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ORIGINAL ARTICLE

Implementation strategies of STEM education in cultivating graduate students' learning ability in Chinese higher education

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ABSTRACT

This paper explores the tailored implementation strategies of Science, Technology, Engineering, and Mathematics (STEM) education in nurturing graduate students' learning abilities within the context of Chinese higher education. The role of STEM education has been globally acknowledged, but its implementation at the graduate level encounters unique challenges requiring specific strategies. The paper discusses the distinct characteristics of graduate STEM education, contrasts them with general STEM education, and provides a thorough analysis of five key strategies: designing appropriate projects, enhancing teacher competence, providing scaffolded instruction, transforming evaluation methods, and creating a conducive learning environment. Each strategy is elucidated with concrete examples and references to existing scholarly viewpoints. The analysis presented in this paper contributes to the understanding of how to optimize STEM education in graduate programs and aims to serve as a beneficial reference for educators, policymakers, and researchers alike.

Key words: STEM education, graduate education, learning ability, characteristics, strategies

INTRODUCTION

STEM, an abbreviation for Science, Technology, Engineering, and Mathematics, has become a fundamental framework in the global educational landscape since the 21st century.[1] Nations such as the United Kingdom, the United States, and Japan have positioned the cultivation of STEM talents as an instrumental component in their strategies for maintaining competitiveness in the global economic arena. Similarly, China has embraced the adoption of STEM education, recognizing its significance across all educational levels, from primary to graduate education.[2] Among these, nurturing the learning abilities of graduate students represents a crucial facet in the actualization of STEM education.[3] However, the practical implementation of STEM education encounters various complexities and challenges, necessitating a comprehensive understanding of its inherent connotation, distinct characteristics, and effective teaching strategies.

Delineating and addressing these challenges is paramount for harnessing the full potential of STEM education in bolstering the graduate learning prowess in the context of Chinese higher education. A critical aspect of this delineation pertains to the distinctions between general STEM education implementation strategies and those tailored for graduate-level STEM education, as well as the correlation between the two. As suggested by existing literature, researchers have examined these unique needs and considerations pertinent to graduate STEM education.[4]

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Therefore, this paper aims to delve into the exploration of STEM education implementation strategies, specifically designed to cultivate graduate learning abilities in the context of Chinese higher education. This exploration will involve not only investigating the overall strategies that have proven effective but also elucidating the nuanced differences in their implementation at the graduate level.

EXPLORATION OF THE MULTIDIMENSIONALITY OF GRADUATE STUDENTS' LEARNING ABILITIES

Understanding learning abilities in the field of education often involves grappling with its multidimensional nature. This notion takes on a heightened complexity within the context of graduate education, particularly given the swift societal and economic changes of our current times. As such, the learning ability of graduate students is seen as a comprehensive, encompassing array of abilities. These span numerous domains such as knowledge mastery, autonomous learning, critical thinking, research capability, communication and collaboration, and innovation.

Knowledge mastery

A cornerstone of graduate students' learning abilities is knowledge mastery. This dimension signifies the extent of understanding and command students have over their specialized knowledge, encompassing both theoretical insights and practical skills. In the ever-evolving academic landscape, graduates must have the capacity to assimilate and understand new theoretical knowledge and practical skills swiftly.[5] Thus, their ability to discern and grasp core theories in their domain, proficiently employ and adapt professional techniques, and remain adaptable to knowledge and technological advancements becomes paramount.

Autonomous learning

Transitioning from knowledge mastery, we enter the realm of autonomous learning. It signifies a graduate students' capacity to actively pursue new knowledge, resolve problems, and keep their knowledge system updated. Knowles emphasized in his adult learning theory that adult learners, such as graduate students, possess a more significant self-directed learning capacity and can actively engage in their learning process.[6] This necessitates a sense of self-motivation for graduates to harness various resources like books, online materials, and academic lectures, enabling them to refresh and add to their knowledge system.

Critical thinking

Critical thinking forms the next dimension, enveloping abilities to analyze, evaluate, problem-solve, and critically assess new knowledge or theories. Paul and Elder underlined the importance of critical thinking as a rational thought process that necessitates the analysis of viewpoints, evaluation of arguments, identification of problems, and proposition of solutions.[7] In the academic realm, critical thinking empowers graduate students to not merely grasp new knowledge and theories, but also evaluate them critically and reflect upon them.

Research ability

Diving into the research ability, this emerges as one of the core skills within graduate education. Graduates are required to formulate research questions, design research methodologies, collect and analyze data, interpret research findings, and craft research reports or papers.[8] Enhancing this ability forms a substantial objective of graduate education and marks an essential step towards becoming an independent researcher.

Communication and collaboration

From research abilities, we transition to communication and collaboration skills. These include efficient communication techniques and the capacity to collaborate with others to accomplish tasks or projects. In the modern societal fabric, effective communication and collaboration skills stand as key requisites. Within the academic sphere, graduates need the capability to clearly, accurately, and persuasively express their ideas and findings and to communicate and cooperate effectively with a range of individuals, from peers and mentors to students.

Innovation

Innovation denotes the capacity of graduate students to think innovatively—to approach problems from varying perspectives, propose new solutions, or uncover new research domains and questions. Amidst globalization and the knowledge economy, innovation has emerged as a crucial skill for the modern era.[9] This necessitates graduate students to scrutinize existing knowledge and theories with an open and critical mindset, challenge conventional viewpoints and practices, and engender new knowledge and solutions.

Amid these dimensions, whether it be knowledge mastery, autonomous learning, critical thinking, research ability, communication and collaboration, or innovation, all are regarded as key abilities for graduates. Importantly, these abilities are not isolated, they are interrelated and mutually reinforcing. Autonomous learning can enhance knowledge mastery; critical thinking can stimulate research abilities; communication and collaboration can boost innovation.[10]

However, while these six abilities form the bedrock of learning and development for graduate students, their learning abilities extend beyond these. Graduates also need a range of other skills, including leadership, project management, time management, and a strong ethical and moral sense, all contributing significantly to their learning and professional growth. Altogether, a graduate students' learning ability is a comprehensive, multidimensional capacity. Its improvement and development necessitate a long-term, continuous process, achieved through self-directed learning and practice, interaction and collaboration with others, and challenges and innovation under the guidance and support of teachers.[11] Concurrently, graduate education should focus on nurturing these abilities in students, laying a solid foundation for their academic and professional progression.

THE CHARACTERISTICS OF GRADUATE EDUCATION

Graduate education is characterized by several distinct features that set it apart from other stages of learning, such as undergraduate study or laboratory education.

Advanced level of study

Graduate education delves into a specialized field of study far beyond the undergraduate level. It demands a higher level of intellectual engagement, with the expectation that students will make original contributions to their respective fields.

Research-centered

Graduate education is typically more research-centered than undergraduate education. Students are expected to conduct original research, develop and execute research methodologies, analyze data, and produce significant findings that contribute to the body of knowledge in their field.

Independent learning

Graduate students are expected to take a more autonomous approach to their learning. While guidance from mentors is crucial, students are encouraged to self-direct their learning paths, demonstrating initiative in identifying research topics, seeking out resources, and problem-solving.

Mentorship

The role of mentors or advisors is a critical component of graduate education. These individuals guide graduate students through their research, offering their expertise and support. This mentor-student relationship can significantly impact the quality and success of a students' research experience.

Professional development

Graduate education often involves elements of professional development, such as teaching, presentation skills, project management, and ethics, among others. This training prepares students for future careers, both within and outside academia.

Collaboration and networking

Graduate education often involves extensive collaboration and networking, within a research group, across departments, or even internationally. These collaborations can lead to interdisciplinary research, enhance the quality of research outputs, and extend students' professional networks.

Publication and dissemination

Graduate students are expected to publish their research findings in academic journals or present at conferences. This process of disseminating research findings is a key aspect of scholarly communication and contributes to the advancement of knowledge in their field.

Critical and innovative thinking

Graduate education seeks to develop students' ability to think critically, question existing knowledge, and innovate by developing new theories, methodologies, or applications.

These characteristics collectively demonstrate the complexity and rigor of graduate education, highlighting its unique aspects compared to other educational stages.

STEM EDUCATION: ORIGINS AND INTERPRETATIONS

STEM education was pioneered in the United States. In 2005, Friedman raised concerns about the relative underperformance of American students in global competition, attributing this to superior STEM education systems in other countries.[12] To address this, the United States government introduced policies promoting the growth of STEM education, ranging from theoretical initiatives like education and curriculum reforms, to practical measures such as the establishment of STEM scholarships and research centers. Graduates were not exempt, as exemplified by the *Graduate STEM Education in the 21st Century* report, advocating for STEM education in graduate programs.[13] The outcomes of these measures in the United States sparked global interest, with governments and institutions worldwide investing in the development and implementation of STEM education.

STEM education, as defined by Bybee, is subject to disagreements.[14] Sometimes it represents four equal, separate disciplines, and other times, a collective whole. Several definitions have been offered from different perspectives. Vasquez *et al*. view it from a learning angle,[15] Bybee from a teaching perspective emphasizing application as the central feature of STEM education,[16] and the California Department of Education provides a broad policy-level definition.[17] Additionally, Shaughnessy considers the interrelationships among the four disciplines in defining STEM education.[18] Despite this diversity in definitions, STEM education consistently plays a pivotal role in nurturing innovative literacy and competitive skills.

In this paper, STEM education is viewed as an interdisciplinary educational model nurturing students' overall literacy in Science, Technology, Engineering, and Mathematics. It underscores the individual value of each STEM subject, while also accentuating their interconnectedness. By way of thematically apt projects for graduate research, students participate in creative learning, leading to tangible conclusions or products.

DISTINCTIVENESS OF STEM EDUCATION

Traditional teaching models typically emphasize single-subject courses with little consideration given to the interrelationships among different subjects.[19] Such models mainly involve imparting knowledge and may not adequately prepare students for interdisciplinary applications of knowledge in real-life scenarios.

STEM education, conversely, adopts a cross-disciplinary integrated teaching approach, intertwining Science, Technology, Engineering, and Mathematics based on their functional interdependencies. This teaching method enables students to understand the world in an integrated manner, thereby fostering their innovative problem-solving abilities. It emphasizes not only subject knowledge but also practical abilities and overall literacy, engaging students' initiative and creativity, and preparing them to tackle future challenges.

STEM education's ability to nurture innovative talents is a result of its unique characteristics, including deep learning and interdisciplinary integration.

Deep learning

STEM education promotes problem-based learning, immersing students in situations to solve real-world problems. This process, known as deep learning, requires active engagement, thorough analysis, and application of knowledge, enhancing students' innovation and learning abilities.[20]

Teachers play a critical role in facilitating deep learning by centering the curriculum around core concepts and basic principles, creating an engaging learning environment, and stressing the importance of applying these principles to practical situations. Effective teaching methods include connecting new knowledge with prior knowledge, bridging abstract and concrete concepts, enabling the understanding and application of knowledge, and fostering learning through role models.

Interdisciplinary integration

The crux of STEM education lies in its interdisciplinary approach, breaking traditional subject barriers and enabling students to solve complex real-world problems. In the United States, successful instances of STEM education, such as the Arts & Bots project, provide valuable insights.[21] For STEM education to be effective, it must be localized to national conditions, otherwise, it could burden schools and society without yielding desired results.

A central challenge of traditional teaching models is their difficulty in achieving interdisciplinary integration. To overcome this, STEM education encourages collaboration among teachers from different subjects in curriculum design and instruction.[22] However, the implementation of interdisciplinary collaboration is fraught with challenges such as professional identity, development issues, and philosophical and cultural differences among different subject teachers. To address these, teachers should prioritize student development, maintain effective communication and collaboration, and engage curriculum experts to guide them regularly, ensuring that the integrated curriculum adheres to educational laws. These measures promote mutual learning among teachers, enhance their professional quality, and advance the comprehensive development of students.

THE APPLICATION AND INSTITUTIONAL SUPPORT FOR STEM EDUCATION IN CHINA'S GRADUATE STUDIES

As China increases its commitment to STEM education at the graduate level, it faces the challenge of how to implement it effectively. There are two critical aspects to consider here: application strategies and institutional support.

Application of STEM education in graduate studies

The application of STEM education in graduate education primarily involves a pedagogical shift from traditional lecture-based learning to an interactive, project-based learning approach. For instance, graduate courses can be designed to encourage students to use scientific principles to solve real-world problems, rather than simply learning theory. Furthermore, interdisciplinary collaboration is key to STEM education. Graduates can be encouraged to work on projects that require the integration of knowledge from various disciplines, promoting the development of a comprehensive understanding of the subject matter.

Moreover, it's necessary to ensure that the course content is current and relevant. STEM fields are rapidly changing, and keeping the curriculum up-to-date with the latest developments can ensure that graduates have the skills needed to stay competitive in the job market.[23] For instance, in the field of computer science, staying updated with the latest programming languages and software development methodologies is crucial.

Institutional support for STEM education

Institutional support is vital for the successful implementation of STEM education in graduate studies. This can come in various forms, such as policy support, infrastructure development, and professional development for teachers.[24]

At the policy level, the government and higher education institutions should formulate policies that promote the development of STEM education. This could include policies to attract and retain talented STEM teachers, or to invest in the development of state-of-the-art STEM facilities. Furthermore, universities and colleges can develop partnerships with industries and research institutions to provide students with practical learning opportunities and to stay updated with the latest industry trends.

Infrastructure is another critical component of institutional support. This includes physical resources such as laboratories and equipment, as well as digital resources like online learning platforms and software. Without the necessary infrastructure, it would be challenging to implement a comprehensive STEM education program.

Lastly, professional development for teachers is vital. Teachers need to be trained to use innovative teaching methods, develop and assess interdisciplinary projects, and adapt to rapidly changing STEM fields.[25] Regular professional development workshops and seminars can help teachers stay updated with the latest pedagogical approaches and industry trends.[26]

In conclusion, the successful implementation of STEM education in China's graduate studies requires a well-planned application strategy and strong institutional support. With these in place, STEM education can play a vital role in equipping Chinese graduates with the skills and knowledge they need to excel in the 21st-century job market.

IMPLEMENTATION STRATEGIES OF STEM EDUCATION TO PROMOTE THE ENHANCEMENT OF GRADUATE STUDENTS' LEARNING ABILITY

The implementation strategies of STEM education are diverse, and one of the strategies that particularly fits is STEM project-based learning. In this learning approach, graduate students can creatively apply their acquired knowledge and skills to solve real-world problems, thereby enhancing their learning ability. Therefore, the characteristics of STEM education are closely related to project-based learning. This article explores how STEM education can promote the enhancement of graduate students' learning ability through the following aspects.

Constructing relevant and culturally-informed projects

The effective design of appropriate and engaging projects plays a paramount role in the learning process of graduate students. Such designs should consider a variety of variables that might influence project execution and outcomes, including regional policies, available resources, demographic factors, and other situational conditions. The negligence of these factors could result in severe project implementation challenges.[27]

Moreover, project designs need to take into account the cultural context of the institution. Designs should align with the school's cultural principles to prevent any discord, which could potentially impede the unique development of the institution's academic environment.

Within the classroom, careful considerations must be incorporated when constructing suitable projects. Primarily, projects need to have explicit guidelines that clearly articulate the objectives and requirements. For example, Thomas proposes that an effective project should be prompted by a question or problem that is inherently open-ended and appealing to students. Such project initiation promotes active student engagement and drives inquisitive learning.[28] In addition, incorporating high-quality project exemplars can greatly facilitate students in comprehending the project's expectations and standards. Ertmer and Simons argue that supplying students with high-quality peer work examples can help set benchmarks, spur creativity, and provide a clearer vision for project outcomes.[29] Moreover, the provision of timely guidance and instructional support from teachers is vital in scaffolding students' project progress. Such support empowers students to overcome obstacles and challenges that they may face during their project journey.[30] Lastly, continuous monitoring and assessment of students' progress and learning status is instrumental in informing necessary adjustments in teaching strategies and methodologies, enabling a more tailored and responsive teaching approach.[31]

To conclude, the construction of relevant and culturally-informed projects, equipped with clear guidelines, high-quality exemplars, teacher support, and continuous progress monitoring, are essential components to facilitate effective project-based learning in graduate education.

Enhancing teacher competence in STEM project-based learning

In the arena of STEM project-based learning, the responsibilities of teachers stretch beyond the conventional impartation of knowledge and skills. Serving as facilitators and evaluators of project-based learning, teachers are required to cultivate a wide array of competencies to assist students in project execution and foster personal growth.[32]

For instance, Blumenfeld *et al.* emphasize that teachers in a project-based learning environment must embody more than just traditional teaching roles; they must also serve as mentors, coaches, and co-learners. It is essential that teachers possess a profound comprehension of the philosophy and objectives of project-based learning. This understanding will enable them to provide requisite guidance during the process of project design and implementation.[33]

Moreover, it is necessary for teachers to exhibit innovative thinking and strong observational skills to create rich and diverse project-based learning experiences. They also need to grasp the evaluation methodologies and standards of project-based learning to assess student learning outcomes accurately.[34] As Helle *et al.* point out, teachers need to be adept at employing multiple evaluation methods, including quantitative and qualitative evaluation, in order to provide students with comprehensive feedback and guidance.[30]

In addition, understanding students' learning needs and interests is integral to providing personalized guidance. In the project-based learning framework, teachers need to forge strong cooperative relationships with students, thereby addressing their issues promptly and extending necessary support.[35] As mentioned by Belland *et al.*, teachers must also encourage students to exercise autonomy and creativity in their learning, thereby fostering their potential and abilities within the project.[36]

Lastly, the dynamic and ever-changing educational environment necessitates continuous enhancement of teachers' competencies and abilities. This encompasses not only incessant learning and knowledge updates but also constant reflection and exploration of teaching strategies and methods to better facilitate student learning and development.[37]

Implementing scaffolded instruction in STEM education

Scaffolded instruction serves as a fundamental strategy in STEM education. Research, including the studies conducted by Simons and Klein, demonstrates that student performance significantly improves when provided with optional and necessary learning frameworks.[38] In a similar vein, Saye and Brush provide further clarity to the concept of scaffolding by dividing it into two types: soft and hard scaffolds.[39]

In more detail, soft scaffolds are adaptable supports that teachers provide during the diagnosis of students' understanding, supplying immediate guidance. For example, in a STEM physics project, when a graduate student encounters difficulty in understanding the principle of mechanical energy conservation, the teacher may use soft scaffolds by explaining the principle with practical examples or demonstrations.

On the contrary, hard scaffolds are pre-arranged supports that aid students in anticipating and planning for difficulties they might encounter during their work. For instance, teachers may provide a step-by-step template for students to follow when conducting a science experiment, or an outline for structuring a research paper. These hard scaffolds serve as essential tools for students to better understand the task's expectations and requirements.

Furthermore, scaffolds can also come from peers and computer tools, which can provide assistance and enrich learning experiences.[40] For instance, collaborative learning groups can foster peer scaffolding, where students help each other in understanding and completing the tasks. Computer tools, such as simulation software, can also serve as scaffolding aids, providing visual and interactive learning experiences for complex scientific concepts or mathematical problems.

These scaffolding strategies help students to gradually become independent learners while enhancing their higher-order thinking skills. They empower students to face and handle challenges on their own, thereby strengthening their problem-solving skills and cognitive development.[41]

Rethinking evaluation methods

Evaluation methods stand as a crucial pillar within the context of graduate students' project-based learning.

With STEM project-based learning aiming to tackle real-world issues, traditional summative evaluations, typically paper-and-pencil tests, prove inadequate and can no longer embody the essence of such comprehensive learning. Consequently, a shift towards a new paradigm—formative evaluation is a necessity, bringing the focus towards ongoing feedback and adjustment during the learning process.

In this light, the concept of authentic assessment, proposed by Wiggins, serves as an effective alternative to traditional assessment methodologies.[42] Authentic assessment requires learners to apply their skills and knowledge to real-world, complex tasks and contexts. For example, in a project-based learning scenario involving the design of a sustainable energy solution, an authentic assessment might involve students presenting their energy model, explaining the science behind it, and providing a cost-benefit analysis.

Moreover, the assessment process within authentic assessment encompasses the entire project-based learning journey, from the brainstorming stage to the final product or result. In this process, graduate students must utilize their perception, association, decision-making, responsiveness, and execution abilities, thus gradually enhancing their comprehensive learning abilities.[43]

Compared to traditional evaluation methods, the strengths of authentic assessment lie in its capability to reflect a more comprehensive understanding of graduate students' performance and abilities throughout the project-based learning process. This evaluation method can accurately assess students' cognitive abilities while also considering their practical operational abilities and problem-solving capabilities. Furthermore, such an approach motivates graduate students to engage more actively in project-based learning, thereby improving their learning motivation, enthusiasm, and promoting accelerated growth and progress.[44]

Constructing a conducive learning environment

The development of a conducive learning environment is an integral aspect of project-based learning, necessitating a symbiotic collaboration between teachers and students. Such an environment supports and promotes the necessary skill acquisition, knowledge construction, and personal development vital for the success of project-based learning endeavors.

Blumenfeld *et al.*[33] propose an environment design that supports successful project-based learning, suggesting three specific requirements: Firstly, the environment should encourage inquiry, prompting students to question, investigate, and explore. For instance, the setup of a lab that allows for hands-on experimentation, or a digital platform that provides access to a wealth of resources, could stimulate student curiosity and initiate a cycle of inquiry and discovery. Secondly, the environment should provide autonomy, granting students the freedom to drive their projects according to their interests and learning goals. This could be facilitated through flexible curriculum structures, where students can personalize their learning paths, or through choice-based assignments, where students can select their projects based on their passions. Lastly, the environment should cultivate a sense of community, fostering collaboration, and shared responsibility among students. This could be achieved through the creation of collaborative spaces, both physical and digital, where students can share ideas, provide feedback, and work together towards common goals.

In sum, these three environmental components work synergistically to enable a more dynamic and immersive learning experience, thereby bolstering the effectiveness of project-based learning in graduate education.[45]

CONCLUSION

This paper discusses and analyzes STEM education from three aspects: connotation, characteristics, and implementation strategies for promoting graduate students' learning ability. Through the implementation of strategies such as deep learning, interdisciplinary integration, designing appropriate projects, improving teachers' professional competence, providing scaffold teaching, transforming evaluation methods, and creating a learning environment, STEM education can promote the improvement of graduate students' learning ability, increase their learning motivation and enthusiasm, and better adapt to the needs of future society.

Although this paper has discussed and analyzed the implementation strategies of STEM education, due to limitations in length and time, specific operational details of some strategies have not been thoroughly explored. In future research, it is necessary to further explore the implementation effects of these strategies and to investigate the influence of STEM education on educational reform and future society from a broader perspective, in order to provide more theoretical and practical support for the development and promotion of STEM education.

DECLARATION

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Author contributions

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