method to make up for shortcomings in the traditional scoring method when applied to originality. The results still showed no significant difference in scores between the identity and physical trait groups. Thus, the results of this study contradict those of previous research, which found that the identity group demonstrated significantly higher scores on a creativity test than did those in the physical trait group. Several potential factors affect this outcome, but it seems that priming to enhance divergent thinking is not particularly effective. Thus, the social priming effect should be pursued with caution regarding both replicability and generalizability.

Keywords: creativity, divergent thinking, multiple identities, social priming, scoring method

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Roshi Khalid,
University of Education Lahore, Pakistan
Manh-Toan Ho,
Phenikaa University, Vietnam

****Correspondence:***
Wen-Jing Yan
eagan-ywj@foxmail.com
Yao-Ju Huang
506237791@qq.com

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INTRODUCTION

Creativity is often emphasized as key training content in education, for it has great meaning both for countries and individuals. Half a century ago, Guilford proposed that divergent thinking (DT) is the core of creativity (Guilford, 1967; Sternberg and Grigorenko, 2001). His claim reshaped our views on creativity, and since then DT has held the dominant position in the field of creativity measurement. In particular, DT is assessed according to three aspects: (1) ideational fluency, or the number of ideas an individual has; (2) ideational flexibility, or the number of different conceptual categories used by the individual; and (3) ideational originality, or the statistical infrequency or uniqueness of ideas (Beketayev and Runco, 2016). DT is not synonymous with creativity, but this is a useful quality, enhancing its measurability in relation to creative potential (Runco and Acar, 2012). Accordingly, increasing DT is regarded as beneficial for improving performance on creative tasks.

Creativity or DT is influenced by the complexity of one's social identification. An individual's various forms of identification provide openings to different mindsets and angles of thought, which facilitate flexible thinking and help with creative problem solving. Several studies have found that bicultural individuals showed enhanced creativity and professional success, as compared with individuals who identified with only a single culture. This may be explained by their greater levels of integrative complexity, an information processing capacity that involves considering and combining multiple perspectives (Benet-Martínez et al., 2006; Maddux and Galinsky, 2009; Tadmor et al., 2012).

Research has shown that the changing mindsets and feelings related to one's identity can instantly improve flexible thinking and solving-problem performance. Gaither et al. (2015) observed that people reminded of their multiple racial or social identities generally outperformed the control group in associative and generative creativity, as measured through word tasks (Gaither et al., 2019). The researchers observed that making children aware of their multifaceted identities promoted flexible thinking. Gocłowska and Crisp (2014) argued that possessing two inconsistent identities could foster superior creativity because it allowed for: (a) alternating identities across contexts, (b) integrating elements of distinct (i.e., remote and uncorrelated) identities and, having formed cognitive and emotional links with a new group, a (c) broadening of self-definition. It is meaningful to verify such an observation and better understand the mechanism in operation because doing so will provide us with a key to understanding and fostering creativity and enhancing problem-solving performance.

One convenient method to make people experience feelings related to various identities is priming. Priming refers to providing environmental stimuli that may affect a subject's responses by activating mental constructs without their conscious realization (Bargh and Chartrand, 2000). In social psychology, researchers call this social or behavioral priming to differentiate it from semantic priming, which refers to the observation that a response from a target (e.g., a dog) is faster when it is preceded by a semantically related prime. Behavioral priming is important in psychological theory because it provide evidence about the influence of automatic or unconscious processes on behavior (Payne et al., 2016). As previous research has shown, the priming of multiple identities seems to improve creativity (flexible thinking). In the present study, we plan to verify the such a priming effect.

With regards to creativity assessments, DT tests are a top priority. Though the validity and reliability of such tests are the subject of much debate, they are still supported by scholars and continue to be popular in research and practice (Runco and Acar, 2012). DT tests are mostly comprised of open questions, requiring subjects to list as many answers as possible, according to the requirements of the question. For example, in one study, participants were asked to write down as many different uses for objects as possible in 2 min (Hass, 2015). Among the DT tests available, the most frequently used include Guilford's Structure of the Intellect (SOI) (Guilford, 1967), the Torrance's Test of Creative Thinking (TTCT) (Torrance, 1972), and less commonly, the Wallach-Kogan test.

This study conceptually replicates Gaither's 2019 research, in which it was observed that making children aware of their multifaceted identities promoted flexible thinking. In this study, we focused on junior middle school students who demonstrated high self-awareness and were asked to solve a problem related to self-identity. Participants of this age have expanded social interactions and a solid understanding of their various social roles (Barenboim, 1981; Burnett and Blakemore, 2009). In addition to the social development of the early adolescents, the schools try to promote the development of creativity at this stage, and middle school students have more time and are more malleable than high school students and adults. By reason, it was assumed that such participants would display a significant effect from multi-identity priming on their creativity or flexible thinking. In Experiment 1, we hypothesized that students primed regarding their multiple identities would offer numerous perspectives, and thus would outperform on DT tests those who were primed regarding physical traits.

EXPERIMENT 1

Participants

Seventy-seven Chinese students in their first year of middle school (aged 13–14) took part in an experiment. These students were selected from two parallel classes in the same grade, with one class in multiple identities condition (39 participants, 19 females) and the other in physical traits condition (38 participants, 18 females). Neither group of students had taken part in a similar type of experiment before.

Materials

All participants were presented with instructions that matched their gender. The subjects were guided to recognize multiple identities or physical traits. In the multiple identities condition, participants were led to identify eight identities or physical traits, and experience what it was like to have them all. For example, "Look at this girl! She is a reader, and she is also a friend. Are you a reader? Are you also a friend?" The physical traits instructions were identical, except participants were told that they had eight physical attributes. For example, "Look at this girl! She has two feet and a mouth. Do you have two feet? Do you have a mouth?" After they read the instructions and indicated that they understood, they were asked to sign their name on the instruction sheet. Then, they were asked to recall and write down the eight identities/physical traits on a separate sheet of paper (see **Supplementary Material 1**).

Procedure

This experiment was a one-factor between-subjects design. The independent variable of priming condition had two levels: multiple identities and multiple physical traits. The dependent variable was their score on the DT test extracted from the

Wallach-Kogan test (Cropley and Maslany, 1969). We selected three items from three sections: Uses, Similarities, and Pattern Meaning. The Kuder-Richardson reliability coefficients on the original test were 0.82, 0.86, and 0.87, respectively. Thus, the DT test in this study consisted of three sections with three items each.

First, the researcher distributed the priming materials (see **Supplementary Material 1**) to the multiple identities and physical traits groups, asked the subjects to read through the materials on page 1, and try to feel the identities or physical traits listed. Then, the subjects signed their names on page 2, and tried to recall the identities or physical traits and list them. Next, the experimenter distributed a DT test. The time limit was 5 min for each section (three items each), for a total of 15 min. The experimenter encouraged the students to write as many answers as possible (see **Supplementary Material 2**). They were not allowed to move to the next section until time was up for the first section.

Data Analysis

Scoring the Tests

One participant was removed from the analysis because they did not complete the test. Answers from 76 participants were input into a computer and scored according to three DT dimensions: fluency, flexibility, and originality. Because manual scoring of DT tests is very time-consuming and laborious, researchers have developed an automatic computer-based processing method for word classification and data analysis (Beketayev and Runco, 2016). Subsequent researchers developed a Chinese version of the computerized scoring system (Shen and Shao, 2019). The Kendall coefficients for the samples were 0.860 for fluency, 0.836 for flexibility, and 0.627 for originality (see **Supplementary Material 3** for details).

Removing Extremes

The data generally followed a normal distribution, with some extremes. For example, most students wrote down fewer than 10 answers for each question, but one listed 18 answers. Extreme values always need to be dealt with because they can significantly impact the average. We calculated the standard deviation of the scores and defined the extreme values as those with standard deviations less than −2.5 or greater than 2.5 (less than 5% of the total data). However, this extreme value was not a mistake and it would not have been suitable to directly eliminate it or replace it with an average. Therefore, the SD of the score outside of the threshold (SD ±2.5) was replaced with the threshold value.

Merging the Data

The scores for the fluency, flexibility, and originality sections were averaged to obtain the overall scores for each. Then, the overall fluency, flexibility, and originality scores were averaged to serve as the DT score for each subject.

Results

An independent samples *t*-test was used to compare the differences in fluency, flexibility, originality, and average scores for the multiple identities and physical traits conditions. The *p* values for these dimensions were close to but greater than 0.05, meaning there may have been marginally significant differences in higher scores for the physical traits rather than the multiple identities condition (see **Table 1**).

TABLE 1 | Divergent thinking (DT) scores for multiple identities and physical traits conditions (*N* = 76).

Dimension	Multiple identities		Physical traits		*t*	*p*
	M	*SD*	*M*	*SD*		
Fluency	4.523	1.597	5.237	1.669	−1.962	0.054
Flexibility	4.088	1.240	4.646	1.338	−1.888	0.063
Originality	6.015	2.173	6.919	2.395	−1.722	0.089
Average	4.875	1.625	5.600	1.784	−1.852	0.068

We hypothesized that the multiple identities condition would show significantly higher scores for all three DT dimensions. However, the results did not support the hypothesis. Actually, the multiple identities condition score was marginally lower than that of the physical traits condition. This may have been because the multiple identities priming in Experiment 1 did not produce the desired effects. The primed identities/physical traits were already presented in the text and the students could simply recall these words, where they didn't genuinely feel these identities. We tried to modify the priming approach in Experiment 2 by asking the students to write down the identities/physical traits by themselves, expecting that such an operation would make them more fully aware of their own identities and have better priming effects. In addition, we used subjective top-scoring to score originality in Experiment 2, considering the drawbacks of the traditional approach to originality scoring and the low reliability of originality in the computerized scoring system.

EXPERIMENT 2

Experiment 2 had a similar design to Experiment 1, but each participant was asked to think by themselves and write about the identities/physical traits. In addition, a subjective top-scoring method was used to score originality. Traditional scoring on DT tests suffers from a high correlation between fluency and originality, meaning that more writing leads to higher scores for originality. Scholars have proposed a subjective top-scoring method, where participants are asked to select a number of their most creative ideas for later creativity ratings, avoiding problems such as not confusing originality with fluency and not affected by large sample sizes. Silvia et al. (2008) considered 2 or 3 raters is satisfactory for reliability. In Experiment 2, each participant was asked to circle their three most "creative" answers. Two raters then rated the circled answers on a scale of 1–5, ranging from "not at all creative" to "very creative." Unusual, distinct, and intelligent (Wilson et al., 1953) were used as scoring criteria. A detailed description is published in the appendix of Silvia et al. (2008). To increase inter-rater agreement, scoring guidelines adapted from Silvia et al. (2008) were learned by the raters. We hypothesized that students primed by multiple identities would score higher on the DT test than those who were primed with physical traits.

Participants

Eighty-four students (ages 13 and 14) in their first year at a Chinese middle school took part in the experiment, with 42 in the multiple identities and 42 in the physical traits conditions. The groups of students from Experiments 1 and 2 were different. None of the students had taken part in a similar type of experiment before that day.

Materials

Instead of recalling the identities/physical traits from instructions (as in Experiment 1), the participants in Experiment 2 were required to think about and write down answers on their own. They were encouraged to write as many as possible (see **Supplementary Materials**). It was expected that such an operation would enhance the priming effect beyond what was seen in Experiment 1.

Procedure

The procedure was similar to that of Experiment 1, except that participants were asked to circle their three most creative answers to each question.

Data Analysis

The computerized scoring was similar to what occurred in Experiment 1. On relatively simple tasks such as rating DT tests, novice raters can often do well (Benedek et al., 2013). Two college students were asked to rate the originality of the circled answers and obtain an average score for each. Raters were not involved in the experiment and did not know its purpose. The raters rated the answers to each question on a scale of 1–5, ranging from "not at all creative" to "very creative."

Results

An independent samples t-test was used to compare the differences in fluency, flexibility, originality, and average scores for the two conditions. Since we used subjective top-scoring for originality, we compared the differences between the two conditions in Originality-S and the corresponding Average-S. The p values for these dimensions were much greater than 0.05, indicating that there was no difference between the two conditions (see **Table 2**).

TABLE 2 | Divergent thinking test scores for the multiple identities and physical trait conditions (N = 76).

Dimension	Multiple identities		Physical traits		t
	M	*SD*	*M*	*SD*	
Fluency	4.886	1.342	4.603	1.312	0.977
Flexibility	4.474	1.012	4.169	1.275	1.211
Originality	7.005	1.965	6.124	2.300	1.887
Originality-S*	6.413	1.082	6.405	1.149	0.033
Average	5.455	1.367	4.966	1.574	1.521
Average-S*	5.258	0.945	5.059	0.975	0.947

**Indicates originality dimensions scored by subjective top-scoring, and thus being represented by different averages.*

GENERAL DISCUSSION

The present study found that priming students with multiple identities yielded no significantly higher scores on DT tests than did the control condition. The logic and design of Experiment 1 were based on Experiment 1 of a previous study (Gaither et al., 2019), but our results were dissimilar from theirs. In Experiment 2, we modified the priming approach and used a subjective top-scoring method, but still failed to see the effectiveness of priming multiple identities on improving DT performance.

The present study is a conceptual replica of Gaither et al. (2019). However, there were several differences, including the participants, materials, and procedure. The participants in Gaither et al. (2019) were elementary students in lower grades, while in the present study they were students in their first year of middle school. Students at such an age have better social interaction and self-identity development, which could learn more roles and understand the differences between self and others. Due to the age difference, the present study employed tasks more suitable for older students. The materials in Gaither et al. (2019) included functional fixedness, multiple uses, and social categorization tasks, while the present study employed multiple uses, similarities, and pattern meaning tasks commonly found in the Guilford's SOI, TTCT, and (the less commonly used) Wallach-Kogan tests. There was some overlapping of tasks and several differences, but all required flexible thinking. Therefore, though there are some differences between the present and previous experimental designs, they are basically the same, and students in adolescence are supposed to show a more significant effect. However, the priming effect was not observed.

Since the results of Experiment 1 were not significant, we made some adjustments. Each participant was asked to think about and write down the identities/physical traits on their own. This was expected to get them more involved in feeling the multiple identities, but it made no difference. Moreover, the subjective top-scoring method was used to score originality, in order to avoid the "bad" scoring by computerized scoring system (i.e., the traditional method). However, there was no difference between the subjective top-scoring and traditional scoring in terms of the results for originality.

One likely explanation is that priming may not always work, or may not be particularly robust. This is not surprising because social (rather than semantic) priming is still a topic of debate. Some classic experiments in this area were found not to be replicable. For example, Harris et al. (2013) conducted two experiments and found achievement priming did not improve participants' performance; thus, the researchers were unable to replicate a previous study (i.e., Bargh et al., 2001). In another study, Shanks et al. (2013) conducted nine experiments and none showed that "intelligent priming" affected performance on a subsequent test of general knowledge (Dijksterhuis and Van Knippenberg, 1998).

Payne et al. (2016) believed that the absence of a social priming effect was caused by problems with the experiment design (as well as other aspects), because social priming studies usually have an inter-subject design and there is only one trial. Also, after an operation begins, it takes some time for the task be completed. Such a design may cause the priming effect to be less significant and not consistently affect subsequent operations. In contrast, semantic priming generally occurs within the subject, there are many trials, and the task is carried out immediately after presentation of the priming trial. Thus, the semantic priming effect is more directly applied to the subsequent task. Thus, the authors designed a social priming experiment using semantic priming as a reference. They obtained consistent results in six experiments. In the present study, as Payne et al. asserted, priming was followed not by just by a small task, but a rather long DT test administered after priming. Thus, the priming effect was very small and we used an inter-subject test. This may explain why there was no effect in the present study. However, our work supports the criticism that the classic social priming paradigm is not robust or even replicable.

Similarly, there have been many studies exploring whether priming can change cheating behavior. However, our previous experiments could not find a similar priming effect in practical situations neither (Wu et al., 2020). At the very least, these findings suggest that the effect of classic social priming is small, so the results must be carefully verified before being applied.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by IRB in Wenzhou University. Written informed consent from the participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

Q-NR and JL conceived and designed the experiments. X-WY and S-LJ performed the experiments. Q-NR, Y-JH, JL, and W-JY analyzed the data and wrote and revised the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2021.704614/full#supplementary-material

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Toward the Development of Key Competencies: A Conceptual Framework for the STEM Curriculum Design and a Case Study

Weiping Hu[1,2]* *and Xipei Guo*[1]

[1]*MOE Key Laboratory of Modern Teaching Technology, Ministry of education, Shaanxi Normal University,Xi'an, China,* [2]*Research Institute of Science Education, Beijing Normal University, Beijing, China*

National attention has been given to science, technology, engineering, and mathematics (STEM) education, which is well recognized as an effective way to cultivate the key competencies of 21st-century talents. However, current STEM education falls short of the desired results. The fundamental reason is that there has not been a clearly and structurally explained systematic construction and effective implementation of STEM curricula. Accordingly, this article systematically expounds on the construction of the STEM curricula system from four aspects. Specifically, we first proposed the components of the STEM competencies as the goal of STEM education to provide a guiding direction for other parts of the design of the STEM curricula. Then, we elaborated on how to cultivate the STEM competencies from two aspects: the design principles of the STEM curricula content and the implementation strategies of STEM teaching. Finally, we explained how to effectively evaluate to monitor and improve the implementation of the STEM curriculum. In addition to the above mentioned, we then presented a case study of STEM courses constructed under the guidance of "think-based instruction theory" (TBIT) to help readers further understand the nature of the STEM curricula.

Keywords: STEM education 1, curriculum 2, systems framework 3, key competencies 4, think-based instruction theory 5

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Correspondence:
Weiping Hu
weipinghu@163.com

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INTRODUCTION

The rapid penetration and wide application of the Internet, artificial intelligence technologies, technological products, and big data in daily life have led to an increasingly close relationship between society, science, and technology. Meanwhile, this also brings some new challenges to human life and development (Pleasants et al., 2019), such as socio-cultural diversity, severe global inequality, complex and changing political landscape, and sustainable human development. These complex challenges further put forward the higher request on talents development. Individuals must master interdisciplinary knowledge and abilities within science, technology, engineering, and mathematics fields to adapt to the environment (Taylor, 2016). As a coherent and interdisciplinary approach, STEM education is therefore widely considered a key way to cultivate 21st-century talents who can adapt to and promote social development, as well as has gained a prominent position in education reform in various countries (Saxton et al., 2014). For example, China, the United Kingdom, Germany, South Korea, and Finland have officially included STEM education in government documents.

There is no denying that all education researchers hope to cultivate talents with the key competencies through STEM education, such as communication and collaboration, critical thinking, problem-solving ability, and creativity. Only with these key competencies, students will be able to adapt to the flexible and complex social environment of the future, actively take up social responsibilities, as well as make efforts and contributions to solve critical problems facing by humanity (Saxton et al., 2014).

However, the implementation of STEM education has not reached the expected results in many countries and regions. For example, South Korea strongly advocates STEM education, but many teachers doubt its aims, methodology, and benefits. Chu et al. (2018) explained that, because the STEM curriculum is not grounded in a sound theoretical system, numerous teachers are skeptical of the potential benefit brought by STEM education (Chu et al., 2018). Korkmaz (2018) states that, although Turkey believes STEM education is necessary, they do not have an appropriate curriculum to implement STEM education (Korkmaz, 2018).

In addition, researchers have shown that, although there are many STEM curricula currently available, the lack of consensus on the content and implementation strategies has led to difficulties for schools and teachers to implement STEM curricula (Kelley and Knowles, 2016). At the school level, their difficulty lies in not knowing how to choose high-quality STEM programs. Many current STEM programs simply make students use bits and pieces of knowledge and manipulative skills to achieve a specific goal. Students do not have a deep understanding of interdisciplinary concepts, the nature of scientific practices, as well as their scientific thinking, attitudes, and responsibilities are not developed (Zeidler, 2014). At the teacher level, their difficulties lie in designing appropriate teaching activities and choosing appropriate instructional strategies to integrate STEM interdisciplinary content knowledge, further developing students' STEM key competencies in a holistic manner (Shernoff et al., 2017; Fan et al., 2020).

One reason for the current less-than-expected implementation of STEM education in many countries might be that the systematic construction and effective implementation of STEM curricula have not been clearly and structurally explained (Shernoff et al., 2017). This can lead to difficulties for many frontline educators to truly perceive the value of STEM education and to effectively implement STEM education in the classroom. Therefore, the key question of this article to be addressed is how can a coherent STEM curriculum system be constructed systematically in developing students' key competencies? Specifically, we construct the STEM curriculum system based on the international STEM education experience and our years of research practice, including 1) STEM competencies, as the goals of STEM curriculum, provide direction for content, teaching, and evaluation, as well as play a leading role in the STEM curriculum design; 2) curriculum content and instructional design are the foundational components for achieving the development of students' STEM competencies; 3) evaluation has an important guiding, diagnostic, and pedagogical improvement function for the effective implementation of the STEM curriculum. Next, we briefly introduced a series of the STEM activity curriculum developed by our team with the goal of key competencies development. Finally, a programming-focused STEM curriculum, along with an illustration of its components, is proposed to help educators understand the construction and implementation of STEM curriculums in practice.

THE CONSTRUCT OF STEM COMPETENCIES

STEM competencies are the necessary characters and key abilities to meet the needs of personal and social development, which gradually form in the process of STEM learning. While STEM competencies are widely considered key goals of STEM education (English, 2017), there is no consensus on what STEM competencies should include. Different stakeholders and people in different fields have various priorities. For example, McGunagle and Zizka (2020) through a literature review found that manufacturing employers consider the most essential competency for STEM talent is cooperating with others; secondly, self-motivation; subsequently, communication with others on verbal and written and proactively solving problems (McGunagle and Zizka, 2020). However, in aerospace and defense companies, the ability to solve complex problems is considered the most critical capability, followed by abilities that are flexible to adapt to different environments, collect and analyze data, teamwork, and communication (Marbach-Ad et al., 2019; McGunagle and Zizka, 2020).

It can be seen from the above information that STEM competencies, as a complex framework, should include diverse social backgrounds, such as economic growth, individual development, and related discipline characteristics (Williams, 2017). Nevertheless, most of the existing STEM competencies frameworks only define it from a single perspective, lacking systematization, universality, and coherence (Chamrat et al., 2019). To this end, based on the interview results of different stakeholders (including scientists, science and technology education experts, philosophy of science and technology experts, psychologists, information technology experts, primary and secondary school teachers, etc.), combined with the analysis of different national curriculum standards, we proposed the composition structure and performance of STEM competencies. In concrete terms, interview and review results revealed five common dimensions of STEM competencies: scientific concepts, scientific thinking, inquiry practice, information literacy competencies, and attitudes and accountability (Hu, 2016).

Scientific Concepts

Scientific concepts are thoughts, views, and opinions on the nature and laws of scientific things, which are developed through learning and practice in STEM fields. In different STEM competency frameworks, scientific concepts are considered a basic competent. For example, Tang and Williams (2018) proposed that understanding disciplinary knowledge and its construction process and flexibly applying it to personal problem solving are fundamental components of STEM competencies (Tang and Williams, 2018).

Unlike traditional instruction that focuses on teaching isolated content knowledge, STEM education emphasizes that students can apply interdisciplinary knowledge to solve real-world problems (Shernoff et al., 2017). Therefore, scientific concepts in STEM education fields have various dimensions: mastering the core ideas of specific fields and interdisciplinary knowledge; understanding how scientific concepts, laws, and principles are formed and constructed; forming a basic understanding of the nature of science and technology; and applying concepts, laws, and principles to explain natural phenomena and solve practical problems.

Scientific Thinking

Scientific thinking is a way of understanding the essential properties, inner laws, and interrelationships of objective things (Hu, 2015). It is embedded in different scientific, engineering, and technological practice processes, such as abstract generalization of ideal models based on empirical facts: questioning, criticizing, testing, and modifying different opinions, conclusions, and solutions based on facts and evidence. It can be analyzed and summarized into four dimensions: scientific modeling, reasoning and argumentation, computational thinking, and creative thinking (Chu et al., 2017).

Each kind of scientific thinking ability is composed of thinking content, thinking method, and thinking quality. Among them, thinking quality is the personality characteristic of people's thinking. It reflects the difference in the individuals' thinking level, intelligence, and ability. The quality of thinking mainly includes five characteristics: profoundness, flexibility, criticality, agility, and innovation.

Inquiry Practice

Inquiry practice is not only the main way to form other competencies in the STEM field but also a key competency, mainly including scientific inquiry, engineering practice, digital learning, etc. On the one hand, developing students' understanding of the content knowledge, principles, and the nature of science—what do we know and how do we know it requires students to participate in scientific practices (Duschl and Grandy, 2013). Besides mathematics and computational thinking, collecting and processing information ability, scientific attitudes and accountability, and criteria for engineering design are essential experiences for inquiry practice (Osborne, 2017). Therefore, inquiry practice is of a great value to the cultivation and development of other competencies (Grob et al., 2019).

On the other hand, inquiry practice refers to people's ability to ask questions, design experiments, implement plans, analyze data, communicate results, acquire scientific knowledge, and solve scientific problems (Bell et al., 2010) as well as the ability to conceive, design, operate, implement, verify, and optimize in engineering and technology practice (English et al., 2016). These competencies are the key for them to work in the STEM fields and coordinate their abilities and knowledge to solve problems.

Information Literacy Competencies

Information literacy competencies involve an individual's judgment of information sensitivity and information value, which mainly include information sensitivity, the value judgment of information, information synergism, and information security. The rapid development of information technology has accelerated the production and dissemination of information, reshaped people's concept of time and space for communication, and profoundly affected people's life, work, and study. Different from the past when individuals could only apply their acquired knowledge to solve problems, people can quickly obtain a large amount of information through the Internet at any time in today's world (Bakermans and Ziino Plotke, 2018). Naturally, information and communication technology tools have become the basic tools for learning, working, and problem solving in almost every industry field in the modern society (NEAP, 2018).

However, the abundance of readily available information is false and contradictory. Therefore, it is important to critically evaluate the information obtained, filter the potentially misleading information, further sort out valid information, and apply it to solve problems (Storksdieck, 2016). For this reason, information literacy competencies are thought to be a key component for people to survive in the information society (Gravel et al., 2017). Information literacy provides learners with competencies necessary to consciously acquire, analyze, evaluate, and justify information in an appropriate way, rationally treating the impact of information technology on the human society to improve people's sense of ease and happiness in life in the information society (Wertz et al., 2013).

Attitudes and Accountability

Competency means not only the mastery of knowledge and skills but also mobilizing the attitudes and accountability in the problem-solving process. Therefore, attitude responsibility is widely accepted as an important element of key competencies (Jho et al., 2013; Sadler and Zeidler, 2005). Attitudes and accountability are the right attitudes, values, and social-scientific responsibilities that individuals hold toward science, technology, and engineering in line with the needs of the society (Lee et al., 2012). It is a stable psychological tendency that individuals gradually form during the STEM learning process (Choi et al., 2011).

In dealing with issues like socio-scientific issues, social justice problems, and sustainable development problems, the application of knowledge and ability is influenced and regulated by attitudes and values (OECD, 2019). These issues are always acute, complicated, and with no clear solutions or answers (Wu and Tsai, 2010). Hence, solving such problems involves not only the application of knowledge and skills but also making appropriate, responsible, and effective action decisions based on ethics, compassion toward others, social responsibility, diversity of cultures and values, etc. (Sadler and Zeidler, 2004; Lee et al., 2012).

DESIGN PRINCIPLES OF STEM CURRICULUM CONTENT

The content of the STEM curriculum is a structured system for competency development and works as a director for the teaching. Therefore, it is crucial to clarify how to systematically construct the STEM curriculum content system. Currently, researchers have constructed the STEM curriculum content framework from different perspectives. For instance, Zhou et al. (2020), based on the Australian education context, a design-led STEM curriculum framework was elaborated to guide the implementation of STEM teaching (Zhou et al., 2020). Fan et al. (2020) constructed a STEM curriculum framework which was used to integrate STEM content knowledge into engineering design (Fan et al., 2020). However, the key problem is that the existing framework lacks a systematic articulation of the ground rules and design principles for STEM curriculum content, resulting in inconsistent depth and breadth of designed curriculum content (Bybee, 2013). An uneven level of STEM curriculum content design will further lead to confusion in the implementation of STEM teaching. For this reason, this research first explains how to systematically design STEM curriculum content and then further constructs appropriate STEM teaching strategies on this basis.

How to integrate content knowledge of multiple disciplines and bridge the STEM competency development of students at different age levels is considered the key to STEM curriculum content design (Fan et al., 2020). Therefore, based on the characteristics and objectives of STEM education, combined with the analysis of the existing theoretical framework of STEM curriculum, we explained how to systematically build a framework for STEM curriculum content from two perspectives: cross-disciplinary content knowledge integration around core ideas from a horizontal perspective and content articulation based on learning progression from a vertical perspective.

Integrating Interdisciplinary Curriculum Content Around Core Ideas

As mentioned earlier, enabling students to apply interdisciplinary knowledge, methods, and abilities to solve real-world problems is one of the goals of STEM education (Hoeg and Bencze, 2017; Jiang et al., 2019; Vaval et al., 2019). STEM curricula are therefore interdisciplinary, requiring individuals to integrate concepts, methods, and/or theories from two or more disciplinary sources to solve complex problems involving core ideas (Bautista et al., 2015). Core ideas refer to the core knowledge, principles, and strategies that can link numerous disciplines (Chalmers et al., 2017). Integrating core ideas into STEM curricula helps teachers to connect concepts from a wide range of disciplines in their curriculum design and further helps students to form interdisciplinary knowledge structures or networks of relationships (Bautista et al., 2015). The reasons are as follows.

First, core ideas could provide guidance for selecting STEM curriculum topics and designing interdisciplinary content. Core ideas are key concepts that can link fragmented knowledge points, including two types. The first type is the key organizing concepts that reflect the essence of a discipline, as well as can be widely used to explain and predict a larger range of natural phenomena, such as all earth's place in the universe (Mitchell et al., 2016). The second type is the concepts that have significant explanatory values and exist in multiple sciences or engineering disciplines at the same time, such as the concept of energy exists simultaneously in the fields of physics, chemistry, biology, and geography (NRC, 2012). Therefore, teachers can consider integrating STEM content through core ideas from two different perspectives. On the one hand, a complex real problem is chosen as a learning situation, and then core discipline concepts that can be integrated and applied to solve the problem across multiple disciplines is selected as the STEM curriculum content. On the other hand, a big interdisciplinary idea that exists simultaneously within multiple disciplines is selected as the STEM curriculum content, which is used to construct the context and expand other disciplinary core ideas involved in the context.

Second, core ideas provide students with a boost to transfer knowledge in authentic STEM learning contexts. In terms of the characteristics of the core ideas, the learning of core concepts must be relevant to students' real-life in order to stimulate their interest in learning and to perceive the meaning of what they are learning (NRC, 2012). STEM learning is set in solving complex, real-world problems. Thus, both core ideas and STEM courses similarly start with authentic contexts to facilitate student's transfer of knowledge to problem solving. In addition, existing cognitive science research suggests that the understanding of core ideas contributes to organize and comprehend knowledge more systematically, which can lead to the transfer of knowledge to problem solving more flexibly (Richland et al., 2012).

The Grade Distribution of STEM Contented to Be Determined With the Guidance of Learning Progression

In recent years, learning progression has a more prominent role in science education research (Herrmann-Abell and DeBoer, 2018) and plays a guiding role in the curriculum standards of various countries (Fulmer et al., 2014). For example, the *Next Generation Science Standards* (NGSS, 2013) absorbed the research results of learning progression, constructed their progression matrices for big ideas, interdisciplinary concepts, scientific practice, STSE, and the scientific essence, and constructed the progression diagram for engineering design.

Learning progression, as the hypotheses or models of how students' thinking advances over time (Sikorski, 2019), is closely linked to the core ideas (Hu and Han, 2015). In other words, learning progression is essentially the in-depth and continuous development of the understanding of core ideas (Sikorski, 2019). In addition, educational research has revealed that, only when education is in line with children's thinking development, education can work most effectively (Salinas, 2009). Learning progression, as a series of continuous and interrelated cognitive models, reasonably explains how students' thinking changes gradually over time and close links to the core ideas (Jin et al., 2019).

Therefore, guiding the STEM curriculum content design of different grades following the learning progress can help students construct new understanding based on their original cognition to connect the core ideas learned at different stages. And, cultivating students' understanding of core ideas through learning progression will help students form good knowledge structures, have a deep understanding of scientific concepts, and improve their ability to solve problems.

Specifically, for STEM education, learning progression is, on the one hand, progressive and continuous development of the understanding of core ideas, which is conducive to develop students' understanding of core ideas, content structure, and knowledge evolution paths. Therefore, learning progression can systematically help students learn the connotations of the core ideas and ultimately lay a solid foundation for a comprehensive, systematic, and in-depth understanding of the core ideas. On the other hand, STEM education aims to "grow STEM competencies based on scientific technology and the ability to solve problems in the real world" (Thuneberg et al., 2018). In recent years, research on learning progression has also expanded to include thinking, practical skills, and attitude development. Thereby, learning progression also means the development of other key competencies for STEM education, such as scientific inquiry, scientific thinking, scientific ability, and scientific attitude.

THEORETICAL FRAMEWORK FOR STEM TEACHING

As previously mentioned, in the goals of STEM education, scientific thinking is the core and the basis for linking and leading the development of other competencies (van der Graaf et al., 2019). In the design of STEM curriculum content, it is necessary to follow the law of students' thinking development. STEM teaching, as a key way for students to master the content of STEM curriculums and achieve the training goals of STEM curriculums, should also take thinking as the core. "Thinking-based instruction theory" (TBIT) is a teaching theory that focuses on developing students' thinking and promoting the overall development of STEM competencies. Therefore, we use the thinking-based teaching theory as a guide to design the STEM teaching framework (Hu, 2015).

Based on the latest advances in learning research, in-depth analysis of core competency development pathways, and the systematic research about the influence of teaching behavior on students' development, we proposed TBIT, which focuses on competency development in which thinking is the core, looks at thinking activities in classroom teaching and aims to improve the quality of teaching in the classroom. Specifically, the TBIT includes five basic principles: inspiring motivation, cognitive conflict, self-construction, self-monitoring, and consolidation transfer (Lin and Hu., 2010). Next, we will elaborate on these five principles in conjunction with the TBIT and basic characteristics of STEM education.

Basic Principles of STEM Teaching Based on TBIT

First, inspiring motivation. A key issue faced by STEM education is the students' low retention rate in the STEM field. Student motivation, especially intrinsic motivation such as curiosity and interest, is a fundamental driver of student initiative and persistence in STEM learning (Hallström and Schönborn, 2019; Thuneberg et al., 2018). Therefore, motivation is not only the driving force of STEM teaching but also the key goal of STEM education (Quinn et al., 2020). TBIT also emphasizes that teachers should pay attention to stimulate students' internal learning motivation, mobilize students' enthusiasm for learning, and make them have a strong desire for knowledge so that students maintain positive emotions and attitudes toward STEM learning.

Second, cognitive conflict. One feature of STEM teaching is allowing students to learn actively (Luo et al., 2019). TBIT suggested that the generation of cognitive conflict is the driving force for students' active thinking and active learning, as well as a key engine for changes in their cognitive structures and perceptions. Cognitive conflict refers to the psychological contradiction or conflict that arises when the students' original cognitive structure in the learning process is inconsistent with the real situation (Ross, 1988). Piaget and Dewey pointed out that the generation of cognitive conflict is a necessary condition for students to actively engage in thinking activities (Dewey, 1896). Because the generation of conflicts challenges students' original scientific concepts, it creates an imbalance in students' cognition and further urges students to adjust their thinking to adapt to the new information (Ross, 1988). Therefore, stimulating students' cognitive conflict through situational creation and appropriate question guidance is a key principle of STEM teaching.

Third, self-construction. STEM teaching is a process of self-construction by students under the guidance of teachers, which is in line with constructivist theory. Based on the analysis of constructivist theory and the research results of brain science, TBIT further proposed that self-construction means learners should explain phenomena and solve problems through self-exploration and cooperative communication based on existing knowledge, experience, and cognitive level, so as to realize the meaningful construction of knowledge (Veldman et al., 2020). The characteristic advantages of self-construction are as follows: 1) it is convenient for students to connect the original knowledge and experience with new information, further establishing the connection between the knowledge learned at different stages; 2) autonomous activities can stimulate students' high-level thinking activities and cultivate students' active, autonomous self-management and regulation of learning activities (Zimmerman, 2013; León et al., 2015); 3) cooperation with others can not only stimulate students' thinking and learning motivation but also develop students' cooperation competency, which is also one of the key goals of STEM education (Slavin, 2014; Roberts et al., 2018; Buckley and Trocky, 2019).

Fourth, self-monitoring. The field of cognitive research, as well as new behaviorism, proposed that self-monitoring enables individuals to systematically direct their cognition and behavior toward the achievement of learning goals, influencing motivation, behavior, and volitional control in the learning process (Zimmerman and Schunk, 2011). Flavell and Brown also proposed that metacognitive monitoring is a core component of metacognitive thinking (Flavell, 1979). Based on this, TBIT proposed the pedagogical principle of self-monitoring, which refers to the active planning, checking, reflecting evaluation, feedback, control, and regulation by teachers and students continuously during the teaching process toward the accomplishment of learning objectives. As a complex learning process, STEM requires teachers and students to design and implement learning plans based on learning objectives, to evaluate and reflect on the learning process and results in a timely manner, and to continuously adjust cognitive strategies to complete learning objectives based on feedback results (Zhou et al., 2020; Fan et al., 2020). Therefore, self-monitoring is one of the key principles of STEM teaching.

Fifth, consolidation transfer. The important role of transfer in learning is emphasized in constructivist theory, schema theory, and information processing theory (Pritchard, 2017; Pritchard and Woollard, 2010). For example, the constructivist theory emphasizes that all learning involves transferring prior experience to new contexts. In addition, the development of key competencies also requires students to apply what they have learned in real situations. Based on the basic requirements of developing students' key competencies and the analysis of learning theories, TBIT further proposes the pedagogical principles of consolidation transfer, emphasizing the application of learned knowledge, methods, and attitudes to problem-solving in authentic situations and to other disciplines and domains (Zhuang et al., 2021).

STEM education aims to develop the key competencies that students need to adapt and contribute to the future life of society (Kelley and Knowles, 2016). To this end, STEM education has always emphasized the transfer of core ideas, principles, and skills to solve real-world problems. Therefore, transfer is also a fundamental principle of STEM teaching (Figliano and Mariano, 2015). Combined with TBIT, consolidation transfer in STEM teaching should include two aspects. On the one hand, it means that students learn STEM by integrating and transferring previously learned knowledge, methods, and attitudes to solve complex problems and explore important principles at a deeper level so that they have a deeper understanding of different disciplines or knowledge areas, further constructing new interdisciplinary cognitive structures and improving practical skills in the process. On the other hand, students are expected to transfer and apply the interdisciplinary concepts and methods constructed in STEM learning to other new real-world situations (Figliano and Mariano, 2015).

Six Elements of STEM Teaching

Based on the above five basic principles, we further proposed six basic elements that should be included in STEM teaching: setting up a learning situation, asking questions, independent inquiry, cooperation and communication, summary and reflection, and consolidation transfer (Hu, 2015).

The situation is a clue for students to make connections between old and new knowledge and is necessary for generating cognitive conflict, perceiving and constructing learning meaning, and motivating students to learn. Moreover, STEM education focuses on interdisciplinary learning, while learning situations could provide context to link up the content of various subjects (Martín-Páez et al., 2019). Therefore, teachers must create reasonable situations in STEM teaching.

Asking questions includes allowing students to independently raise questions based on cognitive conflicts and teachers guiding students' deep learning, stimulating students' positive thinking, and maintaining students' learning motivation through the design of a problem chain in the teaching process. The design of the problem should be thinking and challenging, open and exploratory, accurate and appropriate, hierarchical, and organized.

Students test hypotheses and draw conclusions through an independent inquiry and cooperative learning process (Roberts et al., 2018). These two processes are not significantly different in STEM teaching and can be done simultaneously or collaborately after the independent inquiry is completed. In this process, teachers need to help students complete thinking interaction, emotional interaction, and behavioral interaction through a scaffolding structured design and develop the ability to formulate hypotheses, collect and evaluate data, coordinate evidence and theory, communicate and negotiate, etc. (Wang, Han, and Hu, 2015). In addition, the course content should be mapped to the social environment, helping students to establish the connection between tasks, situations, and cultures, and accordingly cultivating the development of students' attitudes and sense of responsibility.

Summarizing and reflecting is a self-monitoring process that focuses on allowing students to evaluate, summarize, and optimize the learning process, and it results through introspection (ElSayary, 2021). This has the benefit of helping students to develop a deep and general understanding of knowledge, methods, skills, and attitudes, refining cognitive strategies and systematically constructing interdisciplinary networks, thus facilitating subsequent application transfer. Given the complexity of STEM learning, teachers should give students ample time in the summary reflection process and provide appropriate scaffolding, such as problem prompts or mind maps.

Consolidation transfer is essentially using a reasonable cognitive structure formed in the mind to understand new knowledge or solve new problems. Through STEM education, students can flexibly apply the knowledge they have constructed, the competencies, the attitudes, and the responsibilities they have developed to solve a variety of relevant problems that will arise. These abilities and awareness can be effectively developed by consolidating the application of transfer (Lu et al., 2015). Both the structural matching theory and the situated theory emphasize that, when the learning situation is the same or similar to the transfer situation, the transfer is more likely to occur (Zhuang et al., 2021). Therefore, the focus of STEM instruction should be on enabling students to construct knowledge in authentic contexts and to transfer learned knowledge, competencies, and attitudes to new and similar authentic contexts.

CONSTRUCTION OF STEM EDUCATION EVALUATION SYSTEM

Teaching and evaluation are two important links in curriculum implementation, and they complement each other. Evaluation not only monitors the effect of teaching but also integrates with the teaching process to promote and ensure the development of students. The effect of evaluation of the curriculum lies in understanding students' performance in the learning process and their problems, identifying the quality level of learning and further providing guidance for the iteration of the curriculum design.

From the perspective of evaluation methods, STEM teaching evaluation includes formative evaluation and summative evaluation (Jeong et al., 2020). STEM teaching is a flexible process, which involves the iterative cycle of activity process and the constant revision of later conclusions. Students' learning content, methods used, and solutions to problems are mostly open. Therefore, formative evaluation adopted in the teaching process is used to provide guidance and continuous feedback for students to monitor the effect of periodic learning and for teachers to modify classroom practice. On the one hand, formative evaluation helps students to monitor their completion of the phased goals in real time, provides feedback for students' learning, and guides students on the next step. On the other hand, it is beneficial to assist teachers to monitor students' learning performance, learning progress, and existing problems in various aspects to facilitate teachers to provide timely guidance to students.

According to the different evaluation subjects, formative evaluation can be further divided into teacher evaluation and student evaluation. The role of teachers is to promote and help students' learning through interaction with students. This requires teachers to constantly understand students' learning conditions through evaluation and timely adjustment in the teaching process and to effectively help students construct their knowledge. Student evaluation, which includes student self-evaluation and student mutual evaluation, refers to students reflecting on the learning process and exchanging mutual evaluation with others (Herro et al., 2017).

At the end of the curriculum, teachers can understand the students' mastery of the overall learning goals through summative evaluation to provide a basis for the effectiveness of the course implementation and further improvement. The index of the summative evaluation mainly revolves around the STEM curriculum goal to constructscientific understanding and application, scientific thinking and practice, scientific attitude, and responsibility.

Students with STEM competencies should be able to connect what they have learned with real life and solve real-world problems (Shernoff et al., 2017). Therefore, summative assessments should enable students to face challenging real-world problems and use the scientific knowledge, skills, and so on they have learned to solve the scientific problems they encounter either independently or in groups.

In the form of assessment, summative assessment can use different assessment methods such as paper-and-pen tests, performance assessment, and computer interactive assessment. The paper-and-pencil test mainly focuses on the steps and procedures of students to solve problems. It generally includes multiple-choice questions, essay questions, and combination questions. Performance evaluation is a supplement to the paper-and-pencil test (Kim and Kim, 2016). Evaluation is based primarily on the level of thinking and practice reflected in the process of solving scientific problems and the results of solving scientific problems. Computer interactive evaluation gives full play to the advantages of modern information technology, such as the realistic presentation of scientific problems through modern multimedia forms, students can operate virtual programs, and so on.

STEM-INTEGRATED ACTIVITY CURRICULUM

"Learn to Think-Learn to Inquire-Learn to Innovate" Curriculum System

Currently, many educators have made great efforts and contributions to the development of STEM curricula. However, most current STEM curricula lack systematic design and do not cover different stages and domains. To address the above issues, our team has developed an integrated STEM activity curriculum system with learning progressions, including three levels: learn to think, learn to inquiry, and learn to innovate. This STEM curriculum takes STEM competencies as the goal, covers different stages, and is guided by thinking-based instruction theory.

"Learn to think" is based on the integration of thinking methods, mainly including 15 basic thinking methods and five comprehensive thinking methods. "Learn to inquiry" integrates curriculum content based on the core ideas and thinking methods and integrates technology, engineering, and mathematics concepts to solve real problems. "Learn to innovate" integrates thinking methods, core ideas, and inquiry practice as well as uses 3D printing, intelligent robots, virtual reality, and other technologies for creative design and product realization. According to the age and cognitive characteristics of different students, the content design of the three courses is also spirally progressive. Next, we will introduce the three curriculums, respectively.

"Learn to think" has a progressive activity system of 10 grades from the preschool class to the eighth grade. The entire course includes 328 activities, which are divided into the basic thinking part and comprehensive thinking part. The materials and resources provided include student books and teacher books. There are 16 books for students: two books for each grade, each with 14–18 activities and four books for teachers, including one for the middle class to the large class in kindergarten, two books for grades 1–6 in elementary school, and one book for grades 7–8. The results of practical research show that the implementation of the "learn to think" curriculum can effectively stimulate students' learning motivation, improve students' self-esteem, and develop students' key competencies such as scientific thinking, academic performance, and peer interaction ability (Hu et al., 2011; Hu et al., 2013; Hu et al., 2016).

"Learn to inquiry" makes a progressive activity system of 6 grades from the first to the sixth grade, including 72 books for students and six books for teachers, with a total of 288 scientific activities. The team also developed electronic resources including lesson plans, lecture videos, teaching reference materials, courseware, experimental videos, imported videos, AR interactive game, micro-exercises, expansion activities, and so on. One of the highlights of the curriculum is that each class hour is provided with a corresponding activity material, in conjunction with other resources, to build an overall solution for primary STEAM learning. This greatly solves the practical problem of "difficulty in organizing experiments and difficulty in finding materials" among frontline teachers.

"Learn to innovate" is a comprehensive activity course that integrates the maker and STEM under the guidance of new technologies, including five technology-supported comprehensive creative activities: intelligent robot, 3D art printing technology, AI and computational thinking programming, intelligent navigation, and virtual reality. Different activities have a distinctive emphasis on key competencies for cultivation. For example, the main purpose of the 3D printing curriculums is to contribute gradually developing spatial concepts to students from grade one to grade three. The Scratch Jr's programming curriculum, from grade one to grade three, adopts the idea of project-based learning (PBL) and is designed to cultivate students' higher-order thinking skills through situational learning. Next, this article will introduce a creative programming curriculum as an example.

Creative Programming Curriculum

Define the Scope of the Curriculum Goal

With the advent of the artificial intelligence era, programming ability becomes more and more important nowadays. In traditional programming courses, students learn only mechanical programming languages. However, computer science is changing rapidly, and the old programming language is bound to be replaced by a new one. Therefore, the goal of programming courses is not to let students master the existing programming language mechanically, but to master the basic knowledge and thinking methods required by programming, as well as stimulate and maintain students' enthusiasm for programming so that students can solve problems in real life through programming.

Based on this, we mainly construct the curriculum goals of students in different stages from four aspects: basic knowledge of programming hardware (scientific concepts), inquiry practice (programming software abilities, inquiry, and problem-solving abilities), scientific thinking involved in programming, and attitude and accountability.

Basic Knowledge of Programming Hardware

As we all know, programming courses for children and adolescents are mainly divided into two categories: software programming and hardware programming. Our creative programming course emphasizes the process of experiencing programming to realize the product, to achieve the understanding of the integrity and visualization of programming logic, and the realization of the goal state of problem solving. Therefore, we pay more attention to the role of hardware in programming courses, understanding the surrounding intelligent environment, understanding the process of the signal input, programming board processing, and data output through hardware principles, and finally building product entities through building robot suite. A specific programming concept involves four fields: programming suite characteristics, programming board, input components, and output components.

Programming Software, Inquiry, and Problem-Solving Abilities

Inquiry practice mainly includes interdisciplinary scientific inquiry abilities and specific technical practice abilities in the programming field. Interdisciplinary scientific inquiry abilities include putting forward problems and hypotheses, exploring product realization principles, exploring software programming logic, function realization, communication, and collaboration, transfer, and expansion. Specific technical practice abilities are as follows:

- can discover the basic functions of different modules of programming software.
- ability to assign values to various simple data.
- can explore the numerical range of variables through serial port printing.
- able to design the sequence structure, judgment structure, and cycle structure program step by step.
- able to implement and define simple functions and use these functions correctly.
- can correctly handle several data of the same type, as well as the comprehensive application of arrays and functions.

Scientific Thinking Involved in Programming

Scientific thinking mainly has two aspects: basic thinking ability and higher-order thinking (critical thinking and creative thinking). The process of collecting and processing information involves basic thinking methods such as observation, classification, comparison, analysis and synthesis, and abstract summary. In the process of programming implementation, it is necessary to clarify the prerequisites and understand the different requirements for products under the same situation, which is an important content in training students' critical thinking. Improving and optimizing the basic ideas provided by the teacher, realizing more novel functions, or making different improvements in details are all manifestations of creative thinking.

Attitude and Accountability

In the process of learning creative programming, students not only learn programming skills, but also maintain and develop their curiosity and enthusiasm for exploring intelligent working principles (algorithmic thinking) through inquiry practice; form a scientific attitude that attaches importance to logic, being willing to explore and cooperate with others; understand the relationship between technology, society, and environment; and improve the sense of responsibility and cooperation.

Design Learning Activities

Primary Course Content

Through the button, touch, pressure, and other actions, obvious sensible physical changes and other single factors control the product sound, light, action single output product function. Teachers should set up simple programming activities, through visual demonstrations, to guide students to understand the structure of programming sentences that are executed in a certain order. For example, "make a little flash stick" can arrange the following activities:

1) Understand the action of "flashing"—on, off, on...
2) Gesture to demonstrate the flicker of different rhythms and understand the role of the "delay" statement in the program.
3) Use a flowchart to demonstrate the process of light flashing: on-delay-off-delay....... Understand the sequence structure, that is, if you need the flash stick to continue blinking, you need to execute this procedure again.
4) Programming realization: the flashing effect.
5) Innovation and expansion: contacting the previous gesture demonstration to achieve different rhythms of flashing, what changes need to be made in the programming statement?

Intermediate Course Content

Through the control of a single factor such as sensible physical change, the function of the combined output of sound, light, and action is realized. In the teaching process, teachers should guide students to discover the characteristics of hardware, put forward reasonable assumptions based on the context, and solve problems through programming. For example, to make a "loud doorbell", teachers can arrange the following activities:

1) Setting situation: Grandpa's hearing is impaired, so he can't hear the knock on the door. Di wants to make a loud doorbell for Grandpa.
2) Inquiry of components: selecting available components; from the name of "capacitive touch" to guess how "capacitive touch" work and how "capacitive touch" is used; exploring the link method of each component.
3) Solving programming problems: make the doorbell sound as soon as it is touched, and understand the triggering mode of doorbell sound.
4) Solving programming problems: Make the doorbell sound upon touch, but with a delayed stop time.
5) Experimental investigation: If "capacitive touch" can work normally, what characteristics (whether it conducts electricity) are required for the object?
6) Innovation and expansion: For people who have no hearing at all, what can be done to improve the doorbell?

Advanced Course Content

By controlling the nonsensible physical change factors, the product can realize the combined output function of sound, light, and action. In the process of students' learning, teachers should pay attention to guide students to observe phenomena, decompose tasks, and integrate thinking activities through visualized teaching activities. For example, making a "door that opens and closes automatically" can schedule the following activities:

1) Contact the existing life experience: observing, analyzing, and comparing the similarities and differences between the automatic door and non-automatic door; understanding "automatic" is mainly reflected in "automatic detection", that is, automatic doors will send out to the motor according to whether there is some "turn" signal.
2) Live scenario simulation. The "automatic door" is understood as a person, divided into the brain (programming board), eyes (sensor), limbs (motor) to demonstrate the working process of the automatic door. Role arrangement: the programming board, sensor, motor, and pedestrian. The pedestrian is shown in several states: entering the sensing area, passing, and after passing. This will help students to understand the "judgment structure" of the programming statements: the sensor needs to determine at any time whether a person is within the sensing area, and the board issues different commands to the "motor" accordingly.
3) Solving programming problems: set the initial state of the door and understand the "position flag" variable.
4) Solving programming problems: By realizing "detect people, doors open normally", understand "if...Perform..." programming statements.
5) Solving programming problems: By realizing "after the person passes, the door closes normally", understand "if...Perform...Otherwise..."programming statements.

CONCLUSION

STEM education is the main trend of education reform in countries all over the world. However, there is a lack of detailed elaboration on how to systematically implement STEM education, which further leads to the product-oriented characteristics of the current STEM education. In order to change this situation and achieve the goal of cultivating the core literacy required by STEM education in the 21st century, this paper systematically introduces the theoretical construction of a STEM curriculum and provides a specific STEM curriculum design case.

To be specific, a systematic STEM course should include contents in four aspects: 1) education goals. As the goal of STEM curriculums, STEM competencies include five dimensions: scientific concepts, scientific thinking, inquiry practice, information literacy competencies, and attitudes and accountability. Among them, scientific concepts are the foundation for other key capabilities. Scientific thinking is the core of the coordinated development of multidimensional ability. Inquiry practice and information ability run through the STEM practice process and are the main ways to form key abilities. Attitudes and accountability reflect the direction of key competencies. Attitude is the mental stability and evaluation tendency, and accountability is the basic moral standard of citizens; 2) curriculum content. The construction of curriculum content includes interdisciplinary integration around big ideas and longitudinal connection under the guidance of learning progression; 3) STEM teaching. Guided by the think-based instruction theory (TBIT), we proposed five basic principles that should be followed in the process of STEM teaching: inspire motivation, cognitive conflict, self-construction, self-monitoring, and reflection and transfer. In addition, based on the five basic principles, we further proposed six basic elements of STEM teaching: setting up a learning situation, asking questions, independent inquiry, cooperation and communication, summary and reflection, and consolidation transfer; 4) the evaluation system mainly includes two approaches: formative evaluation and summative evaluation.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

WH led the writing, wrote the first draft, created the content ideas and framework, and led the writing and rewriting of the manuscript. XG provided insights, literature search, and collation to the initial draft. Both WH and XG provided initial edits, and contributed to the writing and editing throughout.

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Fostering Creativity and Critical Thinking in College: A Cross-Cultural Investigation

Ji Hoon Park[1†], Weihua Niu[1†], Li Cheng[2] and Heavon Allen[1]*

[1]Department of Psychology, Pace University, New York, NY, United States, [2]Developmental and Educational Research Center for Children's Creativity, Faculty of Education, Beijing Normal University, Beijing, China

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Ze Wang,
University of Missouri,
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Parul Acharya,
Columbus State University,
United States

****Correspondence:***
Li Cheng
licheng11cl@126.com

[†]These authors have contributed equally to this work and share first authorship

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Enhancing creativity and critical thinking have garnered the attention of educators and researchers for decades. They have been highlighted as essential skills for the 21st century. A total of 103 United States students (53 female, 24 male, two non-binary, and 24 non-reporting) and 166 Chinese students (128 female, 30 male, one non-binary, and seven non-reporting) completed an online survey. The survey includes the STEAM-related creative problem solving, Sternberg scientific reasoning tasks, psychological critical thinking (PCT) exam, California critical thinking (CCT) skills test, and college experience survey, as well as a demographic questionnaire. A confirmatory factor analysis (CFA) yields a two-factor model for all creativity and critical thinking measurements. Yet, the two latent factors are strongly associated with each other ($r = 0.84$). Moreover, Chinese students outperform American students in measures of critical thinking, whereas Americans outperform Chinese students in measures of creativity. Lastly, the results also demonstrate that having some college research experience (such as taking research method courses) could positively influence both United States and Chinese students' creativity and critical thinking skills. Implications are discussed.

Keywords: creativity, critical thinking, cross-cultural differences, college, research experience

INTRODUCTION

Creativity and critical thinking have been recognized as essential skills in the 21st century (National Education Association, 2012). Many researchers and educators have focused on these two skills, including acquisition, enhancement, and performance. In addition, numerous studies have been devoted to understanding the conceptual complexities involved in creativity and critical thinking. Although similar to each other, creativity and critical thinking are distinctive by definition, each with a different emphasis.

The concept of creativity has evolved over the years. It was almost exclusively conceptualized as divergent thinking when Guilford (1956, 1986) proposed divergent thinking as a part of intelligence. Earlier measures of creativity took the approach of divergent thinking, measuring creative potential (Wallach and Kogan, 1965; Torrance, 1966, 1988; Runco and Albert, 1986; Kim, 2005). In 1990s, many creativity scholars challenged the validity of tests of divergent thinking, and suggested that divergent thinking only captures the trivial sense of creativity, and proposed to use the product-oriented method to measure creativity (Csikszentmihalyi, 1988; Amabile, 1996; Sternberg and Lubart, 1999). A system model of creativity, which recognizes the important roles individual, field, and domain have played, was used as a framework to conceptualize creativity. A widely accepted definition for creativity is a person's ability to generate an idea or product that is deemed as both novel and appropriate by experts in a field of human activities (Scott and Bruce, 1994; Amabile, 1996; Csikszentmihalyi, 1999; Sternberg and Lubart, 1999; Hunter et al., 2007). Corazza and Lubart (2021) recently proposed a dynamic definition of creativity, in which creativity is defined as a context-embedded phenomenon that is tightly related to the cultural and social environment. Based on this new definition, measures of creativity should be context-specific and culturally relevant, especially when it is examined cross-culturally.

Similarly, the conceptualization of critical thinking has also evolved over the years. Earlier definitions emphasized the broad multidimensional aspects of critical thinking, including at least three aspects: attitude, knowledge, and skills (Glaser, 1941). The definition has been evolved to include specific components for each aspect (Watson and Glaser, 1980). For example, critical thinking is recognized as the ability to use cognitive skills or strategies to increase the probability of a desirable outcome (Halpern, 1999). More specifically, cognitive skills such as evaluation, problem-solving, reflective thinking, logical reasoning, and probability thinking are recognized as parts of critical thinking skills in research and assessments (Ennis, 1987; Scriven and Paul, 1987; Halpern, 1999). Moving into the 21st century, metacognition and self-regulatory skills have also become essential components for critical thinking in addition to the cognitive skills recognized by earlier scholars (Korn, 2014; Paul and Elder, 2019).

Similar to the concept of creativity, critical thinking is also viewed as multidimensional and domain specific (Bensley and Murtagh, 2012). For example, critical thinking in psychology, also referred to as psychological critical thinking (PCT), is defined as one's ability to evaluate claims in a way that explicitly incorporates basic principles of psychological science (Lawson, 1999). As one of the important hub sciences, psychology is often regarded as a foundational course for scientific training in American higher education (Boyack et al., 2005). In psychological discourse, critical thinking is often defined in tandem with scientific thinking, which places significance on hypothesis-testing and problem-solving in order to reduce bias and erroneous beliefs (Halpern, 1984; American Psychological Association, 2016; Lamont, 2020; Sternberg and Halpern, 2020). Based on this definition, measures of critical thinking should assess cognitive skills (i.e., evaluation, logical reasoning) and ability to utilize scientific methods for problem-solving.

In addition to the evolution of the definitions of critical thinking and creativity, research into these two concepts has led to the development of various measurements. For both concepts, there have been numerous measurements that have been studied, utilized, and improved.

The complexities associated with creativity (i.e., context-relevant and domain-specificity) pose a major issue for its measurement. Many different types of creativity measures have been developed in the past. Measures using a divergent thinking approach, such as the Torrance Tests of Creative Thinking (Torrance, 1974) and Alternate Uses Test (Guilford et al., 1960), a product-oriented approach, a third person nomination approach, as well as a self-report approach measuring personality (Gough, 1979), creative behavior (Hocevar and Michael, 1979; Rodriguez-Boerwinkle et al., 2021), and creative achievement (Carson et al., 2005; Diedrich et al., 2018).

Both the divergent thinking and the product-oriented approaches have been widely used in the creativity literature to objectively measure creativity. The tasks of both approaches are generally heuristic, meaning that no correct answer is expected and the process does not need to be rational. When scoring divergent thinking, the number of responses (i.e., fluency) and the rareness of the response (i.e., originality) were used to represent creativity. When scoring products using the product-orientated approach, a group of experts provides their subjective ratings on various dimensions such as originality, appropriateness, and aesthetically appealing to these products using their subjective criteria. When there is a consensus among the experts, average ratings of these expert scores are used to represent the creativity of the products. This approach is also named as Consensual Assessment Technique (CAT; Amabile, 1982, 1996). Some scholars viewed the CAT approach as focusing on the convergent aspect of creativity (Lubart et al., 2013). Recognizing the importance of divergent and convergent thinking in conceptualizing creativity, Lubart et al. (2013) have suggested including divergent thinking and product-oriented approach (i.e., CAT) to objective measures of creativity (Barbot et al., 2011).

Similar to measures of creativity, measurements of critical thinking are also multilevel and multi-approach. In an article reviewing the construction of critical thinking in psychological studies, Lamont (2020) argues that critical thinking became a scientific object when psychologists attempted to measure it. Different from measures of creativity, where the tasks are heuristic in nature, measures of critical thinking require participants to engage in logical thinking. Therefore, the nature of critical thinking tasks is more algorithmic.

The interest in the study of critical thinking is evident in the increased efforts in the past decades to measure such a complex, multidimensional skill. Watson-Glaser Tests for Critical Thinking (Watson and Glaser, 1938) is widely recognized as the first official measure of critical thinking. Since then, numerous measurements of critical thinking have been developed to evaluate both overall and domain-specific critical thinking, such as the PCT Exam (Lawson, 1999; See Mueller et al., 2020 for list of assessments). A few of the most commonly used contemporary measures of critical thinking include the Watson-Glaser Test for Critical Thinking Appraisals (Watson and Glaser, 1980), Cornell Critical Thinking Test (Ennis et al., 1985), and California Critical Thinking (CCT) Skills Test (Facione and Facione, 1994). As the best established and widely used standardized critical thinking measures, these tests have been validated in various studies and have been used as a criterion for meta-analyses (Niu et al., 2013; Ross et al., 2013).

There have also been concerns regarding the usage of these standardized measures of critical thinking on its own due to its emphasis on measuring general cognitive abilities of participants, while negating the domain-specific aspect of critical thinking (Lamont, 2020). The issues associated with standardized measures are not unique to standardized critical thinking measures, as same types of criticisms have been raised for standardized college admissions measures such as the Graduate Record Exam (GRE). To develop an assessment that encompasses a broader range of student abilities that is more aligned to scientific disciplines, Sternberg and Sternberg (2017) developed a scientific inquiry and reasoning measure. This measure is aimed to assess participants' ability to utilize scientific methods and to think scientifically in order to investigate a topic or solve a problem (Sternberg and Sternberg, 2017). The strength of this measure is that it assesses students' abilities (i.e., ability to think critically) that are domain-specific and relevant to the sciences. Considering the multidimensional aspect of critical thinking, a combination of a standardized critical thinking measure, an assessment measuring cognitive abilities involved in critical thinking; and a measure that assesses domain-specific critical thinking, would provide a comprehensive evaluation of critical thinking.

The Relationship Between Creativity and Critical Thinking

Most of the studies thus far referenced have investigated creativity and critical thinking separately; however, the discussion on the relationship between creativity and critical thinking spans decades of research (Barron and Harrington, 1981; Glassner and Schwartz, 2007; Wechsler et al., 2018; Akpur, 2020). Some earlier studies on the relationship between divergent thinking and critical thinking have observed a moderate correlation ($r = 0.23$, $p < 0.05$) between the two (Gibson et al., 1968). Using measures of creative personality, Gadzella and Penland (1995) also found a moderate correlation ($r = 0.36$, $p < 0.05$) between creative personality and critical thinking.

Recent studies have further supported the positive correlation between critical thinking and creativity. For example, using the creative thinking disposition scale to measure creativity, Akpur (2020) found a moderate correlation between the two among college students ($r = 0.27$, $p < 0.05$). Similarly, using the critical thinking disposition scale to measure critical thinking and scientific creativity scale and creative self-efficacy scale to measure creativity, Qiang et al. (2020) studied the relationship between critical thinking and creativity to a large sample of high school students ($n = 1{,}153$). They found that the relationship between the two varied depending on the type of measurement of creativity. More specifically, the correlation between critical thinking disposition and creative self-efficacy was $r = 0.045$ ($p < 0.001$), whereas the correlation between critical thinking disposition and scientific creativity was $r = 0.15$ ($p < 0.01$).

Recognizing the moderate relationship between the two, researchers have also aimed to study the independence of creativity and critical thinking. Some studies have found evidence that these constructs are relatively autonomous. The results of Wechsler et al. (2018) study, which aimed to investigate whether creativity and critical thinking are independent or complementary processes, found a relative autonomy of creativity and critical thinking and found that the variables were only moderately correlated. The researchers in this study suggest that a model that differentiated the two latent variables associated with creativity and critical thinking dimensions was the most appropriate method of analysis (Wechsler et al., 2018). Evidence to suggest that creativity and critical thinking are fairly independent processes was also found in study of Ling and Loh (2020). The results of their research, which examined the relationship of creativity and critical thinking to pattern recognition, revealed that creativity is a weak predictor of pattern recognition. In contrast, critical thinking is a good predictor (Ling and Loh, 2020).

It is worth noting that a possible explanation for the inconsistencies in these studies' results is the variance in the definition and the measures used to evaluate creativity and critical thinking. Based on the current literature on the relationship between creativity and critical thinking, we believe that more investigation was needed to further clarify the relationship between creativity and critical thinking which became a catalyst for the current study.

Cross-Cultural Differences in Creativity and Critical Thinking Performance

Results from various cross-cultural studies suggest that there are differences in creativity and critical thinking skills among cultures. A common belief is that individuals from Western cultures are believed to be more critical and creative compared to non-Westerners, whereas individuals from non-Western cultures are believed to be better at critical thinking related tasks compared to Westerners (Ng, 2001; Wong and Niu, 2013; Lee et al., 2015). For example, Wong and Niu (2013) found a persistent cultural stereotype regarding creativity and critical thinking skills that exist cross-culturally. In their study, both Chinese and Americans believed that Chinese perform better in deductive reasoning (a skill comparable to critical thinking) and that Americans perform better on creativity. This stereotype belief was found to be incredibly persistent as participants did not change their opinions even when presented with data that contradicted their beliefs.

Interestingly, research does suggest that such a stereotype might be based on scientific evidence (Niu et al., 2007; Wong and Niu, 2013). In the same study, it was revealed that Chinese did in fact perform better than Americans in deductive reasoning, and Americans performed better in creativity tests (Wong and Niu, 2013). Similarly, Lee et al. (2015) found that compared to American students, Korean students believed that they are more prone to use receptive learning abilities (remembering and reproducing what is taught) instead of critical and creative learning abilities.

Cultural Influence on Critical Thinking

Other studies investigating the cultural influence on critical thinking have had more nuanced findings. Manalo et al. (2013) study of university students from New Zealand and Japan found that culture-related factors (self-construal, regulatory mode, and self-efficacy) do influence students' critical thinking use. Still, the differences in those factors do not necessarily equate to differences in critical thinking. Their results found that students from Western and Asian cultural environments did not have significant differences in their reported use of critical thinking. The researchers in this study suggest that perhaps the skills and values nurtured in the educational environment have a more significant influence on students' use of critical thinking (Manalo et al., 2013).

Another study found that New Zealand European students performed better on objective measures of critical thinking than Chinese students. Still, such differences could be explained by the student's English proficiency and not dialectical thinking style. It was also revealed in this study that Chinese students tended to rely more on dialectical thinking to solve critical thinking problems compared to the New Zealand European students (Lun et al., 2010). Other research on the cultural differences in thinking styles revealed that Westerners are more likely to use formal logical rules in reasoning. In contrast, Asians are more likely to use intuitive experience-based sense when solving critical thinking problems (Nisbett et al., 2001).

These studies suggest that culture can be used as a broad taxonomy to explain differences in critical thinking use. Still, one must consider the educational environment and thinking styles when studying the nature of the observed discrepancies. For instance, cultural differences in thinking style, in particular, might explain why Westerners perform better on some critical thinking measures, whereas Easterners perform better on others.

Cultural Influence on Creative Performance

Historically, creativity studies have suggested that individuals from non-Western cultures are not as creative as Westerners (Torrance, 1974; Jellen and Urban, 1989; Niu and Sternberg, 2001; Tang et al., 2015). For example, in one study, Americans generated more aesthetically pleasing artworks (as judged by both American and Chinese judges) than Chinese (Niu and Sternberg, 2001). However, recent creativity research has suggested that cross-cultural differences are primarily attributable to the definition of creativity rather than the level of creativity between cultures. As aforementioned, creativity is defined as an idea or product that is both novel and appropriate. Many cross-cultural studies have found that Westerners have a preference and perform better in the novelty aspect, and Easterners have a preference and perform better in the appropriateness aspect. In cross-cultural studies, Rockstuhl and Ng (2008) found that Israelis tend to generate more original ideas than their Singaporean counterparts. In contrast, Singaporeans tend to produce more appropriate ideas. Bechtoldt et al. (2012) found in their study that Koreans generated more useful ideas, whereas Dutch students developed more original ideas. Liou and Lan (2018) found Taiwanese tend to create and select more useful ideas, whereas Americans tend to generate and choose more novel ideas. The differences in creativity preference and performance found in these studies suggest that cultural influence is a prominent factor in creativity.

In summary, cross-cultural studies have supported the notion that culture influences both creativity and critical thinking. This cultural influence seems relatively unambiguous in creativity as it has been found in multiple studies that cultural background can explain differences in performance and preference to the dual features of creativity. Critical thinking has also been influenced by culture, albeit in an opaquer nature in comparison to creativity. Critical thinking is ubiquitous in all cultures, but the conception of critical thinking and the methods used to think critically (i.e., thinking styles) are influenced by cultural factors.

Influence of College Experience on Creativity and Critical Thinking

Given its significance as a core academic ability, the hypothesis of many colleges and universities emphasize that students will gain critical thinking skills as the result of their education. Fortunately, studies have shown that these efforts have had some promising outcomes. Around 92% of students in multi-institution research reported gains in critical thinking. Only 8.9% of students believed that their critical thinking had not changed or had grown weaker (Tsui, 1998). A more recent meta-analysis by Huber and Kuncel (2016) found that students make substantial gains in critical thinking during college. In addition, the efforts to enhance necessary thinking skills have led to the development of various skill-specific courses. Mill et al. (1994) found that among three groups of undergraduate students, a group that received tutorial sessions and took research methodology and statistics performed significantly better on scientific reasoning and critical thinking abilities tests than control groups. Penningroth et al. (2007) found that students who took a class in which they were required to engage in active learning and critical evaluation of claims by applying scientific concepts, had greater improvement in psychological critical thinking than students in the comparison groups. There have also been studies in which students' scientific inquiry and critical thinking skills have improved by taking a course designed with specific science thinking and reasoning modules (Stevens and Witkow, 2014; Stevens et al., 2016).

Using a Survey of Undergraduate Research Experience (SURE), Lopatto (2004, 2008) found that research experience can help students gain various learning skills such as ability to integrate theory and practice, ability to analyze data, skill in the interpretation of results, and understanding how scientists work on problem. All of these learning skills correspond to at least one of the dimensions mentioned earlier in the definition of critical thinking (i.e., evaluation, analytical thinking, and problem solving through). Thus, results of SURE provide evidence that critical thinking can be enhanced through research experience (Lopatto, 2004, 2008).

In comparison to critical thinking, only a few studies have examined the interaction between creativity and college experience. Previous research on STEM provides some evidence to suggest that STEM education can promote the learner's creativity (Land, 2013; Guo and Woulfin, 2016; Kuo et al., 2018). Notably, study of Kuo et al. (2018) suggest that project-based learning in STEM has the merits of improving one's creativity. They found that the STEM Interdisciplinary Project-Based Learning (IPBL) course is a practical approach to improve college student's creativity (Kuo et al., 2018). College research experience in particular, has been reported as important or very important by faculty and students for learning how to approach problems creatively (Zydney et al., 2002).

Although specific college courses aimed to enhance creativity have been scarce, some training programs have been developed specifically to improve creativity. Scott et al. (2004) conducted a quantitative review of various creativity training and found that divergent thinking, creative problem solving, and creativity performance can be enhanced through skill-specific training programs. Embodied creativity training programs, consisting of creativity fitness exercises and intensive workshops, have also been effective in enhancing participants' creative production and improving their creative self-efficacy (Byrge and Tang, 2015).

Both critical thinking and creativity were also found to be important in students' learning. Using a longitudinal design for one semester to 52 graduate students in biology, Siburian et al. (2019) studied how critical thinking and creative thinking contribute to improving cognitive learning skills. They found that both critical and creative thinking significantly contributes to enhancing cognitive learning skills ($R^2 = 0.728$). They each contribute separately to the development of cognitive learning skills (b was 0.123 between critical thinking and cognitive learning and 0.765 between creative thinking and cognitive learning). The results from research on creativity and critical thinking indicate that training and experiences of students in college can enhance both of these skills.

CURRENT STUDY

Previous literature on creativity and critical thinking suggests that there is a positive correlation between these two skills. Moreover, cultural background influences creativity and critical thinking conception and performance. However, our literature review suggests that there are only a few studies that have investigated creativity and critical thinking simultaneously to examine whether cultural background is a significant influence in performance. In addition, most of the past research on creativity and critical thinking have relied on dispositions or self-reports to measure the two skills and the investigation on the actual performance have been scarce. Lastly, past studies suggest that the acquisition and enhancement of these skills are influenced by various factors. Notably, college experience and skill-specific training have been found to improve both creativity and critical thinking. However, it is not yet clear how college experience aids in fostering creativity and critical thinking and which elements of college education are beneficial for enhancing these two skills. The cultural influence on creativity and critical thinking performance also needs further investigation.

The current study aimed to answer two questions related to this line of thought. How does culture influence creativity and critical thinking performance? How does college experience affect creativity and critical thinking? Based on past findings, we developed three hypotheses. First, we hypothesized that there is a positive association between critical thinking and creativity. Second, we suggest that college students from different countries have different levels of creativity and critical thinking. More specifically, we predicted that United States students would perform better than Chinese students on both creativity and critical thinking. Last, we hypothesized that having college research experience (through courses or research labs) will enhance creativity and critical thinking.

MATERIALS AND METHODS

Participants

The study was examined by the Internal Review Board by the host university in the United States and obtained an agreement from a partner university in China to meet the ethical standard of both countries.

Participants include 103 university students from the United States and 166 university students from Mainland China. Among all participants, 181 were female (67.3%), 54 were male (20.1%), non-binary or gender fluid ($n = 3$, 1.1%), and some did not report their gender ($n = 31$, 11.5%). The majority of participants majored in social sciences ($n = 197$, 73.2%). Other disciplines include business and management ($n = 38$, 14.1%), engineering and IT ($n = 20$, 7.4%), and sciences ($n = 14$, 5.2%). A Chi-square analysis was performed to see if the background in major was different between the American and Chinese samples. The results showed that the two samples are comparable in college majors, $X^2_{(3, 265)} = 5.50$, $p = 0.138$.

The American participants were recruited through campus recruitment flyers and a commercial website called Prolific (online survey distribution website). Ethnicities of the American participants were White ($n = 44$, 42.7%), Asian ($n = 13$, 12.6%), Black or African American ($n = 11$, 10.7%), Hispanic or Latinos ($n = 5$, 4.9%), and some did not report their ethnicity ($n = 30$, 29.1%). The Chinese participants were recruited through online recruitment flyers. All Chinese students were of Han ethnicity.

After reviewing and signing an online consent form, both samples completed a Qualtrics survey containing creativity and critical thinking measures.

Measurements

STEAM Related Creative Problem Solving

This is a self-designed measurement, examining participant's divergent and convergent creative thinking in solving STEAM-related real-life problems. It includes three vignettes, each depicting an issue that needs to be resolved. Participants were given a choice to pick two vignettes to which they would like to provide possible solutions for. Participants were asked to provide their answers in two parts. In the first part, participants were asked to provide as many solutions as they can think of for the problem depicted (divergent). In the second part, participants were asked to choose one of the solutions they gave in the first part that they believe is the most creative and elaborate on how they would carry out the solution (convergent).

The responses for the first part of the problem (i.e., divergent) were scored based on fluency (number of solutions given). Each participant received a score on fluency by averaging the number of solutions given across three tasks. In order to score the originality of the second part of the solution (i.e., convergent), we invited four graduate students who studied creativity for at least 1 year as expert judges to independently rate the originality of all solutions. The Cronbach's Alpha of the expert ratings was acceptable for all three vignette solutions (0.809, 0.906, and 0.703). We then averaged the originality scores provided by the four experts to represent the originality of each solution. We then averaged the top three solutions as rated by the experts to represent the student's performance on originality. In the end, each student received two scores on this task: fluency and originality.

Psychological Critical Thinking Exam

We adopted an updated PCT Exam developed by Lawson et al. (2015), which made improvements to the original measure (Lawson, 1999). We used PCT to measure the participants' domain-specific critical thinking: critical thinking involved in the sciences. The initial assessment aimed to examine the critical thinking of psychology majors; however, the updated measure was developed so that it can be used to examine students' critical thinking in a variety of majors. The split-half reliability of the revised measurement was 0.88, and test-retest reliability was 0.90 (Lawson et al., 2015). Participants were asked to identify issues with a problematic claim made in two short vignettes. For example, one of the questions states:

> *Over the past few years, Jody has had several dreams that apparently predicted actual events. For example, in one dream, she saw a car accident and later that week she saw a van run into the side of a pickup truck. In another dream, she saw dark black clouds and lightning and 2 days later a loud thunderstorm hit her neighborhood. She believes these events are evidence that she has a psychic ability to predict the future through her dreams. Could the event have occurred by chance? State whether or not there is a problem with the person's conclusions and explain the problem (if there is one).*

Responses were scored based on the rubric provided in the original measurement (Lawson et al., 2015). If no problem was identified the participants would receive zero points. If a problem was recognized but misidentified, the participants would receive one point. If the main problem was identified and other less relevant problems were identified, the participants received two points. If participants identified only the main problem, they received three points. Following the rubric, four graduate students independently rated the students' critical thinking task. The Cronbach's Alpha of the expert ratings was acceptable for both vignettes (0.773 and 0.712). The average of the four scores given by the experts was used as the final score for the participants.

California Critical Thinking Skills Test

This objective measure of critical thinking was developed by Facione and Facione (1994). We used CCT to measure a few of the multidimensions of critical thinking such as evaluation, logical reasoning, and probability thinking. Five sample items provided from Insight Assessment were used instead of the standard 40-min long CCT. Participants were presented with everyday scenarios with 4–6 answer choices. Participants were asked to make an accurate and complete interpretation of the question in order to correctly answer the question by choosing the right answer choice (each correct answer was worth one point). This test is commonly used to measure critical thinking, and previous research has reported its reliability as $r = 0.86$ (Hariri and Bagherinejad, 2012).

Sternberg Scientific Inquiry and Reasoning

This measure was developed by Sternberg and Sternberg (2017) as an assessment of scientific reasoning. We used this assessment as a domain-specific assessment to measure participants' scientific creativity (generating testable hypotheses) and scientific critical thinking involved in generating experiments. For this two-part measure, participants were asked to read two short vignettes. For one of the vignettes, participants were asked to generate as many hypotheses as possible to explain the events described in the vignette. For the other, create an experiment to test the hypothesis mentioned in the vignette.

After carefully reviewing the measurement, we notice that the nature of the tasks in the first part of this measure (hypothesis generation) relied on heuristics, requiring participants to engage in divergent thinking. The number of valid hypotheses provided (i.e., fluency) was used to represent the performance of this task. We, therefore, deem that this part measures creativity. In contrast, the second part of the measure, experiment generation, asked participants to use valid scientific methods to design an experiment following the procedure of critical thinking such as evaluation, problem-solving, and task evaluation. Its scoring also followed algorithms so that a correct answer could be achieved. For the above reasons, we believe hypotheses generation is a measurement of creativity and experiment generation is a measurement for critical thinking.

Based on the recommended scoring manual, one graduate student calculated the fluency score from the hypothesis generation measurement. Four experts read through all students' responses to the experiment generation. They discussed a rubric on how to score these responses, using a four-point scale, with a "0" representing no response or wrong response, a "1" representing partially correct, a "2" representing correct response. An additional point (the three points) was added if the participant provided multiple design methods. Based on the above rubric, the four experts independently scored this part of the questionnaire. The Cronbach's Alpha of the four expert ratings was 0.792. The average score of the four judges was used to represent their critical thinking scores on this task.

College Experience Survey

Participants were asked about their past research experience, either specifically in psychology or in general academia. Participants were asked to choose between three choices: *no research experience, intermediate research experience* (i.e., research work for class, research work for lab), and *advanced research experience* (i.e., professional research experience, published works).

Demographic and Background Questionnaire

Series of standard demographic questions were asked, including participants' age, gender, and ethnicity.

RESULTS

The Relationship Between Creativity and Critical Thinking

We performed a Pearson correlation to examine the relationship between creativity and critical thinking (the two-c), which include performances on three measures on creativity (*creativity originality*, *creativity fluency*, and *hypothesis generation*) and three measures on critical thinking (*experiment generation*, *CCT*, and *PCT*).

Most of the dependent variables had a significantly positive correlation. The only insignificant correlation was found between Sternberg hypothesis generation and CCT, $r_{(247)} = 0.024$, $p = 0.708$ (see **Table 1**).

Confirmatory factor analysis (CFA) was conducted by applying SEM through AMOS 21 software program and the maximum likelihood method. One-factor and two-factor models have been analyzed, respectively (see **Figure 1**).

As it is demonstrated in **Table 2**, the value ranges of the most addressed fit indices used in the analysis of SEM are presented. Comparing two models, χ^2/df of the two-factor model is in a good fit, while the index of the one-factor model is in acceptable fit. The comparison of the two models suggest that the two-factor model is a better model than the one-factor model.

Cross-Cultural Differences in Critical Thinking and Creativity

We conducted a 2 (Country: the United States vs. China) × 2 (Two-C: Creativity and Critical Thinking) ANOVA to investigate the cultural differences in critical thinking and creativity. We averaged scores of three critical thinking measurement (*experiment generation*, *PCT*, and *CCT*) to represent critical thinking and averaged three creativity scores (*creativity originality*, *creativity fluency*, and *hypothesis generation*).

This analysis revealed a significant main effect for the type of thinking (i.e., creative vs. critical thinking), $F_{(1,247)} = 464.77$, $p < 0.01$, $\eta_p^2 = 0.653$. Moreover, there was a significant interaction between country (i.e., the United States vs. China) and type of thinking, $F_{(1,247)} = 62.00$, $p < 0.01$, $\eta_p^2 = 0.201$. More specifically, Chinese students ($M = 1.32$, $SD = 0.59$) outperformed American students ($M = 1.02$, $SD = 0.44$) on critical thinking. In contrast, American students ($M = 2.59$, $SD = 1.07$) outperformed Chinese students ($M = 2.05$, $SD = 0.83$) on creativity.

Influence of Research Experience on Critical Thinking and Creativity

The last hypothesis states that having college research experience (through courses or research lab) would enhance students' creativity and critical thinking from both countries. We performed a 2 (Two-C: Creativity and Critical Thinking) × 2 (Country: the United States vs. China) × 3 (Research Experience: Advanced vs. Some vs. No) ANOVA to test this hypothesis. This analysis revealed a significant main effect for research experience, $F_{(2,239)} = 4.05$, $p = 0.019$, $\eta_p^2 = 0.033$. Moreover, there was a significant interaction between country (i.e., the United States vs. China) and research experience, $F_{(2,239)} = 5.77$, $p = 0.004$, $\eta_p^2 = 0.046$. In addition, there was a three-way interaction among country, two-C, and research experience. More specifically, with an increase of research experience for American students, both critical thinking and creativity improved. In contrast, for Chinese students, the impact of research experience was not significant for creativity. However, some research experience positively impacted Chinese students' critical thinking (see **Figure 2**).

DISCUSSION

The current study aimed to investigate the relationship between creativity and critical thinking, how culture influences creativity and critical thinking, and how college research experience affects creativity and critical thinking. Our results supported the first hypothesis regarding the positive correlation among all of the dependent variables. The mean correlation between the measures of creativity and critical thinking was 0.230. This result was in line with the findings from previous research (Gibson et al., 1968; Gadzella and Penland, 1995; Siburian et al., 2019; Akpur, 2020; Qiang et al., 2020). Moreover, our confirmatory factor analysis yielded similar results as analysis

TABLE 1 | Correlation coefficients for study variables.

Variable	N	1	2	3	4	5
1. Creativity fluency	210					
2. Creativity originality	197	0.484**				
3. Hypothesis generation	210	0.464**	0.355**			
4. Experiment generation	210	0.302**	0.274**	0.330**		
5. Psychological critical thinking	210	0.265**	0.259**	0.292**	0.367**	
6. Critical thinking test	210	0.153*	0.173*	0.024	0.347**	0.152*

*$p < 0.05$.
**$p < 0.01$.

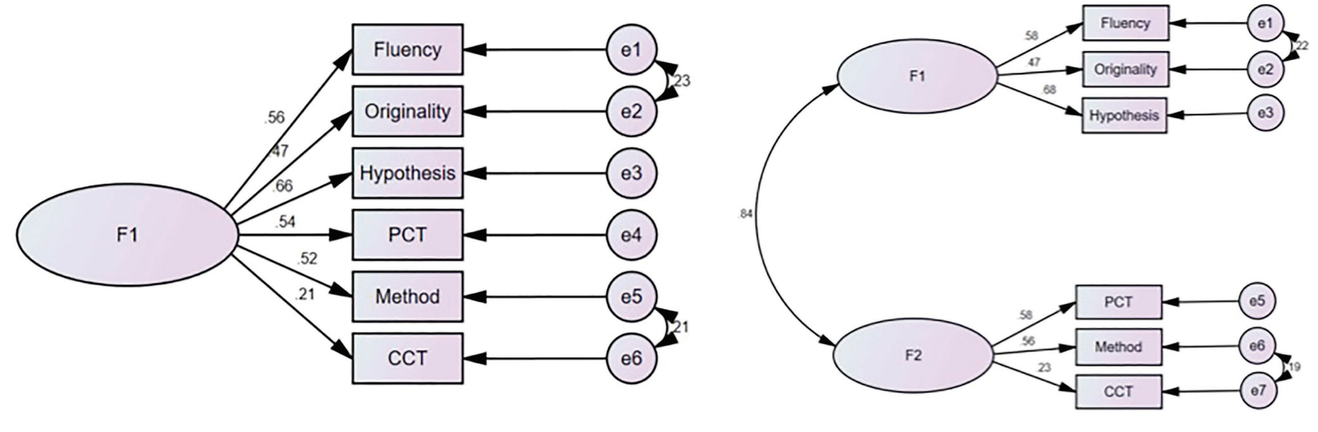

FIGURE 1 | The comparison of the two confirmatory factor analysis (CFA) models: one-factor vs. two-factor.

TABLE 2 | Recommended values for evaluation and the obtained values.

Fit measure	Good fit	Acceptable fit	Obtained values	
			One-factor model	Two-factor model
χ^2/df	$0 \leq \chi^2/\text{df} \leq 2$	$2 < \chi^2/\text{df} \leq 3$	2.24	1.82
RMSEA	0 ≤ RMSEA ≤ 0.05	0.05 < RMSEA ≤ 0.08	0.05	0.04
NFI	0.95 ≤ NFI ≤ 1.00	0.90 ≤ NFI < 0.95	0.96	0.98
CFI	0.97 ≤ CFI ≤ 1.00	0.95 ≤ CFI < 0.97	0.98	0.99
GFI	0.95 ≤ GFI ≤ 1.00	0.90 ≤ GFI < 0.95	0.99	0.99
AGFI	0.90 ≤ AGFI ≤ 1.00	0.85 ≤ AGFI < 0.90	0.97	0.97

RMSEA,root mean square error of approximation; NFI, normed fit index; CFI, comparative fit index; GFI, goodness-of-fit index; and AGFI, adjusted goodness-of-fit-index (Schermelleh-Engel et al., 2003).

of Wechsler et al. (2018) and Akpur (2020) and provides more evidence of the relative independence between creativity and critical thinking. We found that at the latent variable level, the two skills are highly correlated to each other ($r = 0.84$). In addition, we found that although the one-factor model was an acceptable fit, a two-factor model was a better fit for analysis. This result suggests that despite the correlation between creativity and critical thinking, the two skills should be studied as separate factors for an appropriate and comprehensive analysis.

The results of this study partially confirmed our second hypothesis and replicated the findings from past studies (Niu et al., 2007; Lun et al., 2010; Wong and Niu, 2013; Tang et al., 2015). As predicted, there was a significant main effect for culture in students' performance for all six measures in the two-C analysis model. United States students performed better than Chinese students in all three creativity measures, and Chinese students performed better than United States students in all critical thinking measures. Given the diversity in the type of measures used in this study, the results suggest that United States and Chinese students' performance aligns with the stereotype belief found in study of Wong and Niu (2013). The findings from the current study suggest that the stereotype belief observed in both United States and Chinese students (United States students generally perform better on creativity tasks, while Chinese students perform typically better on critical thinking tasks) is not entirely unfounded. Furthermore, the clear discrepancy in performance between United States and Chinese students provides more evidence to suggest that creativity and critical thinking are relatively autonomous skills. Although, a high correlation between these two skills was found in our study, the fact that students from two different cultures have two different development trajectories in critical thinking and creativity suggests that these two skills are relatively autonomous.

Lastly, the results also confirmed our third hypothesis, that is, college research experience did have a positive influence on students' creativity and critical thinking. Compared to students with no research experience, students with some research experience performed significantly better in all measures of creativity and critical thinking. This finding is consistent with the previous literature (Mill et al., 1994; Penningroth et al., 2007; Stevens and Witkow, 2014; Stevens et al., 2016; Kuo et al., 2018). The result of our study suggests that college research experience is significant to enhance both creativity and critical thinking. As research experience becomes a more essential component of college education, our results suggest that it not only can add credential for applying to graduate school or help students learn skills specific to research, but also help students enhance both creativity and critical thinking. Furthermore, it is worth noting that this nature held true for both Chinese and American students. To our knowledge, this

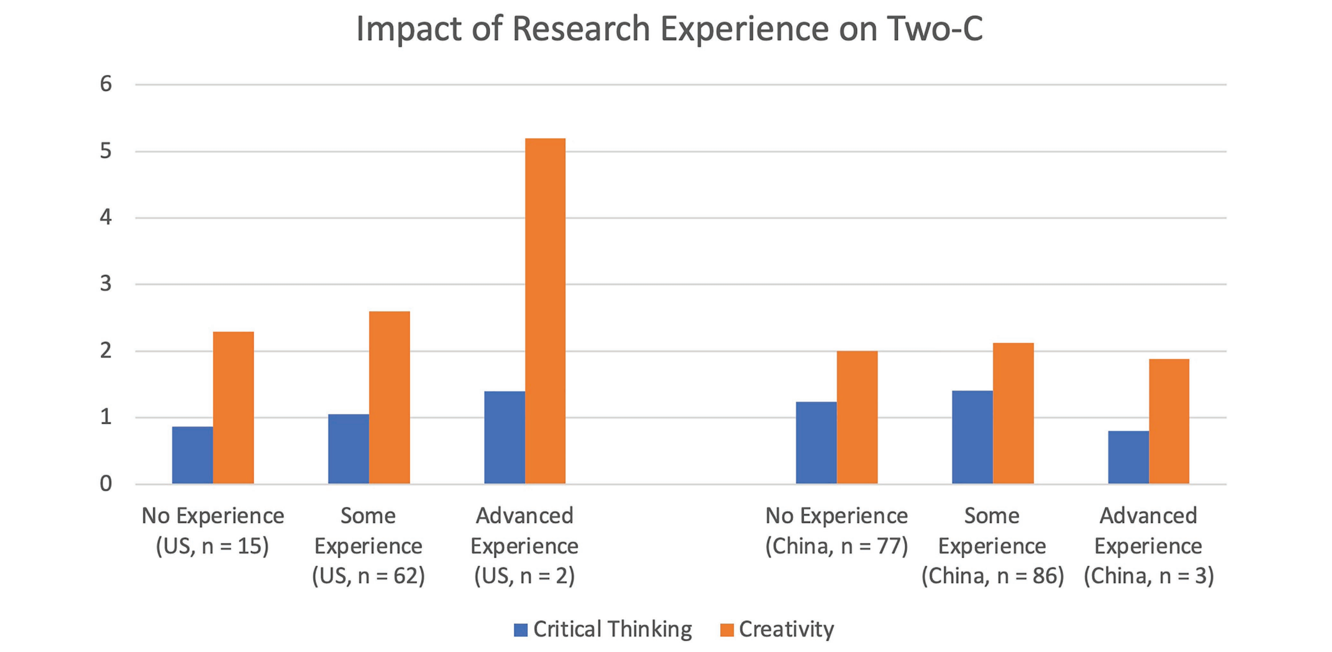

FIGURE 2 | Estimated marginal means of Two-C for the United States and Chinese samples.

is a first investigation examining the role of research experience in both creativity and critical thinking cross-culturally.

In addition to the report of our findings, we would like to address some limitations of our study. First, we would like to note that this is a correlational and cross-sectional study. A positive correlation between research experience and the two dependent variables does not necessarily mean causation. Our results indeed indicate a positive correlation between research experience and the two-C variables; however, we are not sure of the nature of this relationship. It is plausible that students with higher creativity and critical thinking skills are more engaged in research as much as it is to argue in favor of a reversed directional relationship. Second, we would like to note the sample bias in our study. Majority of our participants were female, majoring in the social sciences and a relatively high number of participants chose not to report their gender. Third, we would like to note that our study did not measure all creativity and critical thinking dimensions, we discussed in the introduction. Instead, we focused on a few key dimensions of creativity and critical thinking. Our primary focus was on divergent thinking, convergent thinking, and scientific creativity as well as few key dimensions of critical thinking (evaluation, logical reasoning, and probability thinking), scientific critical thinking involved in problem solving and hypothesis testing. Moreover, our results do not show what specific components of research training are beneficial for the enhancement of creativity and critical thinking.

For future research, a longitudinal design involving a field experiment will help investigate how different research training components affect the development of creativity and critical thinking. In addition, a cross-cultural study can further examine how and why the students from different cultures differ from each other in the development of these two potentials. As such, it might shed some light on the role of culture in creativity and critical thinking.

CONCLUSION AND IMPLICATION

The result of our study provides few insights to the study of creativity and critical thinking. First, creativity and critical thinking are a different construct yet highly correlated. Second, whereas Americans perform better on creativity measures, Chinese perform better on critical thinking measures. Third, for both American and Chinese students, college research experience is a significant influence on the enhancement of creativity and critical thinking. As research experience becomes more and more essential to college education, its role can not only add professional and postgraduate credentials, but also help students enhance both creativity and critical thinking.

Based on our results, we recommend that research training be prioritized in higher education. Moreover, each culture has strengths to develop one skill over the other, hence, each culture could invest more in developing skills that were found to be weaker in our study. Eastern cultures can encourage more creativity and Western cultures can encourage more critical thinking.

To conclude, we would like to highlight that, although recognized globally as essential skills, methods to foster creativity and critical thinking skills and understanding creativity and critical thinking as a construct requires further research. Interestingly, our study found that experience of research itself can help enhance creativity and critical thinking. Our study also aimed to expand the knowledge of creativity and critical thinking literature through an investigation of the relationship of the two variables and how cultural background influences the performance of these two skills. We hope that our findings can provide insights for researchers and educators to find constructive methods to foster students' essential 21st century skills, creativity and critical thinking, to ultimately enhance their global competence and life success.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institutional Review Board at Pace University. The participants provided their informed consent online prior to participating in the study.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

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ORIGINAL RESEARCH
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Exploring the Effectiveness of STEAM-Based Courses on Junior High School Students' Scientific Creativity

Ngoc-Huy Tran, Chin-Fei Huang and Jeng-Fung Hung*

Graduate Institute of Science Education and Environmental Education, National Kaohsiung Normal University, Kaohsiung, Taiwan

The purpose of this study is to explore the effectiveness of a STEAM (Science, Technology, Engineering, Arts, Mathematics) -based curriculum on junior high school students' scientific creativity. The main topic of the STEAM-based curriculum in this study is an ancient mechanical clock that was designed and produced by the authors' team. Further, the main concept of the ancient mechanical clock is about a gear wheel. Hence, this study designed two stages of courses which were gear wheel science courses (2 weeks) and STEAM-based courses (2 weeks). A total of 62 junior high school students from two different courses participated in this study and were divided into a control group and an experimental group. This study adopted a counterbalance design. The control group joined gear wheel science courses first and joined STEAM-based courses second. In contrast, the experimental group joined STEAM-based courses first. Both groups were asked to complete a pre-test, a middle-test, and a post-test by completing the "Scientific Creativity Test (Cronbach's α 0.87)". The results from paired *t*-test analyses showed that control group students did not show significant differences in scientific creativity before and after joining the gear wheel science courses, but they got significantly higher scores after joining STEAM-based courses than before. On the other hand, the experimental group students got higher scores in scientific creativity after joining STEAM-based courses than before, and persisted in getting higher scores after joining the gear wheel courses than before. Furthermore, the results implied that the STEAM-based courses might help students maintain or continue their scientific creativity. Further discussion is provided.

Keywords: scientific creativity, science education, creativity, junior high school, steam

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Weihua Niu,
Pace University, United States

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Zhi Hong Wan,
The Education University of Hong Kong, Hong Kong SAR, China
Kuen-Yi Lin,
National Taiwan Normal University, Taiwan

****Correspondence:***
Ngoc-Huy Tran
huytn@hcmue.edu.vn

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INTRODUCTION

Creativity is a specific human ability that can be used to solve real-life problems in novel and useful ways (Guilford, 1950; Huang et al., 2017; Huang and Wang, 2019). Not only do educators and researchers say that creativity is an important educational purpose for the future (Shi et al., 2017; Suyidno et al., 2019), but also PISA 2021 focused on the issue of creative thinking in schools (Bouchie, 2019). Unfortunately, although a lot of researchers of educators have agreed that scientific creativity is very important for a long time, there are few systematic training courses in formal education (Suyidno et al., 2019). For this reason, this study aims to design a systematic curriculum in school for trying to improve students' creativity.

Many previous studies have investigated the important indices that improve human creativity (Lubart, 1994; Feldhusen and Goh 1995; Thuneberg et al., 2018; Conradty and Bogner, 2019). They discovered that participants with high creativity abilities frequently have a vigorous curiosity and can connect their knowledge and experiences to produce some new ideas. In other words, interdisciplinary thinking skills will be a key factor in training human creativity. STEAM (science, technology, engineering, art, and mathematics) subjects, according to Conradty and Bogner (2019), are a type of interdisciplinary integration, and they investigate 11–12 years old students' creativity by teaching STEAM courses. Besides, Perignat and Katz-Buonincontro (2019) demonstrated in an integrative literature review that the combination of the arts with STEM subjects to become STEAM (Science, Technology, Engineering, Arts, and Mathematics) education can improve student engagement, creativity, innovation, problem-solving skills, and other cognitive benefits. In addition, Conradty and Bogner (2019) claimed that including the arts in STEM education might assist students by fostering innovative solutions. As a result, creativity is linked to the arts and is employed as one of the advantages or learning objectives of STEAM education. They also found that the students' self-reported aspects of creativity were not affected by using a single STEAM intervention. In contrast, Ozkan and Topsakal (2019) used the STEAM design process program to investigate middle school seventh-grade students' creativity and discovered that the students' verbal and numerical creativity had significantly improved. Did the different findings come from different definitions of creativity or from different curriculum designs?

In the aspect of the definition of creativity, Mayer (1999) has already mentioned that the definition of creativity is many and varied. This means the discussion about creativity will be affected by different points of view. Csikszentmihalyi (1996) also indicated that creativity is domain-specific, and although the cognitive structure of creativity is similar, the nature of domain-specific creativity is very different in the individual domains. For example, scientific creativity is a kind of domain-specific creativity, and humans will perform their scientific creativity by combining their science background knowledge and domain-relevant creativity (Sternberg and Lubart, 1993; Amabile, 1996; Hu and Adey, 2002; Ayas and Sak, 2014; Huang and Wang, 2019). In this coming decade, the industrial revolution 4.0 will push forward the transition of science, engineering, and technological knowledge, and students across the whole world should speed up to improve their science background knowledge. Moreover, the problems of environmental change such as climate change, air pollution, micro-fiber or micro-plastic issues in the ocean, etc., need to be solved by using scientific knowledge and creativity. Therefore, this study concentrates the definition of creativity on scientific creativity in this research.

On the other hand, this study also wants to clarify what is a suitable STEAM-based curriculum design for helping students improve their scientific creativity. Ngo and Phan (2019) mentioned that the multi-disciplinary approach in project-based learning (PBL) strategies is suitable to the concept of STEAM. PBL strategies can successfully assist students to increase their creativity and get positive feedback from students; PBL strategies are also recommended to continue to be researched and applied in schools in the future (Gunawan et al., 2017; Ismuwardani et al., 2018; Lou et al., 2017). In Ngo and Phan's research, they referred that some previous research mentioned that PBL strategies could help students improve their attitude and skills, but fewer effects for improving students' knowledge. Ngo and Phan hypothesized that this was due to a lack of suitable projects in the early stages of the research. Therefore, further studies are needed.

Hypotheses

In order to approve that STEAM-based courses are influential on students' scientific creativity, this study designed a two-stage STEAM-based curriculum by using project-based learning strategies. The main topic of STEAM-based curriculum is completing a project–to assemble an ancient mechanical clock and inquiry the reasons of different results from different conditions. The two stages of this curriculum involve "Gear Wheel Science Courses" and "STEAM-based courses". The details of curriculum design will describe in next section (Method section).

In a previous study, Tran et al. (2021) demonstrated that the STEAM-based curriculum could increase students' scientific creativity. In particular, in the three components of scientific creativity (fluency, flexibility, and originality), the fluency and flexibility components showed a significant improvement; and the effects of the STEAM-based curriculum on various genders are obviously similar. This conclusion, however, is restricted to elementary school students. Furthermore, they are unable to indicate which stage supports the students' scientific creativity more actively. Therefore, this study wishes to broaden the participants and better understand which kind of sequence of course stage design is more effective in improving students' scientific creativity, as well as the influence of STEAM-based courses on students' scientific creativity.

This study hypothesized that the whole STEAM-based curriculum could improve junior high school students' scientific creativity when changing the sequence of course stages. Besides, this study also hypothesized that in the two stages of the STEAM-based curriculum, the STEAM-based stage of the course plays an important role and more effectively improves students' scientific creativity.

There are a few scientific constraints to this study. All participants in this study write down their responses to the scientific creativity test at the same time in class. However, if the number of responses is low, this study would be unable to establish whether this outcome is due to a lack of interest on the side of students or whether they do not have enough motivation to complete the test. In other words, all data on the exam paper that contains words will be counted.

MATERIALS AND METHODS

Participants

This study was conducted at an urban junior high school in Taiwan. A total of 62 junior high school students (n = 62, 35 males, 27 females; mean age ± SD = 14.2 ± 0.4 years) participated and were divided into a control group (n = 31, 17 males, 14 females; mean age ± SD = 14.2 ± 0.4 years) and an experimental

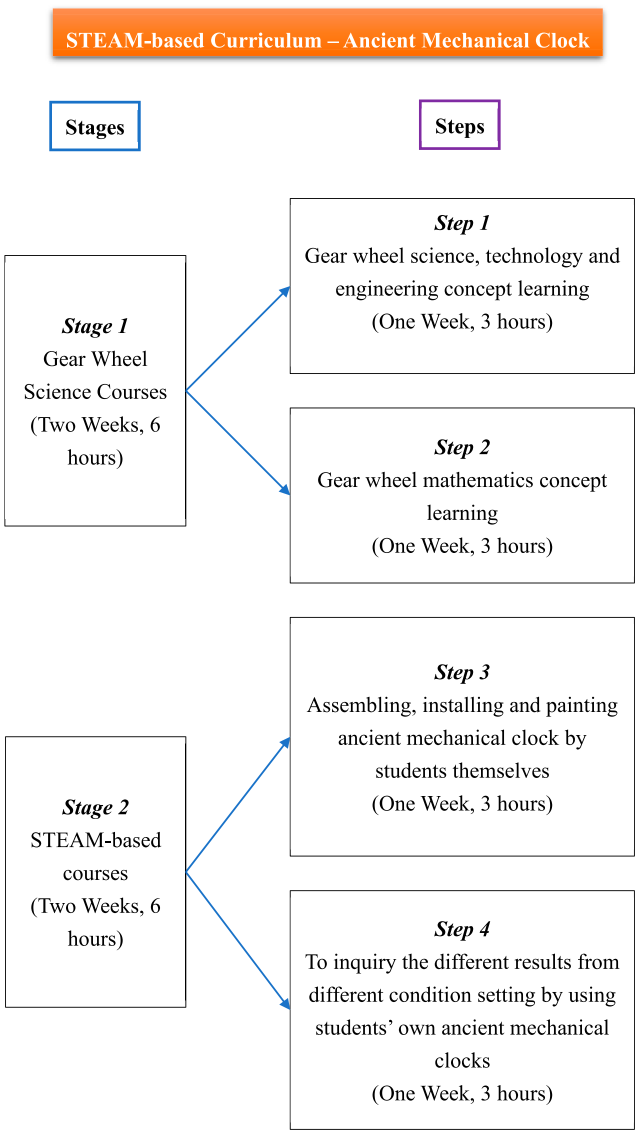

FIGURE 1 | STEAM-based curriculum design about ancient mechanical clock.

group (n = 31, 18 males, 13 females; mean age ± SD = 14.3 ± 0.5 years). All participants were asked to complete the Scientific Creativity test (Hu and Adey, 2002) before the whole course, after the first stage of the course, and after the second stage of the course. However, the two groups of students went through different stage designs. The curriculum design details will be introduced in the next section.

Research Design and STEAM-Based Curriculum Design

The aim of this study is to explore the effectiveness of a STEAM-based curriculum on junior high school students' scientific creativity. The main topic of the STEAM-based curriculum is about an ancient mechanical clock which was designed and produced by the authors' team. To understand the complex ancient mechanical clock, the students need to learn about the gear wheel science, technology, engineering, and mathematics concepts. Besides, this study added STEAM-based courses to enhance students' understanding of the whole concepts of the ancient mechanical clock. All students needed to assemble, install and paint their own ancient mechanical clock by themselves, and inquiry the different results from different condition setting by using students' own ancient mechanical clocks. Hence, this study designed a STEAM-based curriculum which was included in step 2 and step 4 (**Figure 1**). The curriculum design was reviewed and confirmed by three experts (male = 2, female = 1; all experts have majored in science education).

Although all students went through these two stages of the curriculum, this study wanted to clarify both the influences of STEAM-based courses on students' scientific creativity and which kind of sequence of course stage design is more effective in improving students' scientific creativity. To find the possible results of the core research questions, this study adopted a counterbalance design. This design is divided into two stages: stage 1 (gear wheel science courses with two steps) and stage 2 (STEAM-based courses with two steps). In particular, in step 3, students can connect their interdisciplinary knowledge and experiences to generate new ideas by assembling and installing the ancient mechanical clock themselves; additionally, by painting their clock, students' arts abilities are demonstrated and trained, from which the combination of the arts with STEM subjects becomes STEAM and students' scientific creativity will be developed.

The control group students were asked to join stage 1 first and then join stage 2. This kind of curriculum design helps students construct their scientific concepts first and then guides them to integrate their concepts by joining STEAM courses. In contrast, the experimental group students were asked to join stage 2 first and then stage 1 (**Figure 1**). This kind of curriculum design helps students learn the interdisciplinary knowledge in STEAM courses by themselves, and then guides them to generalize their scientific concepts. Photos of students participating in the study are shown in **Figure 2**.

The control group style (stage 1 to stage 2) construct students' scientific concepts first and then guides them to integrate their concepts by joining STEAM courses. The experimental group style (stage 2 to stage 1) leads students to trial and error by themselves in STEAM courses and then guides them to organize their scientific concepts.

As can be seen in **Figure 3**, both the comparison of the pre-test and middle-test and the comparison of middle-test and post-test was used to investigate the research question "the efficiency of STEAM-based courses on students' scientific creativity". Meanwhile, the comparison of the pre-test and post-test was used to reflect the exploring about research question "which kind of sequence of course stage design is more effective to improve students' scientific creativity?".

Instrument and Scoring

This study adopted Scientific Creativity Test (Hu and Adey, 2002) to be the main instrument, and the details of the Scientific

FIGURE 2 | Photos of students participating in the study.

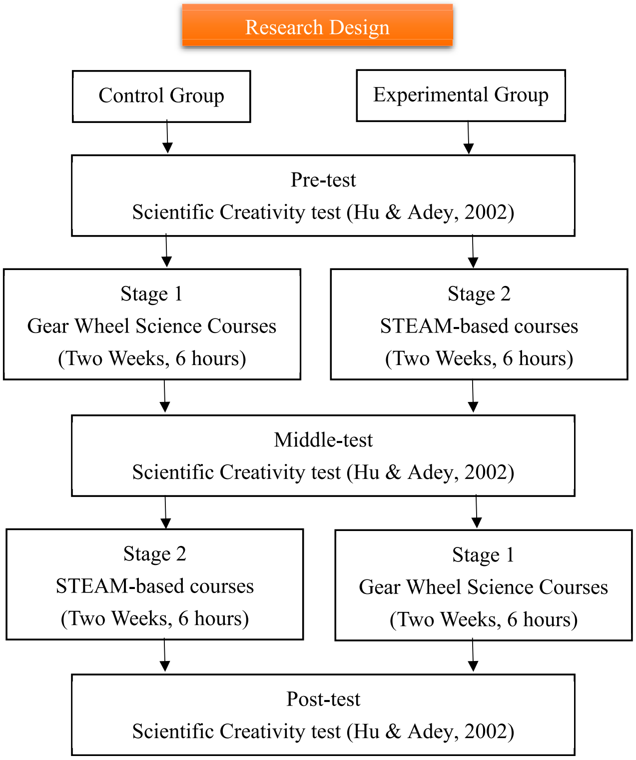

FIGURE 3 | Research Design Structure of this study.

Creativity Test are shown in **Table 1**. This test was re-tested and verified by the Huang and Wang (2019), and the results indicated that both the students' science performances and creativity could reflect their performance creativity well.

In Hu and Adey's research, the Scientific Creativity Test was also used to explore high school students' scientific creativity, and the reliability reached Cronbach's α 0.89. This study translated the test into Chinese and retested it on junior high school students ($n = 82$, 38 males, 44 females; mean age ± *SD* = 14.1 ± 1.1 year) in Taiwan, and the revised reliability reached Cronbach's α 0.87.

1) Fluency score: to count all of the separate responses given by the subjects, regardless of the quality.
2) Flexibility score: to count the number of approaches or areas used in the answer.
3) Originality score (item 1–4/item5/item6/item7): If the probability of a response was less than 5% of all responses, we gave it 3/2/4/5 points; if the probability of a response was from 5 to 10% of all responses, we gave it 2/1/2/3 point; if the probability of a response was greater than 10% of all responses, we gave it 1/0/0/1 points.

There were three professional experts who read all students' answers and gave the scores of fluency, flexibility, and originality individually. Then, they read the other two experts' scores, and then provided their comments or modified their scores. These three experts reached a common consensus for reviewing three times.

RESULTS AND DISCUSSION

This study aims to explore the effectiveness of a STEAM-based curriculum on junior high school students' scientific creativity. There are two main research questions in this study, which were "the efficiency of STEAM-based courses on students' scientific creativity" and "which kind of sequence of course stage design is more effective to improve students' scientific creativity?".

On the whole, the results from **Table 2** show that not only all participants, but also the control group and the experimental group got significantly higher scores of scientific creativity after the whole STEAM-based curriculum than before. This result supports that the curriculum design in this study could improve students' scientific creativity.

The result could be supported by previous studies which mentioned that a multi-disciplinary approach project-based design STEAM curriculum could improve students' creativity (Ngo and Phan, 2019; Ozkan and Topsakal, 2021). Further, Ozkan and Topsakal's research found that a STEAM design program can enhance students' verbal and numerical domain-relevant creativity, and this study confirms that the STEAM-based curriculum can improve students' scientific creativity.

TABLE 1 | Scientific creativity test (Hu and Adey, 2002; 2003; Huang and Wang, 2019).

Items	Contents	Scoring
Item 1: unusual uses	*Please write down as many as possible scientific uses as you can for a piece of glass*	Fluency, flexibility, originality
Item 2: problem finding	*If you can take a spaceship to travel in outer space and go to a planet, what scientific questions do you want to research? Please list as many as you can*	Fluency, flexibility, originality
Item 3: product improvement	*Please think up as many possible improvements as you can to a regular bicycle, making it more interesting, more useful and more beautiful*	Fluency, flexibility, originality
Item 4: scientific imagination	*Suppose there was no gravity, describe what the world would be like*	Fluency, flexibility, originality
Item 5: problem solving	*Please use as many possible methods as you can to divide a square into four equal pieces (same shape)*	Flexibility, originality
Item 6: science experiment	*There are two kinds of napkin. How can you test which is better? Please write down as many possible methods as you can and the instruments, principles and simple procedure*	Flexibility, originality
Item 7: product design	*Please design an apple picking machine. Draw a picture, point out the name and function of each part*	Flexibility, originality

The definition of scoring (Hu and Adey, 2002; 2003; Huang and Wang, 2019).

TABLE 2 | The comparison table of pre-test and post-test data.

Group	Pre-test (mean ± SD)	Post-test (mean ± SD)	*t*	*p*
Control group (*n* = 31)	57.26 ± 15.67	72.19 ± 15.43	−5.27	<0.001
Experimental group (*n* = 31)	56.74 ± 20.86	70.77 ± 18.22	−6.71	<0.001
Total (*n* = 62)	57.00 ± 18.30	71.48 ± 16.76	−8.29	<0.001

TABLE 3 | The comparison table of counterbalance designed about join STEAM-based courses.

Group	Pre-test (mean ± SD)	Middle-test (mean ± SD)	Post-test (mean ± SD)	*t*	*p*
Control group (*n* = 31)		57.90 ± 17.36	72.19 ± 15.43	−4.90	<0.001
Experimental group (*n* = 31)	56.74 ± 20.86	63.42 ± 18.07		−4.52	<0.001

(Note: the analysis is comparing the post-test and middle-test data of the control group, and the middle-test and pre-test data of the experimental group).

TABLE 4 | The ANCOVA analysis to compare different group students' scientific creativity (*n* = 62).

Sources	SS	df	MS	F	*p*	η^2
Corrected model	8299.97	2	4149.984	27.737	<0.001	0.485
Intercept	7080.840	1	7080.840	47.326	<0.001	0.445
Pre-creativity	8268.742	1	8268.742	55.265	<0.001	0.484
Group	18.445	1	18.445	0.123	0.727	0.002
Error	8827.517	59	149.619			
Total	333944.000	62				

To investigate "the efficiency of STEAM-based courses on students' scientific creativity", this study compared both the post-test and middle-test data of the control group and the middle-test and pre-test data of the experimental group (the research design is in **Figure 3**; the result is in **Table 3**).

Since the control group joined the STEAM-based courses in stage 2 and the experimental group joined the STEAM-based courses in stage 1, this analysis compared the post-test and middle-test data of the control group, and the middle-test and pre-test data of the experimental group. The results from **Table 3** demonstrate that both the control and experimental groups got significantly higher scores after joining the STEAM-based courses than before, no matter what the last courses is. This finding could initially prove that the STEAM-based courses in this study are helpful for improving junior high school students' scientific creativity.

Ugras (2018) indicated that the STEM education approach is teaching individuals to establish the mesh network from interdisciplinary knowledge, behavior, belief, skills, and action and to prepare their problem-solving abilities for real life. To go back to look closely at the contents of the scientific creativity test (Hu and Adey, 2002), we can find that most items of scientific creativity test are close to real-life problems such as "*Please think up as many possible improvements as you can to a regular bicycle, making it more interesting, more useful and more beautiful*" (Hu and Adey, 2002). This might be a reason to explain why the students' scientific creativity performances could be significantly improved by joining STEAM-based courses.

Next, this study investigated which kind of sequence of course stage design is more effective to improve students' scientific creativity. There are two kinds of curriculum design in this study (**Figure 2**). The first one is used on the control group, and the students need to join stage 1 (gear wheel science courses) first and then join stage 2 (STEAM-based courses) second. This kind of curriculum design constructs students' scientific concepts first and then guides them to integrate their concepts by joining STEAM courses. The second design was used on the experimental group, and the students need to join stage 2 first, and then stage 1 s. The curriculum design leads students to inquire by themselves in STEAM courses and then guides them to organize their scientific concepts. Which kind of sequence is better for improving junior high school students' scientific creativity?

Table 4 indicates that there are no significant differences between the control and experimental groups after they had joined the STEAM-based curriculum than before. In other words, the different sequence of courses design did not affect the students' final performance of scientific creativity. Following up, this study analyzed different group students' performance of scientific creativity in different stages.

In **Table 5**, the results show that the control group students did not get significantly higher scores in stage 1, which means the control group students did not perform higher scientific creativity after joining gear wheel science courses, compared to before. But the control group students got significantly higher scores in stage 2, which indicates that the control group students performed more scientific creativity after joining STEAM-based courses, compared to before. Unlike the control group, the experimental group students performed significantly higher scores before joining the course in both stage 1 and stage 2. These results imply that the STEAM-based courses might help students maintain or continue their scientific creativity ability. It demonstrates that the research hypothesis given by this study

TABLE 5 | Different group students' performance of scientific creativity in different stages (control group n = 31; experimental group n = 31).

Group	Frequencies of stage	Test 1 (mean ± SD)	Test 2 (mean ± SD)	*t*	*p*
Control group	Stage 1 (Pre-test—Middle-test)	57.26 ± 15.67	57.90 ± 17.36	0.91	0.371
	Stage 2 (Middle-test—Post-test)	57.90 ± 17.36	72.19 ± 15.43	4.90	<0.001
Experimental group	Stage 2 (Pre-test—Middle-test)	56.74 ± 20.86	63.42 ± 18.07	4.52	<0.001
	Stage 1 (Middle-test—Post-test)	63.42 ± 18.07	70.77 ± 18.22	5.66	<0.001

(Note: stage 1 is gear wheel science courses; stage 2 is STEAM-based courses).

is appropriate, that the entire STEAM-based curriculum might boost junior high school students' scientific creativity when the sequence of course stages is changed. The STEAM-based stage courses, in particular, play an important role in the two stages of the STEAM-based curriculum and more effectively foster students' scientific creativity.

Thuneberg et al. (2018) indicated pre-knowledge was significantly influenced by creativity. That means constructing students' scientific concepts first or generalizing students' science knowledge after trying to find out by themselves might cause different results in fostering students' scientific creativity. This could support that the different curriculum design sequences may cause different advancing effects on students' scientific creativity. Moreover, Torrance (1990) mentioned that imagination and breaking through stereotypes would be the most important factors in improving human creativity. In the control group, the students were asked to join gear wheel science courses in the first stage. This kind of scientific knowledge might be a kind of "stereotype" and might be the reason why the control group students did not show significant differences in scores of scientific creativity in the first stage. However, these implications and hypotheses should be confirmed by further studies.

According to Perignat and Katz-Buonincontro (2019), a small group of scholars consider creativity to be an inherent aspect of the arts; however, the majority of authors argue that creativity is inherent in all disciplines, not just the arts, as it is commonly perceived. That means creativity can be expressed and developed through all aspects of STEAM education, not just the arts. This highlights the importance of all the different aspects of STEAM education in developing creativity in students. Besides that, it is important not to stress the art form or final product over the artistic process itself, and focus on the process of learning through thinking, planning, and creating or performing an artwork rather than on a finished product.

This study used PBL strategies to design a two-stage STEAM-based curriculum and showed its effectiveness in enhancing students' creativity. However, the use of other teaching strategies such as problem-solving learning, programming learning, etc. in STEAM education is also likely to have a positive impact on student creativity (Bicer et al., 2017; Noh and Lee, 2020; Perignat and Katz-Buonincontro, 2019). Therefore, further research and application of these teaching strategies, or the combination of active teaching strategies together, is necessary for the future.

CONCLUSION AND SUGGESTION

This study aims to investigate the effectiveness of a STEAM (Science, Technology, Engineering, Arts, Mathematics) -based curriculum on junior high school students' scientific creativity. The two core research questions are as follows: 1)What are the influences of STEAM-based courses on students' scientific creativity? 2) Which kind of sequence of course stage design is more effective to improve students' scientific creativity?

The main topic of the STEAM-based curriculum in this study is about an ancient mechanical clock that was designed and produced by the authors' team. Further, the main concept of the ancient mechanical clock is about a gear wheel. A counterbalance design was used in this study. The control group joined gear wheel science courses first and joined STEAM-based courses second. In contrast, before joining the gear wheel science courses, the experimental group first joined the STEAM-based courses.

Based on the data analysis, the results in this study show that the whole STEAM-base curriculum could improve junior high school students' scientific creativity, no matter which kind of sequence is used in the course stage design. Besides, the results support that the STEAM-based courses in this study could improve junior high school students' scientific creativity.

Although the results from ANCOVA analysis demonstrate that there are no significant differences between the control group and experimental group students' scientific creativity performances after joining the whole STEAM-based curriculum, the results in this study show that the students did not improve their scientific creativity after the gear wheel science courses but before STEAM-based courses. In other words, these students' scientific creativity has been induced in only one stage (STEAM-based courses stage). However, the students who joined STEAM-based courses first could improve their scientific creativity in both stage 1 (gear wheel science courses stage) and stage 2 (STEAM-based courses stage).

The results imply that the STEAM-based courses might help students maintain or continue their scientific creativity ability. This study suggests further research to diversify the contents of STEAM-based curriculums is not limited to using available kits but can encourage and require students to solve problems in study and life with their interdisciplinary knowledge and skills. Not only that, in addition to quantitative research, qualitative research through student feedback can also help better understand students' scientific creativity. Alternatively, lengthening the research time or delaying the posttest may also be considered.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the National Kaohsiung Normal University Human Ethic Committee. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin. Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

The first author HT organized the whole article and provide the research ideas. The second author C-FH analyzed the date and provide opinions about the data explanation. The third author J-FH re-organized and reviewed the whole article.

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Design My Music Instrument: A Project-Based Science, Technology, Engineering, Arts, and Mathematics Program on The Development of Creativity

Li Cheng[1,2], Meiling Wang[2], Yanru Chen[2], Weihua Niu[3], Mengfei Hong[4] and Yuhong Zhu[5]*

[1]Faculty of Education, Beijing Normal University, Beijing, China, [2]Developmental and Educational Research Center for Children's Creativity, FE, Beijing Normal University, Beijing, China, [3]Department of Psychology, Pace University, New York, NY, United States, [4]Hangzhou Caihe No.2 Primary School Education Group, Zhejiang, China, [5]Department of Physics, Hangzhou Normal University, Zhejiang, China

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Min-Hsien Lee,
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Hsu-Chan Kuo,
National Cheng Kung University,
Taiwan
Sílvio Manuel da Rocha Brito,
Instituto Politécnico de Tomar (IPT),
Portugal

***Correspondence:**
Weihua Niu
wniu@pace.edu

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Creativity is an essential factor in ensuring the sustainable development of a society. Improving students' creativity has gained much attention in education, especially in Science, Technology, Engineering, Arts, and Mathematics (STEAM) education. In a quasi-experimental design, this study examines the effectiveness of a project-based STEAM program on the development of creativity in Chinese elementary school science education. We selected two fourth-graders classes. One received a project-based STEAM program (the experimental group, $n = 33$), and the other received a conventional science teaching (the control group, $n = 33$) over 6 weeks. Students' creativity was assessed before and after the intervention using a multi-method approach, including a test of divergent thinking, a story completion through the Consensus Assessment Technique (CAT), a creative self-efficacy (CSE) measure, and a group-based creative project. Moreover, all students received a test of their science knowledge after the intervention. The results showed that compared with the control group, the creativity of the experimental group students improved significantly for 6 weeks at both individual and group level, even though their knowledge in science were comparable. This result confirmed the effectiveness of a project-based STEAM educational program improving elementary school students' creativity. Implications are discussed.

Keywords: STEAM curriculum, project-based learning, creativity, learning by doing, multi-method approach

INTRODUCTION

Creativity has become an increasingly important factor in ensuring the sustainable development of a society and is one of the essential skills in the 21st century. The definition of creativity has been evolved. Guilford (1950) referred to creativity as one of many aspects of intelligence and believed it included two thinking processes: divergent and convergent thinking. To Gilford, divergent thinking stimulates individuals to generate new ideas and make creative products novel. In contrast, convergent thinking is conducive to the individual's idea of adapting to the environment and increasing the applicability of new products. Later, Torrance (1963) proposed creativity as creative problem-solving, and creative thinking was viewed as a particular method or form to solve problems. Toward the end of the 20th century, there is a consensus to the definition of creativity among creativity researches that creativity is a person's ability to produce something that is deemed as novel and appropriate by experts of a field (Amabile, 1996; Csikszentmihalyi, 1997; Lubart, 1999; Kaufman and Beghetto, 2009).

Many theories have been proposed to explore the nature and contributing factors for creativity *via* different approaches, such as psychometric, cognitive, developmental, and social approaches. Most scholars took the confluence approach in which creativity is viewed as an ability to be influenced by multi-factors. Besides examining different elements that contribute to the development of creativity, some scholars focus on exploring creativity at different levels. Many scholars took a dichotomies view and concentrate on examining creativity at either eminent level, such as studying creative genius and their work (e.g., Simonton, 1994), or ordinary level such as everyday creativity (e.g., Torrance, 1969). These studies typically referred to creativity as Big-C or little-C (Richards, 1990; Kaufman and Beghetto, 2009). In advancing this approach, Kaufman and Beghetto (2009) proposed a new model, which they called the Four-C model of creativity. According to this model, creativity can be manifested in four different levels, namely, the Big-C, referring to the creative genius who brought a significant breakthrough in a field, the Pro-C, referring to the type of creativity that is important to an area but not at the level of a substantial breakthrough. The third level of creativity is called little-c, also referred to as everyday creativity; the type of creativity exhibited by ordinary people, yet the level of creativity is still needed to be recognized by experts in a given field. Lastly, there is a type of creativity that is only significant to individuals without fully been recognized by others. Kaufman and Beghetto called it mini-c.

Some scholars have suggested using a multi-method approach to capture creativity (Cropley, 2000). The multi-approach of studying creativity at a multilevel indicates that no single method can fully capture creativity. In other words, creativity has to be measured *via* a multi-method approach. The most common measurements to creativity include divergent thinking, such as the Torrance Test of Creative Thinking (TTCT), product-orientated measure *via* consensus assessment technique (CAT), various self-report measurements on creative personality, activities, thinking styles, and creative self-efficacy (CSE), as well as ratings from others, such as teachers, parents, experts, and peers. These methods measure the level of little-c and mini-c.

Another critical question in creativity is how to nurture creativity. It is especially important in education (Scott et al., 2004; Sannomiya and Yamaguchi, 2016). One approach to fostering creativity is by promoting intrinsic motivation (Amabile, 1988, 1996). Another approach is through innovative teaching (Baer, 1996). Many studies have been conducted to actively explore effective educational models to improve students' creative abilities. Among them, the approach of Science, Technology, Engineering, Arts, and Mathematics (STEAM) education provides a comprehensive and practical method to develop creativity and has gained worldwide popularity.

STEM and STEAM Education

Science, Technology, Engineering, and Mathematics (STEM) originated in the United States, emphasizing interdisciplinary integration of the above four disciplines to address real-life problems or projects. With the rapid development of STEM education, the call for increasing humanities and art education in society is getting stronger and stronger. In 2006, STEM added art and formed STEAM education, which emphasized the cultivation of all-around development people with creativity and innovation spirit for future inventors and creators (Connor et al., 2015). STEAM education emphasizes the essential role of individual students in learning to stimulate individual curiosity and effectively promote students to go deep into scientific inquiry.

Science, Technology, Engineering, Arts, and Mathematics education takes the student as the center and cultivates students' ability to solve problems and innovate. In the teaching process, teachers tell students how to do it and guide students to experience the process of solving practical problems and improve students' creativity level in exploration (Zhao and Lu, 2016).

There are four standard teaching methods in STEM or STEAM education: problem-based learning, inquiry-based learning, design-based learning, and project-based learning (PBL). Among them, the role of PBL in STEM/STEAM education has been widely concerned. PBL is an approach for students to construct knowledge through teamwork and problem-solving using various scientific methods (Krajcik et al., 1999). This approach pays special attention to students' awareness of "learning by doing." Mustafa et al. (2016) made a meta-analysis of STEM in the first decade of the 21st century. They found that PBL was the learning model with the most significant number of integrated STEM curriculum. The meta-analysis results also revealed that an integrative approach could be expanded for students' development in motivation, interest, achievement, performance, attitude, and perception if the integrated STEM is implemented at the school and higher education levels.

STEAM/STEM Education and Creativity

Many studies have examined the relationship between STEAM/STEM education and creativity and found a positive association between the two using elementary school to college participants. Some studies focused on STEM-related learning in higher education and examined how STEAM/STEM education influences creativity in higher education. For example, Kuo et al. (2018) applied a STEM Interdisciplinary PBL approach to teaching 45 university students to develop a human-computer interaction (HCI) system to solve real-world problems.

Several studies explored how STEM education could affect student creativity before college. For example, using a single group pre-and post-test design, Lou et al. (2017) examined how a STEM-PBL teaching program affects creativity among ninth graders. Their results supported the program's effectiveness in promoting students' creative personalities, such as adventurousness, curiosity, imagination, and accepting challenges.

Similarly, Ozkan and Topsakal (2021) conducted a quasi-experiment to compare two different teaching approaches on students' learning outcomes. In one session, two seventh-grade classes learned about the concept of "power" in physics. The instructor did not directly teach the idea in the experimental class and asked the students to brainstorm possible solutions. The role the teacher played in the experimental class was scaffolding and facilitator. Students were encouraged to study the phenomenon and came up with their answers. The results demonstrated compared to the control class, students from the STEAM class showed a significant improvement in their creative thinking, measured *via* both verbal and nonverbal forms of the TTCT. In comparison, the teacher in the control class taught the concept directly following the traditional model. Students from the control class were recipients of knowledge rather than explorers of problems.

Some studies conducted direct observation and interviews with students and teachers to examine the benefit of STAEM education on creativity. For example, He et al. (2019) studied how a STAEM teaching model positively influenced middle school students' creativity. Unlike previous studies, students in this study were asked to make an art project, pottery, through self-exploration and teacher's scaffolding. In addition, to have experts evaluate students' creative products, teachers were also interviewed and asked to assess students' creations in originality and appropriateness.

Case studies provide more in-depth information about how and why STEAM education is beneficial to students' creativity. In a quasi-experiment, Hathcock et al. (2015) randomly assigned eight ninth-graders into two groups: the treatment and control groups. They asked them to design a buoy that could hold as many golf balls as possible using any materials provided. The teacher adopted an inquiry-based approach in the treatment group, asking questions about their buoys to encourage students to think and discuss more ideas with their partners and peers. In the control group, students were given strategies to solve the program. The study found that students from the experimental group outperformed on measures of creativity than those from the control group. They also interviewed their teachers and concluded that teachers' guidance and encouragement play a vital role. Teachers' guidance and support can effectively facilitate students' creativity than simply asking students to self-explore ways to form innovative products. Moreover, a cooperative learning model also promotes communication among students, thus promoting the solution of problems. Both teachers' support and students' cooperation are essential elements of STEAM and STEM education.

Science, Technology, Engineering, Arts, and Mathematics education at the elementary school level also effectively promotes students' learning outcomes, including creativity. For example, Oh et al. (2013) developed a STEAM Education Program in a sixth grades science class and tested its influence on students' creativity. This study adopted a Scratch-based STEAM education program for an experimental class of Korean students, whereas students from the control class adopted the traditional learning method. They found that Scratch-based STEAM education had a positive effect on the improvement of creativity.

Siew and Ambo (2018) had two classes of fifth-grade students, one received PBL-STEM learning, and the other received a conventional teaching format. The only difference between the two classes is that the experimental class encouraged students to self-explore but used a more traditional approach. They used the Scientific Creativity Test (SCT) to assess scientific creativity. The results show that the students' creativity in the experimental group has been improved more than those from the control group.

To sum up, cumulative evidence has demonstrated a positive influence of STEAM/STEM education on creativity. We want to highlight three essential elements in these educational programs: cooperative learning among students, teacher guidance and support, and PBL. We also observed some limitations of these studies. First, the measurement for creativity was primarily based on a narrow definition of divergent thinking, and as a result, scores on TTCT were the only indicator for creativity. As discussed earlier, creativity is a multilevel and multi-facet concept, one measurement cannot fully capture the essence of creativity. Second, although STEAM/STEM education adopted an integrated approach across different subject areas, most studies focused on just one or two subject areas, such as technology or science. Third, many studies adopted a single-group pre/post experimental design and did not have a control group, which cannot rule out the influence of many confounding variables. Lastly, we noticed that some studies have adopted the PBL approach and have students completed a final project as part of the learning curriculum. Unfortunately, the final product was rarely used as an indicator of creativity. We believe the final projects often involved creative thinking and should be assessed to examine creativity.

Current Investigation

Based on the results of previous studies, we propose a new PBL study, in which we integrated five subject areas of STEAM *via* a fourth-grade science class. The five subject areas include science, technology, engineering, art, and mathematics.

The purpose of this study is to compare a new PBL STEAM educational program to a conventional science educational program to see the effectiveness of their learning outcome. We also compared their creativity at both individual and team levels. We took a multi-method approach to assess students' creativity, including an assessment of divergent thinking, a project-orientated measure *via* the CAT, and a measurement of CSE. Additionally, we assess students' creativity at the group level by having experts evaluate the final group product.

We chose two classes and randomly selected one as the experimental group and the other as the control group. The two classes are comparable in their academic preparation. We started the study at the beginning of a fall semester, which they began a new unit in a science class. The same instructor taught the two groups at the same time, with the same objective. Additionally, we gave the two groups the same creativity measures before and after the intervention. The only difference between the two groups is the teaching approach, detailed in the Materials and Methods section.

There are two major hypotheses. First, we hypothesize a multi-approach measurement of creativity can effectively capture creativity; therefore, there is a consistency among all measurements of creativity. The scores on these measurements positively correlated to each other. Second, we hypothesize that students from the experimental group improve more than those from the control group on creativity after the intervention.

MATERIALS AND METHODS

Participants

Participants were 68 fourth graders (40 male, 28 female) from two natural classes in a southern city, China. The two classes were comparable in terms of student academic preparation and students' performance in science education. Among the 68 participants, two students did not complete the measurement of creativity and were excluded from the sample. For 6 weeks, one of the two classes was randomly selected as the experimental group ($n = 33$, 12 female) to receive a PBL STEAM program. In contrast, the other class was selected as the control group ($n = 33$, 14 female), in which students received a traditional science class at the same time. A female science teacher served as the instructor for both classes.

Measurements

All students received creativity measurements before and after the 6-week classes. During the intervention, students worked in groups of four members to produce a musical instrument, which was rated twice by experts for creativity, one at an earlier design and the other when the product is completed In addition, they also completed a test on scientific achievement after the intervention. The measurements include the following.

Creativity Measurements

We used a multi-method approach to examine student creativity dynamically at both individual and team levels. It includes a test of divergent thinking, a story completion using the consensus assessment technology, and a self-report on self-efficacy. In addition, we asked the students from the two classes to complete a creative product in teams. Details for each assessment are introduced as the following:

Test of Divergent Thinking

Based on Guilford's divergent thinking theory, the test asked participants to generate as many unusual uses for an ordinary object as possible such as "paperclip" (in pre-test) and "match" (in post-test) as contents of tests. We only calculate the fluency score on this task, the number of different ideas a person generated in a specific time. Two graduate students counted independently, and their agreement was above 0.90.

Story Completion

We gave students a word prompt and asked students to complete a story based on a prompt word, which was "keyhole" (in the pre-test) or "robot" (in the post-test). Using postgraduate students to serve as expert judges for creativity has been used extensively in creativity literature (Kaufman et al., 2008). Using the CAT (Amabile, 1982), three graduate students with at least 1 year of experience studying creativity served as expert judges. They each independently rated all stories based on their subjective criteria, providing a rating on originality, using a seven-point scale, with a "1" representing least original and "7" representing most original. The inter-rater reliability of the experts was above 0.85. We calculated the average scores of the three experts' ratings to represent a student's originality on this task.

The Idea Evaluation Self-Efficacy Measure

It was developed by Steele et al. (2018) to measure CSE by having participants rate the level of confidence toward their abilities to evaluate new ideas using a five-point Likert scale. A sample item is, "When evaluating new ideas, I can quickly and accurately determine if it will be successful." The survey has established an acceptable internal consistency ($\alpha = 0.76$).

Creative Products

Throughout the 6-week intervention, students worked in groups of four members and were asked to create a blueprint for a musical instrument, construct the instrument, and then perform a piece of music using the instrument. Two specific creative products were evaluated: the blueprint and the performance of the musical instrument (a video clip). Similar to the procedure for assessing the story completion tasks, we invited three graduate students to independently rate the products on originality and appropriateness. They were asked to use a seven-point scale, with a "1" representing least original (or appropriate) and "7" representing most original (or appropriate). Each group of participants obtained two originality and two appropriateness scores, one for the blueprint, and the other for the final product. The inter-rater reliability of the three experts was above 0.80. We calculated the average scores of the three judges to represent originality and appropriateness scores at the team level.

Scientific Achievement Test

Under the current educational environment in China, many teachers are hesitant to carry out STEAM education because they are worried that STEAM education will negatively affect students' learning and academic achievements. To investigate whether STEAM education will affect students' academic achievements, we also require all students to complete the scientific achievement test in the school district.

Experimental Design, Curriculum, and Teaching Approach

The study adopted a quasi-experiment with a pre-test/post-test. There were two groups, the experimental group, and the control group. The same teacher taught the two groups based on the same science curriculum in Zhejiang Province. Students from the two groups had the same learning objective: understanding the sciences of music and sound. In 6 weeks, students learned about different subject areas relating to music and sound. These areas are (1) physics, learning about the mechanism of vibration and sound waves; (2) engineering, understanding how to construct objects with different pitches of sound; (3) mathematics, measuring in pitch, volume, tempo, and rhythm; (4) music, appreciating tunes, pitches, tempo, and rhythm; and (5) art, drawing a design for an instrument. As a part of the class evaluation, students worked in groups to design and construct a musical instrument, which they would play at the end of the study unit.

The two groups differed in teaching approaches. In the experimental group, the teacher adopted a PBL based STEAM program. Using an interdisciplinary approach, the teacher taught the knowledge of the five subjective areas in an integrated fashion, assisting students to complete a music instrument. Therefore, the course was project-based and student-orientated. Students were asked to work in groups to engage in hands-on learning from the beginning to design and construct a musical instrument. They were encouraged to self-explore and problems-solve using various knowledge (i.e., science, technology, engineering, arts, and mathematics).

On the contrary, the teacher used a conventional teaching approach to teach the same content in the control group. Different from the experimental class, the teacher adopted the traditional science teaching approach when delivering the same content across five different subject areas to the control class. The primary teaching mode was lecturing, and only toward the end did the teacher ask students working in groups to incorporate the knowledge learned in previous lectures to make a musical instrument.

The Curriculum of Experimental Group

In the experimental group, students received a project-based STEAM program to create a ukulele. Students were asked to integrate knowledge from different subject areas in STEAM and work to produce their creative products.

The program included six different sessions based on the principle contents of the Chinese national standard of science education. The teaching objective was to make a ukulele and to play a piece of music. There are five objectives in learning about science, technology, engineering, arts, and mathematics. The scientific aim is to have students understand the sound principle, recognize a ukulele's vocal principle, and observe, compare, and analyze the ukuleles made of different materials. The technical goals are using networks to collect useful information, using various tools to make the Ukulele, designing the Ukulele according to requirements, and drawing a diagram to make it visible and operable. The engineered objectives are selecting appropriate materials to make a ukulele, producing a ukulele according to blueprint, testing, and adjusting during and after the production process, and evaluating others' designed products, and making suggestions. The art objectives are to design and decorate the Ukulele. The mathematical objectives are calculating the project cost and measuring the length of the string accurately. Each subject has specific objectives for students, while all program sessions focus on reaching the final goal: to make ukuleles as groups and play them. The program includes six sessions, which are described below.

Session 1 involved an introduction of the Ukulele, knowing the history, structure of the Ukulele, and learning about the vocal principle of the Ukulele. Moreover, the students were asked to disassemble the Ukulele to understand the system and principles of the Ukulele and comparing different materials to choose the most suitable one as the strings. And create a real scene for them, telling them that they need to design and make Ukulele for the factory.

In Session 2, students were to design a ukulele and draw the blueprint through group cooperation. Session 3 allowed students to have opportunities to make the Ukulele according to the schematic diagram. Through discussion, the teacher leads students to think about the possible problems through the making process.

In Session 4, students were to decorate the Ukulele. The teacher and members of the groups can evaluate the quality of the products and team cooperation through the program.

In Session 5, students made a four-string ukulele in groups and marked the syllables. After that, they were asked to play the Ukulele they made and discuss the advantages and disadvantages of the products and make progress in them.

Students' products, including blueprints and performance of musical instruments, were collected to evaluate students' creativity during the STEAM program. In Session 6, students indicate the price of the product and explain the product. After that, both the teacher and students evaluate the creative product and assess the participating situation throughout the whole project. Teachers also presented a review of all lessons and asked students to make improvements to their Ukulele.

The Curriculum of Control Group

In the control group, students received regular science classes with objectives on mastering sound and core concepts and were evaluated by homework, class performance, and tests.

The teacher used a standardized textbook as the primary resource for the science class. The class also includes six sessions.

In Session 1, students were asked to describe the sound around them and introduce the principle of making sounds. In Session 2, the teacher using different materials to help students understand how the sound travels. Session 3 allowed students to know about the auditory sense through models. In Sessions 4 and 5, students learned about the relationship between amplitude and loudness, the vibration frequency, and sound level separately. In Session 6, students were asked to make instruments in groups.

Intervention Process

Before conducting the study, we obtained approval from an ethical review committee at the host university in Beijing and a letter from the collaborative school (a public school in southern China) to meet the ethnic standard. The school has allowed the intervention program to integrate into the existing academic curricula as a part of their educational reform in science education. Both students and their parents received a welcome letter explaining the purpose and procedure of the study. Parents' consent and student assent were obtained.

The study took place in 8 weeks in the fall semester of 2020. The first and the last week were to assess students' outcomes. The 6 weeks in the middle were used for intervention, in which students received a 45-min class each week. A female teacher with a bachelor's degree in science education and 2 years of science teaching experience taught both groups. Details of the program and different teaching approaches are listed in **Table 1**.

Compared with the control group, the experimental group has the following characteristics: Firstly, emphasis on multidisciplinary integration, requiring students to apply knowledge to solve problems interdisciplinary; Secondly, teachers have adopted the PBL teaching method, highlighting the concept of "learning by doing" in the teaching process, guiding students to explore with the goal of product production, and giving appropriate support to students when exploring; Thirdly, students solve problems through group cooperation in each lesson. However, the control group did not emphasize subject integration; teachers did not adopt the PBL teaching method; students learn scientific knowledge in the first five sessions and were asked to work together to produce a product in the last session.

RESULTS

Creativity Across Different Measurements

We adopted a Pearson correlation analysis to examine the first hypothesis regarding the consistency across all three measurements for individual creativity: the divergent thinking task, the story completion task, and the CSE measurement. The results showed that all three individual creativity scores (fluency, originality, and CSE) are moderately correlated (*r*s are 0.47, 0.22, and 0.13, respectively). Principle Analysis supported a one-factor model, explaining 52.65% of the total variance. All three variables loaded on the factor at above 0.5, suggesting although the three measurements may capture different aspects of creativity, they are also consistent in capturing one principal component.

The Impact of Teaching Methods on Creativity

Domain-Specific Knowledge Through Test of Academic Achievement

The school district provides academic tests for all students who participate in new knowledge about "sound" 6 weeks. An independent-sample *t*-test was applied to examine the difference between the two groups on their academic achievement. The results showed no difference between the two groups ($t = -1.16$, $p > 0.05$).

These results reflect the fact that students from both groups have accomplished the unit objective in the fourth-grade science education, which is to understand the science of music and sound.

Impact of STEAM Education on Individual Creativity

Figure 1 showed that after a 6-week intervention, students from the experimental group improved significantly on overall ratings of creativity across different tasks (fluency score on

TABLE 1 | Main contents of sessions in the experimental group and the control group.

Sessions	Contents		Subjects	
	Experimental	Control	Experimental	Control
Pre-test	Divergent thinking, story completion, and self-efficacy			
Session1	Sound creation, Sound perception, and Instruments	Sound creation and Sound perception,	Sciences Art	Sciences
Session2	Instrument design	Transmission of sound	Sciences, Technology Engineering Art	Sciences
Session3	Material selection, Instrument creation	know about the auditory sense through models	Sciences, Technology Engineering Art Mathematics	Sciences
Session4	Sound volume, Sound pitch, and instrument-music modification	relationship between amplitude and loudness, the vibration frequency, and sound level separately	Sciences, Technology Engineering	Sciences
Session5	Instrument and Sound instrument play		Sciences and Engineering	
Session6	Instrument appearance, Instrument price, and Instrument's instruction	Instrument's creation	Sciences, Technology Engineering Art Mathematics	Sciences Technology Engineering Art Mathematics
Post-test	Divergent thinking, story completion, and self-efficacy			

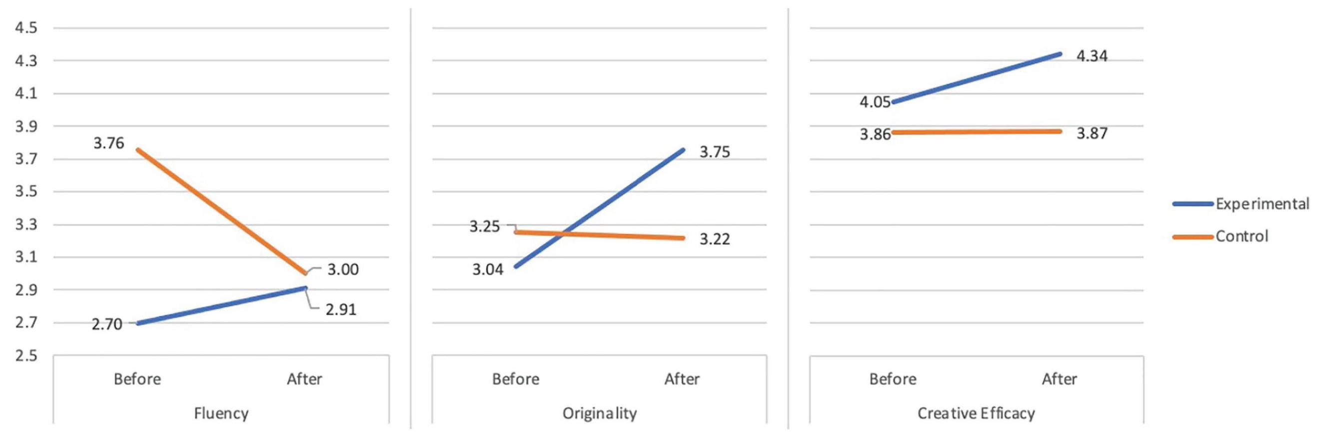

FIGURE 1 | The improvement of individual creativity in the experimental group and the control group.

divergent thinking test, originality score on story completion, and CSE). In contrast, the control group showed no improvement.

To examine the effectiveness of the STEAM program in the improvement of students' creativity, a 2 (Group: Experimental vs. Control) × 3 (creativity: fluency, originality, and CSE) × 2 (time: before vs. after) mixed design ANCOVA was conducted with "group" as a between-subject variable, and "creativity" and "time" as within-subject variables, and the academic achievement as covariate variable.

The results showed a marginally significant interaction between time and group [$F_{(1,64)} = 3.286$, $p = 0.075$, $\eta_p^2 = 0.050$]; this result supported the second hypothesis that students from the experimental group improved more on creativity than those from the control group (**Table 2**).

TABLE 2 | The statistical results of ANCOVA.

Variables	*df*	*MSE*	*F*	*p*	η_p^2
Group	1	0.093	0.015	0.902	0.000
Time	1	0.842	0.277	0.601	0.004
Time × Group	1	10.009	3.286⁺	0.075	0.050
Academic Achievement	1	15.385	15.385	0.119	0.038

⁺*p* < 0.1.

Impact of STEAM Education on Creative Projects (Team-Level)

To examine the effects of the intervention on team-level creativity over intervention, we conducted two multilevel nested model analyses, one for each of the two difference scores, namely, the difference between blueprints and final products on team originality and team appropriateness. For each analysis, two independent variables were selected, which were (1) changes in individual originality (i.e., differences in expert ratings on story completion between pre-and post-test) and (2) group (i.e., experimental vs. control). The results showed a significant main effect for the group on team originality ($t = 3.573$, $p < 0.05$), which indicated that the experimental group improved (mean difference = 0.99) more than the control group (mean difference = −1.29). Moreover, we also found a significant main effect for time ($t = -2.306$, $p < 0.05$). The changes of individual originality from time 1 (mean = 3.04, *SD* = 0.89) to time 2 (mean = 3.75, *SD* = 1.25) from the experiment group had a significant impact on team originality; however, no such effect was found in the control group.

The results support our second major hypothesis, which states that students from the experimental group improved more than those from the control group on creativity after the intervention.

Figures 2, 3 further illustrate the difference between the two groups in terms of blueprint and final product (the performance of the musical instrument).

From the above figures, the differences in blueprints between the two groups may not be noticeable in terms of originality (see **Figures 3A,B**). However, the final products from the experimental group showed more novelty in both material selection and production delivery (**Figure 3C**) than those from the control group (**Figure 3D**). We should also mention that we recorded students' performance and found that the quality of the sound generated by the instruments from the experiment group closely resembled the actual instrument than those from the control group.

Two primary reasons might be attributable to the overall advanced performance on creativity from the experimental group than the control group. First, when teaching the experimental group, the teacher consciously applied an interdisciplinary approach and encouraged students to use the approach to solve problems. This approach allowed students to think holistically and engaged in more divergent thinking. In contrast, when teaching in the control group, the teacher primarily adopted a dedicative approach to delivering basic knowledge of the science of music and sound. As a result, she provided students with less opportunity to self-explore.

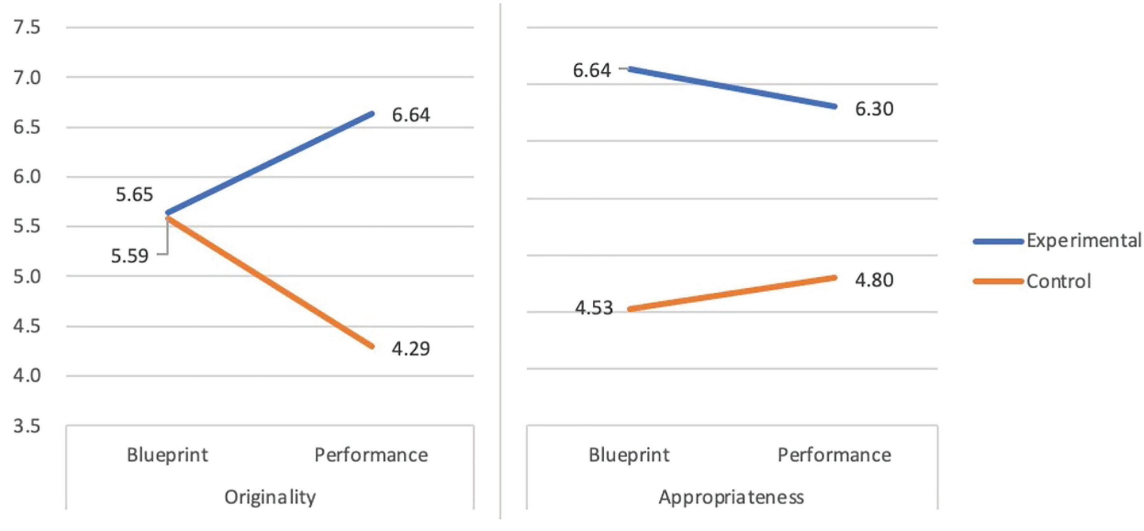

FIGURE 2 | The improvement of team-level creativity in the experimental group and the control group.

Second, by using the PBL approach, students from the experimental group were involved in more hands-on activities than the control group. The learning objective of creating a musical instrument was made clear from the very beginning. In contrast, students from the control group spent a significant amount of time learning knowledge in different disciplines related to the production of the instrument. Yet, they only engaged in a hands-on learning experience toward the end of the unit study. As a result, students from the experimental group seemed to have a higher level of intrinsic motivation, which might lead to more original products than the control group.

DISCUSSION

In this study, we used a quasi-experimental pre-test/post-test design to explore the effectiveness of a project-based STEAM program in improving student creativity. After a 6-week intervention, we measured the creativity level of the two groups of students by various methods to compare the effects of two different teaching methods. We found that diversified creativity measurement methods measure students' creativity effectively. Students in the experimental group who received the PBL STEAM program improved creativity at both individual and team levels.

One significant feature of this study is to use a multi-method to measure students' creativity. Compared with previous studies, we measure students' creativity at the individual level and reflect students' creativity at two levels: the little-c and the mini-c. At the same time, Pearson correlation results show that all the scores for measuring individual creativity are positively correlated. And they can be loaded in one factor. That is to say, all the measures of creativity used in this study are consistent. This verifies our first hypothesis (A multi-approach measurement to creativity can effectively capture creativity; therefore, there is a consistency among all measurements of creativity. The scores on these measurements positively correlated to each other). In addition, we also test whether there is consistency among the various introductions of creativity. Our research measures and analyzes creativity from different angles and levels, avoiding the one-sidedness of a one-dimensional test and making our results more convincing.

Our results showed no difference between the two groups in tests of science achievement. Such a result reflects that students from both groups have the same level of mastery in understanding the science of music and sound. It is important to note that although students from the experimental group spent less time learning specific topics in science education than the control group, they gained more time on hands-on experience, which may help them gain a deeper understanding of the concept. More importantly, through PBL, students from the experimental group may have a higher level of intrinsic motivation toward the science, and as a consequence, enhance their STEAM-related creativity. These results demonstrate the primary benefit of STEAM education on student learning outcomes may not depend on their academic achievement but creativity.

The fact that the creativity level of the experimental group is higher than that of the control group at both the individual level and the group level verifies our second hypothesis, which states that students from the experimental group improved more than those from the control group creativity after the intervention. Our results are consistent with the research results of Oh et al. (2013); Siew and Ambo (2018); and He et al. (2019).

One unique feature of this study is to measure team creativity in addition to individual creativity. Our results regarding the significant improvement in team creativity from the experimental group provided additional evidence to the benefit of PBL based STEAM education in improving both

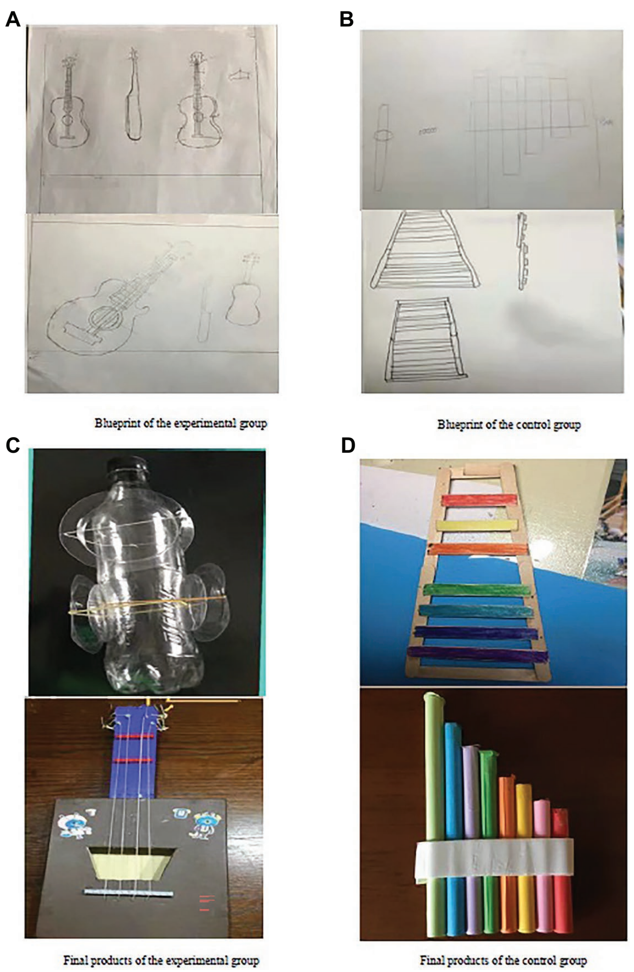

FIGURE 3 | Creative products (blueprint and the pictures of final products) from the experimental group and the control group.

individual and team creativity while ensuring the quality of knowledge learning. We suspected that the improvement of the creativity level of the experimental group might be due to the following reasons.

First, the teacher in the experimental condition adopted a multi-discipline and integrated approach to teaching science. In the teaching process, the teacher encouraged students to integrate knowledge across different disciplines to solve practical problems. Interdisciplinary or interdisciplinary knowledge can often provide learners with a variety of problem-solving methods, broaden their thinking, and enable individuals to break through the stereotype caused by specific domain knowledge and solve problems creatively. This transcendence reflects the originality, fluency, and flexibility of thinking (Zhang and Gu, 2004). However, in the control condition, the teacher used a more conventional approach, in which students learn different units of science sequentially. For example, unlike teaching in the control condition, the teacher integrated different subjective goals in the experimental condition, that every session included different goals from STEAM subjects. For example, in Session 2, students from the experimental group were asked to work designing a ukulele and drawing a blueprint that later is completed. The creation process of a ukulele involves the knowledge of science, technology, engineering, and arts. With direct guidance from the teacher, students were reinforced with the concept of integration of various disciplines.

The second reason to explain why having the 6-week intervention can be effective, using the PBL teaching method; students were clear what the end product would be. Students were consistently reinforced to use multidisciplinary knowledge to solve the problems, with a great emphasis on "learning by doing." This feature allowed students to have more chances to take self-explored learning. This stimulated students' interest and promoted their intrinsic motivation, subsequently encouraging students' creativity (Kuo et al., 2018). For example, students in the experimental group were more eager to express their ideas and raised their hands to answer the questions more often. And in the process of inquiry, students have been given more specific guidance from the instructor. For example, in making a Ukulele, if students encounter difficulties and cannot make musical instruments sound, teachers will lead and encourage students to find out the problems and provide some ideas to solve them. Therefore, with teachers' help and encouragement, students were able to work more effectively and creatively in creating the music instrument throughout the invention process. This result supports a claim that explicit motivation can also facilitate Chinese students' creativity (Kaufman and Niu, 2012). It is also consistent with findings from a previous study in which Chinese students produce more creative products under a more elaborated instruction on how to be creative than a mere encouragement of creative expression and a control condition without mentioning creativity (Niu and Liu, 2009).

Lastly, students in the experimental condition also began working in groups of four from the first week of intervention to brainstorm ideas and collaborate in learning, which allowed more collaboration among the team members. In contrast, students in the control condition learned various contents by listening to teachers' lectures and demonstrations. Although students from the control group also had an opportunity to form a group and complete the same assignment as their counterparts in the experimental group, the group formation took place in Session 6 of the intervention in the control condition, rather than in all sessions in the experimental condition. Through the interaction among group members, students in the experimental group were allowed to exchange their ideas and communicate to gain deeper learning, which positively impacted their creativity. The previous research also showed that through the cooperation of different subjects, students' creativity could be improved after the STEAM program (Siew and Ambo, 2018), which is consistent with our study.

LIMITATION AND FUTURE RESEARCH

The study has some limitations. The first one is the task itself. Students only engage in one project during the intervention period: the design and creation of a musical instrument. Future studies should design STEAM programs that allowed students to create different instruments and implement them to examine the effect. The second limitation is the presence of the experimenter effect. We invited one teacher to teach both experimental and control groups. Although the instructor realized a comparison between the two groups, the instructor tried to exhibit the same level of enthusiasm. She may unconsciously bring her own bias into the study. Because of the easy implementation, the teacher used Ukulele as an example. Future research should recruit two teachers with comparable teaching experience and styles to implement STEAM programs and groups.

This study offers two important implications. First, our study demonstrates that using a multi-method approach to measuring creativity is a better way to capture student creativity in a broad sense. This can also help educators see the level of changes in creativity throughout the intervention to be more aware of creativity as an essential learning outcome. Second, an important observation from this study is that a PBL based education not only can have a direct benefit to students, but it may also have a direct impact on teachers. Educators are more willing to encourage students to think divergently and express themselves more, positively influencing student creativity. Previous studies have shown that creativity is not a trait that educators are particularly interested in promoting (Zhang, 2009). We believe the STEAM program like the one described in this study will long-term impact students' learning outcomes, especially promoting their creativity.

CONCLUSION

In conclusion, this study contributes to creative research by using a multi-method approach to measure creativity. It also demonstrates that a PBL and an integrative, multidisciplinary approach in science education can improve students' creativity, which provides practical insights in promoting creativity in education in general.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by The Research Ethics Review Board at Beijing Normal University (ethical review number BNU202106100010). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

All authors contributed to the study. LC and WN: conceptualization, design, and methodology. LC, WN, MH, and YZ: formal analysis and experimental operation. MW and YC: writing – original draft preparation. LC and WN: writing – review and editing. LC: funding acquisition. LC and YZ: resources. LC and WN: supervision. All authors contributed to the article and approved the submitted version.

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ORIGINAL RESEARCH
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Teaching Reform to the Biology Major During the COVID-19 Pandemic: A Study of the Method of Teaching Industrial Innovation and Entrepreneurial Talents

*Zhe Liu[1,2], Jingwei Wang[1], Zhiming Liang[1], Hongbo An[1], Liyang Li[1], Zhongjing Zang[1], Jing Li[1], Yang Xi[3], Tong Han[1], Shaobin Liu[1] and Cheng-Hao Jin[1,2,4]**

[1]College of Life Sciences and Biotechnology, Heilongjiang Bayi Agricultural University, Daqing, China, [2]National Coarse Cereals Engineering Research Center, Daqing, China, [3]College of Science, Heilongjiang Bayi Agricultural University, Daqing, China, [4]Department of Food Science and Engineering, College of Food Science and Technology, Heilongjiang Bayi Agricultural University, Daqing, China

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Weihua Niu,
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***Correspondence:**
Cheng-Hao Jin
jinchenghao3727@qq.com

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The biology major has developed rapidly in recent years. Biology is a science that penetrates every aspect of human life and is one of the core majors in most agricultural colleges and universities. However, many teachers lack practical experience in the subject. To overcome this problem, in recent years, we have been trying to introduce new reforms into our teaching. This article provides some insight into the way that biology majors have been reformed, which will help educators in agricultural colleges and universities. At present, teachers implement the "Industrial Innovation and Entrepreneurship Talent Cultivation" (IIETC) model, but it is not clear whether this helps biology majors to master the course and improve their practical skills. In this study, the IIETC model is outlined, and the academic achievement and satisfaction of students taught under the IIETC model are assessed. A *T*-test is used to examine potential differences between IIETC and traditional teaching models. In-depth interviews and questionnaires were given to two groups of students who followed different teaching models as part of an exploratory study. The aim was to explore how effective IIETC is at helping biology majors master the course and improve students' wellbeing. Our results show that compared with traditional teaching methods, the IIETC model has a significant positive impact on the academic performance and happiness of biology students. Students trained under the IIETC model were more active and scored more highly in their final exams. They were more likely to feel that they had achieved success and happiness through the course ($P = 0.03$). The outcomes of this research reveal a novel teaching reform that improved students' enthusiasm for innovation and entrepreneurship during the ongoing COVID-19 pandemic. The effects are very encouraging and deserve further exploration and expansion in future work.

Keywords: innovation, entrepreneurship, training, biology major, cultivating talents

INTRODUCTION

Under the background of the COVID-19 pandemic, the endowing status of biology talents by employers has put forward a severe test for the employment of biology college students who are about to graduate. Facing the stressful employment situation, more and more college students realize that only with innovative ideas and entrepreneurial thinking can they be competitive in the increasingly fierce competition and rapidly changing world (Katper et al., 2020; Afshan et al., 2021; Liu et al., 2021; Tunio et al., 2021a,c). To improve the quality of teaching during the COVID-19 pandemic, teachers have implemented the "Industrial Innovation and Entrepreneurship Talent Cultivation" (IIETC) teaching method. Industrial innovation and entrepreneurship are reflected through cooperation between schools and enterprises (Hu et al., 2021). Students have two mentors: one is a teacher in school, and the other is in an enterprise. Entrepreneurship education has advantages for cultivating talents and developing practical skills (Fan, 2021).

Entrepreneurship education began in 1947 when Myles Mace offered the course "start-up business management" for MBA students of Harvard Business School. This course is considered to be the starting point of entrepreneurship education (Liu et al., 2021). Entrepreneurship education is to train students' entrepreneurial spirit, to train students from job seekers to job creators, to provide jobs, and create jobs (Liu et al., 2021). Our teachers provide entrepreneurship education for students majoring in biology and take responsibility for their practical skills (Chen et al., 2020). In recent years, teachers have faced increasing pressure to devise teaching methods that include modern educational innovations alongside core scientific knowledge, helping students to meet the expectations of employers and other stakeholders (Guimarães et al., 2017). In the mid-1990s, there was a gradual international movement toward dual eligibility, but this has slowed or stopped in the past decade (Khalil et al., 2018). China's recent strategic guidance proposes to encourage undergraduate universities to become more focused on practical training. There are a lot of problems with how biology is taught. As a lot of enterprises' data is confidential, it is difficult for teachers to obtain real and useful business case studies. Most teachers completely rely on courseware, teaching means and methods are single, unable to vividly interpret the nature of biology major.

Given the opportunities for educational development provided by COVID-19, teachers should adopt the IIETC model (Galindo-Martín et al., 2021; Ratten and Jones, 2021). The COVID-19 outbreak has forced students to stay in their hometowns instead of going back to school or to take online classes while schools are closed. The pandemic has transformed traditional offline education into online education (Dzara et al., 2019; An and Xu, 2021; Krouska et al., 2021; Troussas et al., 2021). IIETT teaching is part of the plan for education reform for students of a certain characteristics of the times. Our teaching methods are both online and offline, combining theory with practical experience of business (Geng et al., 2021; Hu et al., 2021). Teachers should strategically use the Internet and mobile devices to organize students, manage resources, and carry out tasks (Kanetaki et al., 2021; Yao et al., 2021). The outbreak of COVID-19 has forced teachers to switch freely between online and offline teaching methods. With the help of platform resources such as XuetangX provided by Tsinghua University and Superstar Learning, multiple teaching evaluation systems have been innovated and reformed (Ma et al., 2020; McCullough et al., 2020). In terms of content, teachers must make timely adjustments to their teaching methods in accordance with the latest industry trends (Tunio et al., 2021b). They must constantly update their content and teaching methods according to the market demand for relevant content and learning technologies. Once the risk of an outbreak in a particular region lowers from high or medium to no risk, students can enter enterprises and receive practical training from the mentors in the enterprise.

Corporate mentors, who are different from students' tutors for their senior thesis, provide one-to-one mentoring for students. Graduates then rotate between different companies and attend standard training sessions. School teachers provide theoretical guidance on technical and research issues. Corporate mentors do the same, but they take a personal interest in the mentees' professional (and sometimes even their personal) development (Li et al., 2020). Meanwhile, teachers can actively contact outstanding experts in relevant industries, who are the technical backbone of certain companies. They can invite these masters, who have rich practical experience, to enter the school and provide practical guidance. They can help students to solve the problems they encounter in actual workplace scenarios.

Moreover, curricular innovations require that attention is also paid to topics like the formation of professional identity, professionalism, and commitment to social accountability (Rogan and Anderson, 2011). Since experimental learning through practice is not ideal, students do not like to think. This means that there will inevitably be reforms to teaching models. The practical training provided by IIETC has offers a mature and effective model for innovation and transformation that has been very successful. This study was inspired by the expanding of innovation and entrepreneurship education during the COVID-19 pandemic. Since the implementation of the IIETC model, the relevance and effectiveness of teaching have been significantly improved, and the appeal of teaching has increased. The satisfaction rate of students majoring in biology has been rising year on year, as shown in **Figure 1**.

Autonomy and independence have always been core parts of student entrepreneurship (Rouleau et al., 2019). Therefore, we have established a set of practical teaching systems that cover a variety of technologies. In practice, we are constantly developing new, personalized courses. Also, we have set up a cloud classroom teaching platform. Online and offline teaching methods complement each other (Kang and Kim, 2021). We came up with the following hypothesis: if schools engaged in national practical education increase along with the growth of biopharmaceutical companies (and the sustainable development of biopharmaceutical companies is crucial), then the system can help schools to cope with future pandemics. We are currently assessing the IIETC model to check whether it allows biology majors to master their courses. We are trying to understand what the impact of improving practical

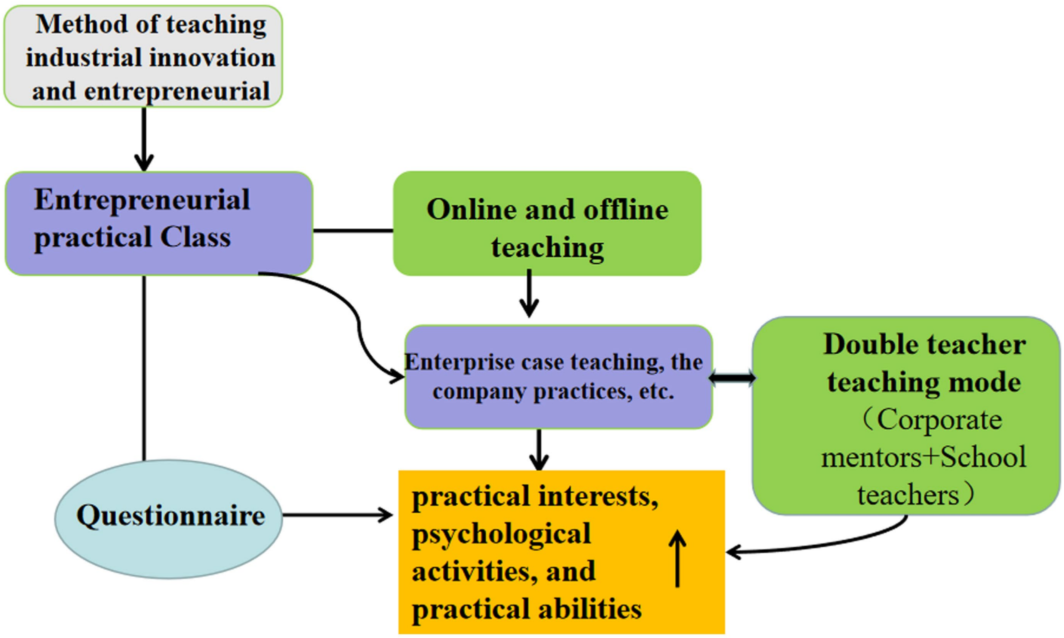

FIGURE 1 | The relationship between the entrepreneurial interest of biology major students in and college teaching.

ability is. Therefore, this study evaluates students' academic performance and satisfaction under the IIETC model.

MATERIALS AND METHODS

Sample of Students

In China, most students at the College of Life Sciences study professional course in their third year. The baseline pairs before the study were IIETC and traditional teaching type (TTT) students from Heilongjiang Bayi Agricultural University, as shown in **Table 1**.

A total of 432 students from these two groups were divided based on the two teaching methods and whether they had completed their final exams at the end of 2021. There was no statistically significant difference between the two groups when it came to other course-related variables, such as admission scores in English and pre-study courses ($p > 0.05$).

TABLE 1 | Baseline comparison before the study.

Variables	IIETC	TTT	*P*-Value
Admit a mark	medium	medium	>0.05
English achievement	medium	medium	>0.05
Academic performance before the study	good	good	>0.05

IIETC, Industrial Innovation and Entrepreneurship Talent Cultivation; TTT, Traditional teaching type.

Questionnaire

In the context of COVID-19, the psychological state of college students majoring in biology needs in-depth research and analysis. This research should focus on two aspects: teaching activities and practical psychology. This will help students to establish positive and practical psychological coping mechanisms, while also improving their practical interest and practical skills. To understand the impact of IIETC teaching on students' psychology and academic performance during the pandemic, we designed a questionnaire with 16 questions.

In addition to their typical course assessments, students were asked to fill out a questionnaire about the course over several months (Xin et al., 2020). From September to November 2021, the questions were sent to students electronically. The responses were anonymous (Yao et al., 2021). A total of 228 questionnaires were issued. The questionnaire was divided into two parts. The first part focused on basic information about the college students, including their gender, the age, hometown, religious belief, and major. The second part focused on assessing the students' psychology and practical skills. Then, the Likert five scale is used as a measuring tool to calculate the score of the subject's cognitive feelings quantitatively (Zhang and Song, 2021). A total of 220 valid questionnaires were collected, a recovery rate of 96.49%, meaning that the data could be analyzed.

Comparison of Student Performance Under Different Teaching Methods

Class 1 uses a traditional teaching methods, whereas Class 2 uses online and offline teaching methods and IIETC. To compare the performance of the two groups of students under different teaching methods, through interviewing and mobile teaching software "Super Star Learning," the following measures were assessed as: the number of students participating in the two different teaching methods, attendance rate, homework completion, in-class responses, post-class feedback, student quality, teacher satisfaction, and students' perception of pain (headaches).

We used "Super Star Learning" to compare students' performance under the two teaching methods. Evaluating student performance involved average time spent watching videos, and the average score of in-class activities, consulting literature, viewing to answer first, taking group competitions, engaging in group tasks, and performing classroom exercises. In addition, the teaching effect and the distribution of students' scores in the two different teaching methods were analyzed.

Statistics

Graphpad Prism version 8.0 (La Jolla, CA, United States) was used to analyze the data from the questionnaire. The data were denoted as mean ± standard deviation. Furthermore, the differences between the two groups were compared using a *t*-test (two tailed). A value of p less than 0.05 was considered statistically significant, and a value less than 0.01 was considered markedly significant.

RESULTS

Analysis of the Results of the Questionnaire

The questionnaire shows the basic information of college students majoring in biology, including their gender, family situation, and religious beliefs. As can be seen from **Figure 2**, the proportion of girls is 55.0% and that of boys is 45.0%. A 97.27% students have no religious belief, and the percentage of Buddhist and Christian students is less than 4%. A 56.82% of the subjects came from urban areas, and 43.18% came from rural areas. The number of male and female students in urban areas is the same as that in rural areas. These does not affect our statistical results. The students majored in biological sciences (27.2%), edible fungi (13.64%), microbiology (26.825), and bioengineering (32.27%). The results of the questionnaire show that biological engineering students paid more attention to developing their practical skills. The age statistics of college students who participated in the questionnaire were shown in **Figure 3**. As can be seen from **Figure 3**, the age range of students participating in the questionnaire ranges from 20 to 25 years old, among which the most students are 21 years old.

To study the influence of the IIETC teaching method on the practical psychology of college students majoring in biology, we conducted a statistical analysis of the questionnaire survey. We analyzed the students' practical interests, psychological activities, and practical abilities. The results are shown in **Figure 4**. It can be seen from **Figure 4A** that 31.09% of the IIETC students were very interested in practical skills, 25.21% were moderately interested in practical skills, and 4.20% were not at all interested in practical skills. A 20.79% of TTT students were very interested in practical skills, 24.75% were moderately interested in practical skills, and 14.85% were not at all interested

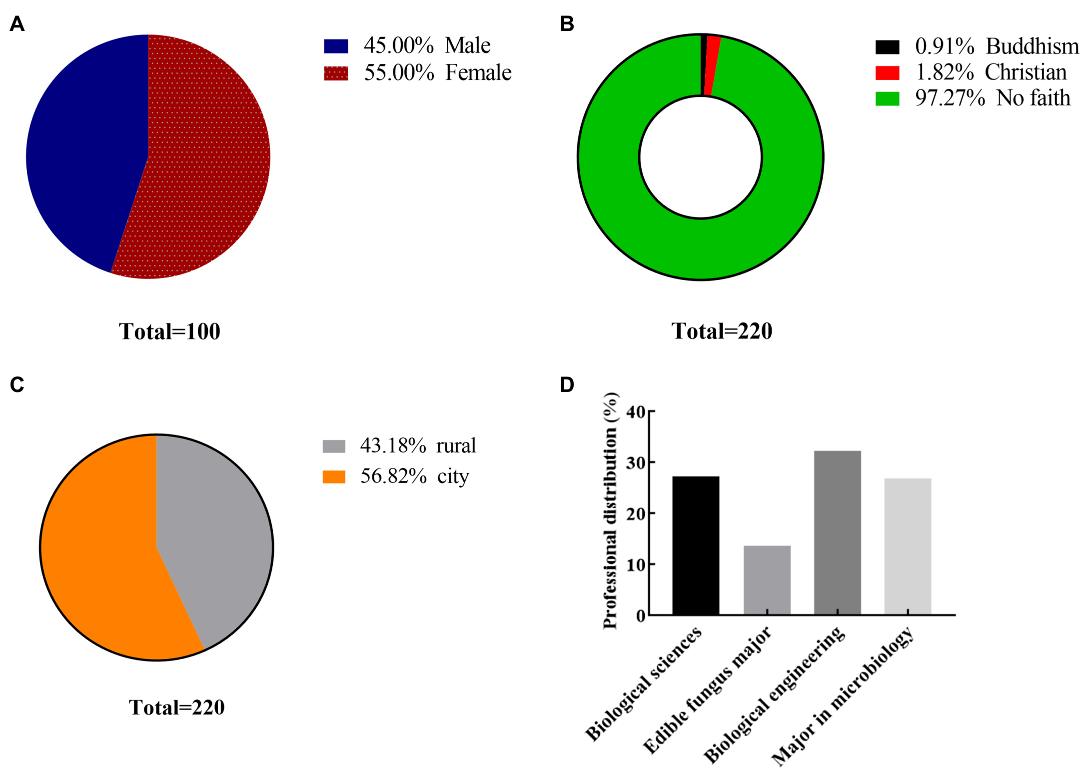

FIGURE 2 | Basic information of the research object. **(A)** Gender ratio; **(B)** religious beliefs; **(C)** family situation; and **(D)** professional distribution.

in practical skills. Compared with the TTT group, the percentage of students in the IIETC group who were very interested was significantly larger ($p < 0.01$); the percentage of students who were not interested at all was significantly smaller ($p < 0.01$). There was no significant difference in the percentage of those who showed some interest in practice ($p > 0.05$). The investigation and analysis of students' practice psychology show that students have good practice enthusiasm under the new teaching method environment (Reis, 2018).

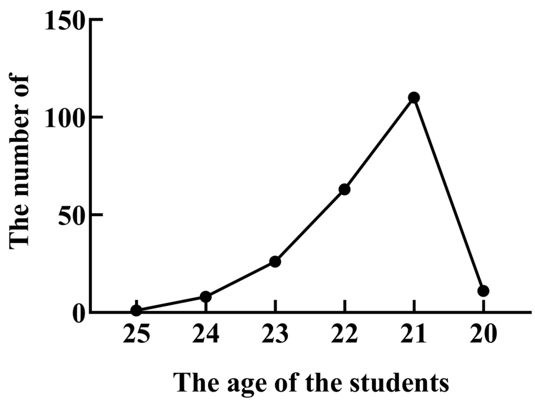

FIGURE 3 | The age statistics of college students who participated in the questionnaire.

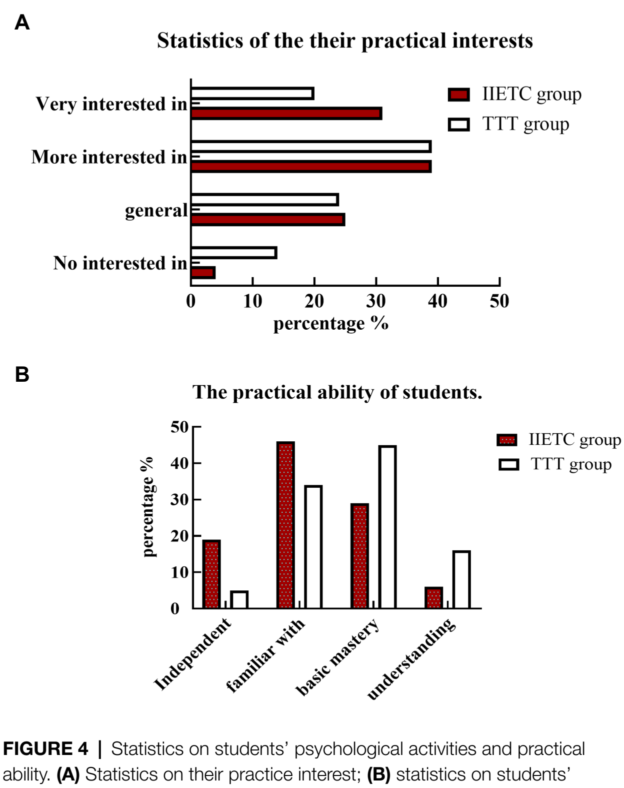

FIGURE 4 | Statistics on students' psychological activities and practical ability. **(A)** Statistics on their practice interest; **(B)** statistics on students' practical abilities.

In THE IIETC group, 6% of students had no practical skills at all, 19% of students had independent practical skills, and 46% of students were familiar with practical skills. In the TTT group, 16% of students had no practical skills, 5% of students had independent practical skills, and 34% of students were familiar with practical skills. Compared with the TTT group, the IIETC group had significantly better practical skills and were more familiar with practical skills ($p < 0.01$, **Figure 4B**); the IIETC group had a significantly lower percentage of students who had a basic grasp of practical skills and who understood practical skills ($p < 0.01$).

IIETC Has a Significant Positive Impact on Student Welfare

This study investigated the impact of IIETC teaching methods on student wellbeing. To our surprise, the students in the IIETC group all completed the non-essential study module assignments. We found that biology students in the IIETC group showed higher levels of cohesion on campus and had significantly reduced levels of anxiety, stress, and depressive symptoms. The innovative IIETC model helps to limit the pressures of the course, benefitting students' mental health. Students in the IIETC group reported less "pain" (defined as depression, physical discomfort, hostility, or anxiety) on the questionnaire than students in the TTT group (see **Table 2**).

Comparison of Student Performance Under Different Teaching Methods

This study describes the observed effects of IIETC on the teaching activities of a single biology course. **Table 3** summarizes the assessment of the classroom performance of the two classes. We were surprised to see differences in the quantity and quality of excellent results between the two groups.

From an analysis of the mobile teaching software "Super Star Learning," there was no significant difference between the TTT group and the IIETC group when it came to the average duration of teaching that involved watching a video ($p > 0.05$).

TABLE 2 | The impact of IIETC on the students' performance of biology major.

Behavioral engagement indicator	IIETC	TTT	*P*-value
Registration number (*n*)	236	196	0.04
Attendance	100%	98.50%	0.6
Assignments completed	All	78(39.8%)	0.04
Response (In-class group)	66(28%) students voluntarily posted responses	25(12.8%) prompted interactions during class	0.01
Feedback (Out-of-class group)	44(18.6%)	7(3.6%)	0.01
Quality of student	Substantive and constructive	Superficial	
Perceived pain (Headache)	0	5	0.02
Faculty satisfaction	High	Low	0.03
perceived pain (headache)	0	5	0.02

n, No. of students; IIETC, Industrial Innovation and Entrepreneurship Talent Cultivation; TTT, Traditional Teaching Type.

TABLE 3 | The impact of IIETC on students response (in-class group).

Variables	IIETC	TTT	*P*-value
Average time spent watching videos (Minutes)	43.19	34.22	>0.05
Average score for in-class activities	30.1	16.4	<0.01
Consulting literature	82.10%	56.30%	<0.01
Viewing to answer first	25.00%	9.80%	<0.01
Group competition	66.10%	12.60%	<0.01
Engaging in group tasks	98.52%	74.34%	<0.05
Practice in class	84.70%	42.30%	<0.01

TABLE 4 | The achievement analysis of biological students with two culture conditions.

	Analysis of results of group IIETC	Analysis of results of group TTT
Lack of the number of test	0 (0%)	0 (0%)
100–90 score	19 (15.25%)	0 (0%)
89–80 score	99 (41.94%)	54 (27.55%)
79–70 score	79 (33.47%)	120 (61.22%)
69–60 score	22 (9.32%)	22 (11.22%)
≤59	0 (0%)	0 (0%)
Average score (the total score was 100)	86.31	77.01
Overall number of people	236	196

The average score for classroom activities, literature reviews, quick answers, animal cell engineering group competition, group task completion rate, and classroom exercise results was significantly improved in the IIETC group ($p < 0.01$). A high completion rate for group tasks demonstrates teamwork. In other words, biology students trained using the IIETC method have high levels of cohesion on campus (Zhao et al., 2020).

In the IIETC group, the effect of the teaching was positive. The teachers were satisfied with the results. Most students could analyze and solve problems reasonably. The percentage of students who achieved excellent was 15.25%, and the average score in the class was 84.52%. In the TTT group, teachers were generally satisfied with their grades, and the average score in the class was 77.01%, though there were no excellent grades and no low grades (**Table 4**). The normal distribution of the two scores was reasonable, as shown in **Figure 5**.

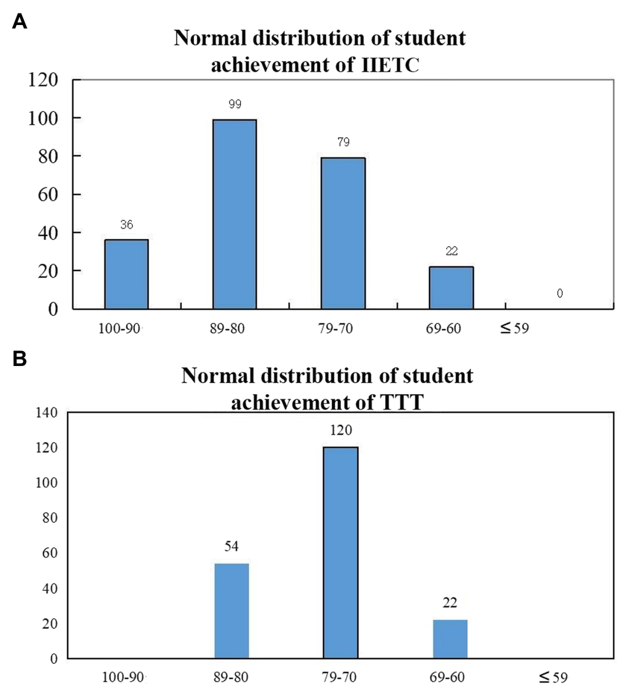

FIGURE 5 | Normal distribution of student achievement. **(A)** IIETC culture conditions; **(B)** TTT culture conditions.

DISCUSSION

The purpose of this study was to explore the current situation and suggest reforms to the education of students in biology, particularly given the situation of the pandemic. The purpose was also to support the development of the biological industry through the cultivation of strong talents. Biology undergraduates lack practical skills when they graduate because most of them do not have the opportunity to work with businesses while at school. They do not understand how to pursue a career after graduation. Moreover, many students change their careers to be in sales (Wang et al., 2021b). This is not a minority phenomenon. It may be because schools do not stimulate students' interest in biology as a major or because many students are confused about how to plan their future careers (Kong et al., 2020). Therefore, we have compared teaching methods focused on innovation and entrepreneurship with TTT. The IIETC method can increase students' enthusiasm for professional development and fulfillment. It can even limit their pain and increase their happiness. By working with schoolteachers and business mentors, students can discuss any problems they have, allowing them to strengthen their relationship with their teachers and to identify and resolve any physical or mental health problems during the pandemic. Innovation and entrepreneurship among technical professionals are important for the future development of the economy and society.

During the ongoing COVID-19 pandemic, teachers should consider the mental health of students, as well as the practical impact of their teaching methods (Dong et al., 2019; Wang et al., 2021a). Teachers can use interactions with students to promote and consolidate their online, independent learning. IIETC is a new method of education. By organically integrating online and offline education with cooperation between schools and businesses, it can help students to increase their knowledge and strengthen their theoretical understanding through comprehensive learning (Xi and Liu, 2020). Students taught using the IIETC method seem to be more active in curricular learning and are more capable of solving real problems and have high enthusiasm for innovation and entrepreneurship. This gives them a deeper understanding (Wei, 2021). Since the IIETC reform combines theory and practice, it allows students to develop their thinking and grow. It combines individual unity and overall development.

There is a great difference between theoretical education and practical life. The practical skills of college students will arouse students' thinking. The IIETC method, the double teacher teaching mode, improves the ability of team cooperation and project communication needed by the talents to start their business. We should pay close attention to the relationship between students and IIETC strategies to better understand how IIETC strategies affect students' interest in academic research. We should help teachers to promote student development. Teachers could increase their research, learn from successful experiences at home and abroad, and try to understand and respect the opinions of different industries and universities. They should increase their cooperation with enterprises and promote enthusiasm in both sectors. In this study, teachers improved the teaching effect and provided the most solid guarantee for the establishment of an education platform and applied university. This study makes practical contributions to the cultivation of students' innovation and entrepreneurial skills.

CONCLUSION

The present study shows that IIETC teaching is an effective teaching method and is appreciated by biology students. It deserves to be introduced as a teaching method in other subjects. These effects are very encouraging and deserve further exploration and expansion in future work in order to determine the sustainability of the methods proposed in this study.

Limitations of this work include that it focuses on biology major students as well as it assessed the utilization of IIETC but not compared to Learning Management Systems approaches. This research serves for recommending teachers to enrich the tutoring process by using alternative innovative approaches with pedagogical potential as well as students to be obtained their practical ability.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

ZL conceptualized the manuscript and provided data and developed **Figure 1** and **Tables 3** and **4**. JW, ZL, JL, YX, TH, and SL conducted the statistical analyses. ZL and HA generated **Figure 2** and **Figure 4**. LL and ZZ generated **Figure 3** and **Tables 1** and **2**. CJ revised the paper. All authors contributed to the article and approved the submitted version.

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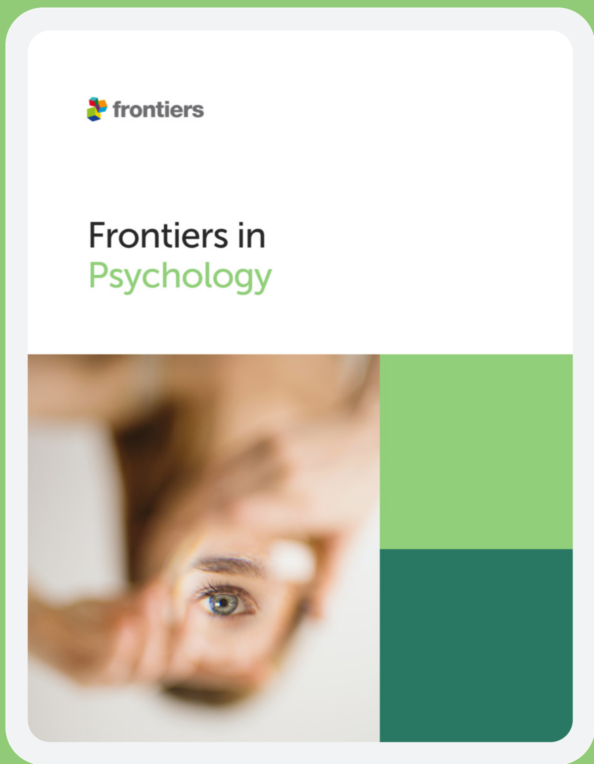

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