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Original Paper

Based on Productive Failure Theory Apply in STEM Learning

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Abstract

From the perspective of existing research results, the application of effective failure theory in education has been proven to promote students' conceptual understanding, transfer, and problem-solving abilities. In terms of the scope of research implementation, most studies have focused on single disciplinary approaches to solving fixed answers, with little in-depth research in interdisciplinary fields, especially STEM education. Kapur's four student behaviors need to be adapted and improved to facilitate teachers to construct frameworks more accurately.

Keywords

Productive Failure Theory, STEM learning

1. Introduction

As an interdisciplinary instructional approach focused on solving real-world problems, STEM (science, technology, engineering, and mathematics) education eliminates the barriers of traditional disciplines (Chalmers et al., 2017; Kelley & Knowles, 2016; Margot & Kettler, 2019). The implementation of STEM approaches to learning is valuable in fostering problem-solving skills and creativity and promoting knowledge transfer (Fan et al., 2021; Mar ń-Mar ń et al., 2021; Quigley & Herro, 2016). Regarding the design of STEM instruction, most research emphasizes how teachers can scaffold learners to be “successful” in problem-solving. While scholars have focused on these skills, less attention has been given to the importance of “failure” from the students’ perspective (Henry et al., 2021; Simpson & Maltese, 2017). In general, failure is an inevitable aspect of the learning process, especially when students are navigating complex tasks in the STEM classroom for the first time. These obstacles arise due to the integrative, multi-dimensional, and real-world-oriented characteristics of the STEM learning content (Fan et al., 2021). Meanwhile, identifying the failed attempts at problem-solving in the classroom may provide teachers with a nuanced perspective on designing STEM instruction and understanding students’ actual level of competence.

A survey constructed by the Organization for Economic Cooperation and Development (OECD) revealed that about 78% of 15-year-old students in secondary four in Singapore reported fear of failure (Today online, 2019), with an index of fear of failure (M = 0.50, SD = 0.99) above the global average index (M = 0.01, SD = 0.98) (OECD, 2020). Nevertheless, fear of failure may limit or prevent students' engagement in STEM learning (Zhang et al., 2018). Nowadays, advancing STEM necessitates a highly skilled workforce as well as the ability to navigate scientific challenges, overcome difficulties, and cope with failure, especially as scientific problems become more complex and interdisciplinary (Henry et al., 2019). Studies found that STEM instructors can help undermine students' fear of academic failure through environmental interventions (Choi, 2021; Henry et al., 2019). Furthermore, failure has the potential to have a positive impact on academic success (Clifford, 1984). Productive failure theory advocates that learners struggle to generate solutions when confronted with ill-structured questions rather than direct instruction on a targeted concept (Kapur, 2008). In recent years, a growing body of literature shows that temporary failure in pre-learning can significantly facilitate complex conceptual understanding and the transfer of learning (Jacobson et al., 2017; Lai et al., 2017; Loibl & Rummel, 2014). In addition to these studies, explicit failure-driven scaffolds have been found to provide better learning outcomes than success-driven ones (Sinha & Kapur, 2021a). However, cultivating students' failure tolerance and coping strategies in STEM classrooms is an under-explored topic.

After the primary school leaving examination, students with lower academic scores will be placed in the Normal Academic and Normal Technical tracks (Tan et al., 2016). In 2020, approximately 37.9% of students continued their secondary studies in the Normal tracks (Ministry of Education, 2021). Singapore has a higher proportion of low-performing students than other top education systems across the world (Wang, 2021). Despite their poor performance in academic subjects, low-achieving students in Singapore often demonstrate that they are on an equal footing with their high-ability peers in acquiring 21st-century skills, such as problem-solving skills (Kapur & Bielaczyc, 2012). Meanwhile, a six-month study of a biology course indicated that a well-designed productive failure intervention had a powerful effect on the improved performance of low-performing freshmen (Chowrira et al., 2019). However, it is concerning that little attention has been paid to their science education (Teo et al., 2018) or the implementation of problem-solving followed by instruction research in the regular classroom (Sinha & Kapur, 2021b). When faced with real-world problems that do not involve exam preparation, many studies show that low-achieving students have the potential to perform similarly or better than high-achieving students (Adesoji, 2008; Teo & Goh, 2019; Yang et al., 2015). Exposure to authentic tasks with non-routine questions contributes to higher-order problem-solving abilities (Foo & Fan, 2007). As a result, like their gifted peers, students on the lower track must have adequate access to high-quality pedagogies and a more challenging curriculum (Boykin & Noguera, 2011; Wang, 2021).

In summary, to transfer from intuitive ideas to deep conceptual understanding, students need to realize their gaps in knowledge by learning from their failures (Loibl & Rummel, 2014). Failure is a significant part of problem-solving-oriented instruction. To date, there is a lack of research on whether high-achieving students can overcome failure in STEM learning better than low-achieving students.

Notably, not all types of failure will significantly improve students' knowledge, understanding, and transferability. Research also indicates that if students keep making mistakes without thinking deeply, it will also lead to unproductive failure (Holmes et al., 2014; Kapur, 2016). Nevertheless, some forms of scaffolding can help students learn from their failures. It is critical for teachers to design scaffolds that allow students with varying academic achievements to experience productive failure in problem-solving-oriented STEM learning. This strategy will help students avoid unproductive failure and reduce fear of failure to help the entire student develop perseverance and challenge-engaging dispositions within STEM contexts.

2. Preliminary Research Questions

1. What are the behavioral features of productive and unproductive failure in STEM learning?
2. What are the differences in overcoming failure for students ?
3. How can teachers facilitate productive failure in STEM learning ?

3. Literature Review

3.1 The Research of Productive Failure

Kapur (2008) first developed the concept of productive failure. Prior to the concept being defined, scholars had already focused on the meaning of failure in different terminologies. John Dewey (1916) emphasized the importance of "Trial and Error". Piaget (1985) proposed that learning is triggered by perturbations and reaches a new balance through assimilation and adaptation. Subsequently, VanLehn (1988) extended Piaget's discussion of perturbations by designing failure into instruction. His theory of Impasse-driven Learning indicates that successful learning involves students reaching an impasse -a form of failure- in problem-solving, thus prompting them to process a canonical solution more deeply (VanLehn et al., 2003). Similarly, Schmidt and Bjork (1992) introduced the notion of "Desirable Difficulties". The above studies have concentrated on how and why difficulties or errors benefit learning but have not generated a systematic theory of failure.

Inspired by Schwartz's (2004) framework of preparation for future learning, Kapur (2012) designed an intervention using either well-structured, scaffolded problems or ill-structured problems before formal learning. As part of the design, students struggled with analysis, problem-solving, and even failed to generate effective solutions in the ill-structured condition. Nonetheless, the purpose of the research demonstrated that these experiences, which he referred to as "productive failure", contributed to students' conceptual understanding and knowledge transfer, systematically illustrating the value of failure for learning (Kapur & Bielaczyc, 2012). As research progresses, a growing body of evidence from quasi-experimental and controlled experimental studies reveals that the productive failure learning design can also lead to significant learning of complex systems concepts (Jacobson et al., 2020; Newman & DeCaro, 2019) and positively impact students' curiosity and affect (Lamnina & Chase, 2021; Sinha & Kapur, 2021).

Failure, although considered as an opportunity to learn from errors, in educational settings, typically represents an unfavorable, anxious, and tough experience. Fear of failure can negatively affect students' willingness to embrace challenges engagement, intrinsic motivation, and other achievement outcomes (Choi, 2021), especially for students with a fixed mindset (Henry et al., 2019). In addition to productive failure, Kapur posited that learners also experience unproductive failure in unguided problem solving (Kapur, 2016). Several findings indicate that failure comes in a variety of shapes and sizes, and therefore not all failures are equally productive (Anderson et al., 2018; Holmes et al., 2014). While research indicates that individual differences and diverse learning capacities can lead to people reacting differently to failure, little information is currently available about these complexities (Sinha & Kapur, 2021b).

3.2 The Implementation of Productive Failure in STEM Learning

The present application of productive failure theory focuses on single disciplines such as physics and mathematics to learn concepts, with relatively little research in interdisciplinary or integrated STEM education (Sinha & Kapur, 2021). Among those few studies, most of the participants are undergraduate or high school students. Weaver et al. (2018) applied the theory of productive failure to university STEM classrooms by comparing the instructional effects of the explore-first condition and the construct-first condition. They found that students in the explore-first condition exhibited better conceptual understanding and equal procedural knowledge. In addition, in the high school context, research conducted by Searle et al. (2018) suggests that in STEM-oriented maker activities, productive failure plays an equally important role in open-ended design tasks.

Table 1. A Comparison of Traditional Monodisciplinary and STEM Lessons

Categories	Traditional monodisciplinary lessons	STEM lessons
1. Characteristics of the lesson	• Routine questions • Fixed correct answers • Unique knowledge and skills in a single discipline	• Open-ended, flexible, and challenging tasks for students • Dynamic, diverse solutions • Holistic, integration and application of interdisciplinary knowledge and skills
2. Instructional approaches	• Mainly direct instruction or problem-solving learning oriented towards monodisciplinary knowledge	• Inquiry-based, problem-based, or project-based activities for real-world situations
3. Instructional process	• Regular and controlled instructional procedures	• More uncertain elements
4. Learning goals	• Developing students' ability to apply and transfer disciplinary knowledge	• Cultivating real-life problem-solving skills, creativity, and the ability to cope with failure adaptively

	• Helping students understand the core concepts of each subject

By comparing monodisciplinary and integrated STEM lessons (Table 1), the researchers identified that STEM learning focuses on complex, dynamic, and open-ended problems to foster the integrated application of knowledge and competencies from different disciplines (Tan et al., 2019). When students confront these more challenging tasks, they may experience a great deal of failure, which requires teachers to allow adequate time to help students develop the ability to navigate failure (Henry et al., 2019). This finding coincides with critical concepts involved in productive failure. More importantly, productive failure theory and STEM education share the same goal: authentic learning to develop students' ability to transfer and utilize interdisciplinary knowledge flexibly to solve complex 21st-century problems (Teo et al., 2021).

It takes deliberate planning efforts while attempting to design an integrated and interdisciplinary curriculum. However, many teachers lack knowledge about how STEM education could be implemented (Kelley & Knowles, 2016). Moreover, explicit discussions of integrated STEM proposals are often either absent or vague (Ortiz-Revilla, 2020). To increase clarity in STEM integration, Tan, Teo, Choy, and Ong (2019) proposed an instructional framework named the S-T-E-M Quartet, which takes complex, persistent, and extended problems at its core and treated the problem-solving process as the overarching frame. Kapur's productive failure learning includes two phases and four core interdependent mechanisms that can be embedded into the S-T-E-M Quartet framework (Kapur & Bielaczyc, 2012). Further exploration of the application of these approaches to STEM learning is necessary.

From the perspective of available research outcomes, the applications of productive failure theory in education have validated that it promotes students' conceptual understanding, transfer, and problem-solving skills. In terms of the scope of research implementation, most studies have focused on a mono-disciplinary approach to address fixed answers, with little more intensive research in interdisciplinary areas, particularly in STEM education. Combined with the nature of STEM learning, Kapur's four types of students' behaviors require adaptation and refinement to facilitate more accurate scaffolding by teachers, which provides some potential for breakthroughs in this area of research.

4. Theoretical Framework

While failure and success may appear to be diametrically opposed, research and approaches in learning sciences, STEM, and open-ended design tasks emphasize that failure is frequently critical for eventual success (Searle et al., 2018; Sinha & Kapur, 2021; Steenhof et al., 2020). In addition, theories of preparation for future learning and productive failure suggest that prior to formal instruction, students should be encouraged to struggle and formulate multiple solutions while engaging in ill-structured tasks often beyond their abilities (Kapur, 2012). These experiences are a significant component toward robust learning later on (Schwartz & Martin, 2004).

Nevertheless, there is still a gap in the research concerning the construction of failure in interdisciplinary instruction that aims at complex, extended real-world problem-solving. STEM education involves integrated multidisciplinary knowledge, which provides a rich context for students to experience and respond to failure. Meanwhile, productive failure theory offers the perspective that teaching new concepts should begin with problem-solving, which is instructive and valuable for STEM education. It means that when students develop multiple solutions, their prior knowledge will be activated and differentiated, thus promoting a more engaging and persistent understanding of the target concepts and transferability to novel situations (Kapur, 2010). There are commonalities within the goals of STEM education that aim to develop students' higher-order thinking skills to formulate multi-faceted solutions to complex problems of the twenty-first century (Tan et al., 2019).

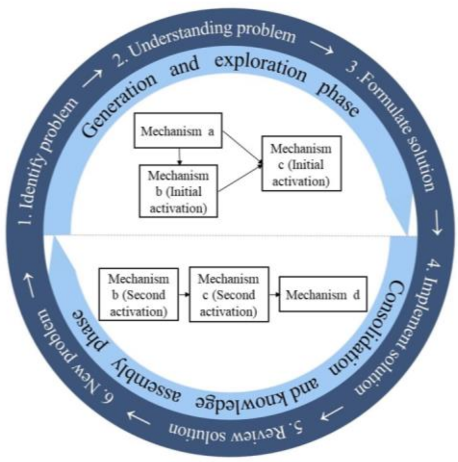

Figure 1. Two Phases and Four Mechanisms of Productive Failure Instruction Embedded in the S-T-E-M Quartet

By combining productive failure theory and the S-T-E-M Quartet framework aligned with the process of productive failure instruction, this study aims to explore the extension and application of productive failure in STEM education. Productive failure instructional design consists of two phases of four core, interdependent mechanisms: (a) activation and differentiation of prior knowledge; (b) attention to critical conceptual features; (c) explanation and elaboration of these features; and (d) organization and assembly into canonical representations and solution methods (Kapur & Bielaczyc, 2012). The specific design phases and core mechanisms of each lesson are shown in Figure 1. The order in which each mechanism is triggered varies within each phase. At the start, the teacher provides students with complex, open-ended problems. It provides students with an opportunity to activate their prior knowledge as much as possible when generating multiple solutions, thus understanding, explaining, and elaborating on the conceptual features involved in the problem. In the next section of implementation and review of solutions, critical conceptual features are activated a second time by teachers organizing whole class comparisons, discussions, and reflections on solutions. Teachers then elaborate and explain the target concepts to assist students in developing a deeper knowledge of the selected topics. Finally, new problems across contexts facilitate students' active attention to the transfer and underlying characteristics of knowledge.

This theoretical framework constructs a clear process for moving from solution generation to conceptual consolidation by embedding the two phases of productive failure into STEM learning. It also presupposes teaching behaviors that are consistent with Cropley's (1997) proposal to nurture creativity: encouraging flexible thinking, having a collaborative instructional style, delaying judging students' thoughts, and assisting students to cope with frustration and failure. Overall, the above discussion implies that the integration of productive failure into STEM education may reinforce the development of students' creativity, problem-solving skills, and the ability to embrace challenges without fear of failure.

The theoretical framework still needs to be further iterated and optimized in specific experiments. Within the literature on productive failure, Kapur points out that students will experience both unproductive and productive failure in the generation and exploration phase, but without explicitly defining their behavioral characteristics. It also implies that more research is needed to understand how to provide the types of guidance that avoid unproductive failure to support the optimal effectiveness of student learning (Holmes et al., 2014; Kapur, 2016). In the consolidation and knowledge assembly phase, there is rarely a standard answer to open-ended problems in STEM learning. Teachers and students also need more extended discussions, reviews, and evaluations of the fundamental principles to reflect deeply on the conceptual features, the feasibility of the solution, and the potential for extension (Polya, 1945; Teo et al., 2021).

Furthermore, the quantitative analysis based on Kapur's numerous experiments showed that the impact of solution diversity on learning outcomes significantly outweighed the preexisting differences in individual prior knowledge and schools. It demonstrated that low and high knowledge could benefit from productive failure pedagogies (Kapur, 2013; Kapur & Bielaczyc, 2012; Kapur & Kinzer, 2009). Considering Murphy's (2010) recommendations, the challenging curriculum and explicit instructional support can also facilitate narrowing the achievement gaps between schools. Another contribution of this study would be the selection of research participants, as I will attempt to summarize the behavioral features of how students from different tracks, including the less-focused lower track students, may overcome failure when solving complex problems in STEM learning. Subsequently, I will explore how teachers can more strategically support the development of higher-order skills .

5. Methodology

5.1 Research Design

This study utilizes a quasi-experimental, pre-/post design in three schools with Express, Normal Academic, and Normal Technical tracks, adopting a mixed-method approach with the concurrent triangulation strategy (Creswell et al., 2003). Qualitative and quantitative data will be collected and analyzed in the same research phase. These different approaches and complementary findings will subsequently be integrated to provide the best interpretation of the research questions.

The research design and procedures are identical in all three schools, and each class will have two different series of lessons on productive failure in STEM. Each lesson series will be based on the problem-centric framework of the S-T-E-M Quartet: after identifying and understanding the problem, students will engage in a solution formulation and implementation phase (the Generation and Exploration phase of productive failure learning) to solve an interdisciplinary problem with authenticity, persistence, and complexity (Tan et al., 2019). Following this task, there will be a solution review and new problem generation phase (the Consolidation and Knowledge Assembly phase of productive failure learning) in which different solutions will be discussed, compared, and analyzed against the canonical ways shared by teachers.

The difference between the lesson series is that teachers provide poor or suitable scaffolds for the formulated solutions phase during the lessons. In the second stage, teachers will provide tailored scaffolding interventions for unproductive failure in each group, and the scaffolds implemented in each class will be nearly identical. Additionally, all students will complete a pretest before each stage to measure their prior knowledge of the targeted concepts. After the intervention stage, all students will take a posttest and a questionnaire assessing their fear of failure. The procedure for research design is shown in Figure 2.

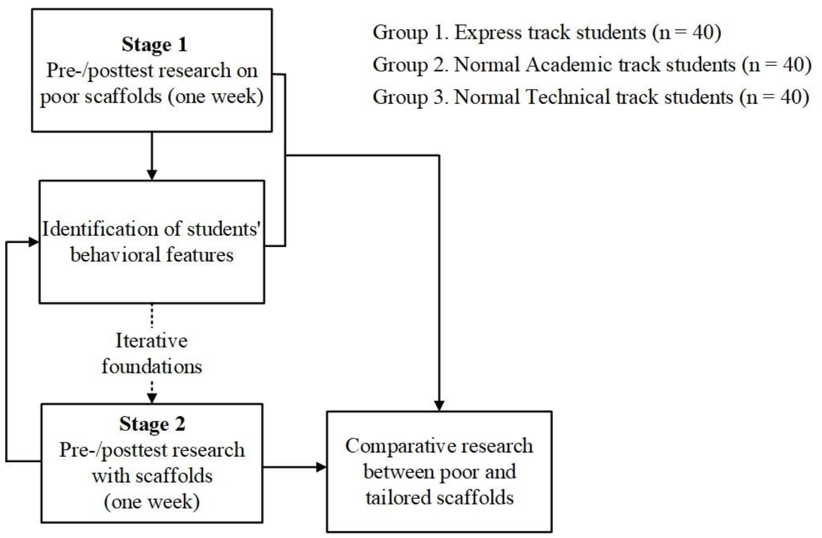

Figure 2. The Experimental Design about Productive Failure in STEM Learning for Different Track Students

5.2 Participants

Participants are secondary school students from Express, Normal Academic and Normal Technical track schools in Singapore. In total, 120 students agreed to participate with written parental consent forms. Students attend co-educational public secondary schools in different tracks based on their Primary School Leaving Examination (PSLE) scores. Students from the school in the Express track, on average, received the highest PSLE scores, followed by those from Normal Academic school and then Normal Technical track school. Each school selects 40 students through teachers' recommendations and students' academic achievement (mainly according to their math and science grades) to represent three experimental classes of high, middle, and low-achieving students, and each class has ten groups with four students.

5.3 Scaffolds

The scaffold (Wood et al., 1976) is provided by tutors for students to support them in tasks that they have difficulty accomplishing independently. It is an essential tool in STEM instruction and can guide, construct, and limit the scope of failure (Belland et al., 2017). Not all failure is meaningful for learning, so following productive failure theory does not exclude teachers' support entirely. In contrast, it means that teachers need to design more explicit and oriented scaffolds to support the initial problem solving (Kapur, 2016). The aim is to enable students to experience learning-worthy failures adequately and avoid meaningless ones as much as possible. It requires that skilled teachers must diagnose and address those difficulties promptly.

Table 2. A Summary of Some Scaffolds in STEM Learning

	The first lesson series (Poor scaffolds)	The second lesson series (With scaffolds)
Hard scaffolds	• Blank sheets of A4 paper • Multiple instructional materials or resources	• Pre-planned worksheets or hand notes • Limited instructional materials or resources • Procedures or arguments for students
Soft scaffolds	• Provision of minimal levels of soft scaffolds and emotional support	• Explicit success-driven or failure-driven scaffolds • Encouraging students' explanations, marking, or highlighting relevant information • Heuristic questions or paradigms

In the context of problem-centric frameworks in STEM learning, scaffolds can be delivered in two forms: either as a predefined hard scaffold built into the learning environment or as a timely, flexible soft scaffold that assists students' knowledge construction (Saye & Brush, 2017). The scaffold types are summarized in Table 2.

Based on the unproductive failure of student groups and the fear of failure during the formulation and implementation of solutions phase in the first stage, I will incorporate the teachers' discussions, and the scaffolding intervention will be integrated into the second lesson series to minimize these negative factors for students. Therefore, I will focus on assessing the interaction fragments in which teachers discuss a subject problem with students in the videos of the second stage to explain which scaffolds are more beneficial for the different students.

5.4 Instruments

The Performance Failure Appraisal Inventory (PFAI)

The scale applied in this study is adapted from the PFAI (Henry et al., 2021). All questions are in the form of a five-point Likert scale, including fear of an uncertain future, fear of important others' losing interest, fear of upsetting important others, and fear of experiencing shame or embarrassment in four dimensions. Since the prototype scale has been designed for STEM undergraduates, 200 secondary school students are invited to take the initial test after modification, and SPSS 25.0 software will be used to analyze the overall reliability and validity of the modified questionnaire.

Pre-/posttest

The paper-and-pencil pre-/posttest will require a deliberate design and detailed scoring criteria. The pretest will consist of objective questions that measure prior knowledge of STEM subjects such as science and mathematics. The posttest will be comprised of objective questions, open-ended questions, and a subjective reflection question, which will assess students' conceptual understanding, transfer, and subjective perceptions of the lesson. The scores will be individually assessed by several professionals based on an initiative-developed assessment scale, which will be adjusted according to any scoring discrepancies that arise, and finally discussed in order to arrive at a consensus score. The keywords in students' answers will be categorized and statistically analyzed for the subjective reflection questions.

5.5 Procedure

Firstly, by incorporating literature and instructional content, I will develop two lesson series on productive failure in STEM learning with different target concepts and themes. Next, I will recruit students interested in participating in the lessons at three different track schools. Experimental classes will be selected based on mid-term exam scores and teacher recommendations to represent high, middle, and low achievers.

Before the first stage, I will dedicate a week to training teachers in the skills and concepts related to productive failure theory and instructional design, especially ways of delivering different scaffolds. In stage 1, after completing the pretest, students will begin STEM lessons with the poor scaffolds provided by the teachers. At the end of the stage, I will distribute the posttest and PFAI questionnaire and interview students and teachers. The data will be collected and analyzed to summarize the types of failure behaviors among different achieving students. Afterwards, appropriate scaffolding strategies can be discussed with teachers. In stage 2, I will collaborate with teachers to design the second lesson series using scaffolds. Before the lesson, the same student groups will finish a pretest containing conceptual knowledge from the previous lesson and a priori knowledge of the new curriculum. After the stage with scaffolds is implemented, students complete the posttest and the PFAI questionnaire. In follow-up interviews with students and teachers, I will focus on their different feelings about the two stages.

When analyzing the data, I will compare the results with the first lesson series to observe changes in the frequency of unproductive failure and posttest scores for each group, contrasting the learning outcomes of different academic performers. Finally, more iterative experiments would be required to optimize the appropriate scaffolds for different track students.

5.6 Data Collection

All classroom sessions will be video-recorded, and I will examine group artefacts to determine the number of groups that successfully solved complex problems and the diversity of solutions proposed by the groups. After the lesson, I will collect quantitative data like questionnaires and qualitative texts of students' written artefacts, such as notes, design diagrams, and audio interviews with students and teachers. I will obtain informed consent from all participants before collecting data. The anonymity, confidentiality, disclosure, and any other ethical considerations of all information will be reviewed with the advisors and the university's ethics committee to ensure the privacy and security of all participants.

Field Observation

I will participate and record throughout the teachers' training, curriculum design, and instructional process. iPads will be used to record the entire learning activities of each group and the scaffolding provided by the teachers, especially during the solution formulation and implementation phase. Although the project is time-consuming and laborious, it has the potential to reveal unique questions and details about the students' collaborative attempt process that should not be missed. Discourse analysis will be used to code and count students' conversations, transforming each group's discussion process from qualitative to quantitative data, thus enabling subsequent statistical analysis.

Interviews

Interviews will enable me to capture a more realistic feeling of students and teachers. I plan to interview teachers at the end of each lesson to collect their evaluations of their instruction. Then, after coding and aggregating statistics on students' behaviors and posttest scores, a few representative groups will be selected for interviews, which will be combined with the playback of video clips. I can ask students questions such as how they felt at that moment and their potential solutions. All interviews are captured on audio.

5.7 Data Analysis

For qualitative data analysis, the recordings of interviews will be transcribed, labelling each participant individually to maximize the reproduction of the conversations. The analysis of classroom videos will focus on the sections in which students discuss solutions, excluding episodes of non-task behavior and social talk. Three researchers will independently divide the conversations into multiple turns, coding and counting the students' behavior types, the teachers' scaffolding types, and keywords in the interviews with high reliability.

According to pre-designed criteria, all group solutions and individual student performance will be scored independently by teachers and myself, followed by discussions to reach a consensus. The scoring of questions in the pre- and post-test can be weighted for questions of varying difficulty levels.

After each stage, analysis of variance (ANOVA) will be used to compare whether there are significant differences in the types of behavior and performance of different track students. Following the experiment, I will apply a paired sample t-test to compare changes in the same track student's performance. Finally, students' behavioral types and posttest performance will use descriptive statistics to illustrate the learning outcomes of all students, supported by different scaffolds to experience productive failure in STEM learning.

6. Preliminary Findings

This study attempts to define the behavioral characteristics of productive and unproductive failure in STEM learning for different track students, which can assist teachers in identifying students' unproductive failure in time and providing appropriate scaffolding interventions to facilitate productive instruction. Theoretically, this study integrates and complements productive failure theory and STEM education to ensure that all students can benefit from instruction designed to foster higher-order cognitive skills.

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