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Article

Exploring college students' perceptions of STEAM education in China—Taking Jiang'xi province as example

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Abstract: STEAM (science, technology, engineering, arts, and mathematics) education has recently been encouraged and attracted much national attention. This qualitative study aimed to conduct a thematic analysis of college student STEAM open responses to provide an examination of college students' perceptions of their STEAM experiences into the STEAM field. Based on transformative learning theory, a thematic analysis of 756 written responses to seven prompts by 108 college student participants revealed three primary themes: (1) exciting and challenging difficulties, and transdisciplinary learning in STEAM; (2) STEAM learning of gradual process, problem-oriented instruction, and creative problem solving; and (3) metacognition development in STEAM. The findings revealed that undergraduates' STEAM perceptions provide strong support for STEAM implementation to enhance teaching effectiveness in higher education.

Keywords: STEAM; STEAM education; STEAM experience; perception; transdisciplinary learning

1. Introduction

Numerous countries have embarked on comprehensive educational reforms to reshape teaching and learning, emphasizing the implementation of STEAM education to better prepare students for the challenges of the modern world (Park et al., 2016; Wahono et al., 2018). Evolving from STEM education in the United States, STEAM education emerged over a decade ago and has garnered significant attention and support both in Western nations and across Asia (Honey et al., 2014; Quigley and Herro, 2016; Wahono and Chang, 2019). STEAM education is an educational curriculum that integrates all the disciplines of STEAM to teach students to find answers to real-world problems (Guzey et al., 2017; Yildirim and Altun, 2015). Teachers intend to use various approaches to integrate these disciplines in a context or problem to help students learn from authentic experience or problem solving. The significance of STEAM education has also grown and attracted attention in the context of integrated education in China. The "13th Five-Year Plan Period to Comprehensively and In-depth Promote Education," published by the Chinese Ministry of Education in 2015, underscores the need to "explore new education models such as STEAM education and Maker education" (MOE, 2015). A subsequent report in 2016, titled "Education Informatization on Thirteenth Five-Year Plan," further emphasizes the imperative to "explore the implementation of STEAM education, Maker education, focusing on the improvement of students' information literacy, creativity, and innovation awareness" (MOE, 2016). These reports underscore the significance of STEAM in China and mark the initiation of its incorporation into the country's education system (China STEAM Report, 2017).

The integration of arts into STEM education represents a progressive trend aimed at enhancing the overall quality of education. Park et al. (2016) posit that the crucial link between subjects and real-life challenges serves as a cohesive force driving the integration of one or more disciplines within the STEAM (Science, Technology, Engineering, Arts, and Mathematics) framework into school curricula. The adoption of an integrated STEAM learning approach yields specific and acknowledged benefits for students. Firstly, the inclusion of arts serves as a strategy to engage a broader spectrum of learners, particularly those situated outside the traditional STEM disciplines (Ahn and Kwon, 2013; Ozkan and Topsakal, 2017). Moreover, this approach empowers students to employ creative thinking and imagination in addressing real-life problems with the aim of contributing to societal improvement (Daugherty, 2013). STEAM education becomes a catalyst for fostering students' innovation and creativity, as highlighted by Maeda (2013). Additionally, Liao (2016) contends that the incorporation of arts might be the missing element facilitating interdisciplinary learning experiences.

Despite the increasing acknowledgment of the potential benefits associated with STEAM education, the existing body of research in this domain remains limited. While a growing literature base delves into teaching practices and various models related to STEAM instruction (Bush and Cook, 2019; Bush et al., 2016; Camacho-Tamayo and Bernal-Ballen, 2023; Kong and Huo, 2014; Phonnong and Keeratichamroen, 2023; Quigley and Herro, 2016), there is a noticeable scarcity of empirical evidence appraising the effectiveness of STEAM teaching.

A predominant focus on teachers rather than students characterizes the current state of research (Bush and Cook, 2019; Ortiz-Revilla et al., 2023; Quigley et al., 2019; Silva-Hormazábal and Alsina, 2023; Voicu et al., 2022). Nevertheless, the limited research addressing student achievement presents promising findings, indicating that an integrated STEAM approach can exert a positive influence on students' learning outcomes in related subjects.

For instance, Arpaci et al. (2023), in their study involving primary school students, discovered that a space-themed STEAM learning module had the potential to enhance both academic achievement and students' interest in STEAM-related subjects. Quigley et al. (2017) adopted a project-based learning approach to integrate art into a marine science classroom, revealing that their integrated STEAM teaching stimulated students to explore additional academic subjects, including mathematics, foreign languages, liberal arts, and social studies. In another study, Miller and Knezek (2013) observed an increase in students' involvement, confidence, and personal discoveries, leading to the emergence of new opportunities and professional paths. While these findings offer promise, they underscore the need for further research to comprehensively assess the impact of STEAM education on both teachers and students.

In the landscape of STEAM education, the role of perceptual information and assessments becomes paramount in gauging the efficacy of instructional methods and student experiences (Bushe et al., 2020; Nelson et al., 2015). The significance of students' perceptions lies in their potential to enhance the fields of science, technology, engineering, arts, and mathematics (STEAM). By evaluating the content, processes, and overall scope of STEAM activities, students contribute valuable insights that position them as crucial resources for assessing the quality and richness of teacher feedback and, consequently, the effectiveness of instructional strategies. Despite the pivotal role that student perceptions play in shaping the trajectory of STEAM education, there exists a notable gap in research, particularly concerning college students. This is a critical gap considering the increasing prevalence of STEAM in educational settings. As STEAM gains prominence, engaging college students in this innovative and inclusive educational space designed for in-depth exploration of science and mathematics content becomes especially important. In addition, there is little research focusing on students' perceptions of STEAM, compared with other countries, such as South Korea, Germany, and America. With regards to students' perceptions of STEAM, we consider that the features of Chinese college students and STEAM effectiveness can be speculated by comparing them with college students from other countries. This study aims to fill this research void and contribute to the field of STEAM education by presenting insights into college students' perceptions of STEAM in China. The inquiry is guided by two core research questions: What are the perceptions of college students regarding STEAM and its impact on their learning? What challenges do college students encounter when engaging in STEAM? By addressing these questions, this research seeks to provide valuable guidance and research-based insights for educators and practitioners in higher education, fostering a more informed and effective integration of STEAM at the collegiate level.

2. Literature review

STEAM education, encompassing the integration of Science, Technology, Engineering, Arts, and Mathematics disciplines, represents a longstanding endeavor within the educational realm to fuse diverse perspectives, skills, and practices (Choi and Pak, 2006). This practice aligns with the broader concept of integrating various disciplines, reflecting the understanding that grappling with real-world complexities often necessitates a multidisciplinary approach (National Science and Technology Council, 2018; Shaw et al., 2018). While the integration of disciplines is a common practice, the empirical exploration of its effectiveness in enhancing learning outcomes has predominantly focused on specific STEAM subgroups, such as science and technology, mathematics and technology, or mathematics and engineering.

For instance, investigations by Hurley (2001) into 31 integrative studies of mathematics and science in classrooms revealed positive effects on students' academic achievement in both subjects. Becker and Park (2011) delved into the realm of integrated STEM disciplines in K12 education, reviewing empirical literature spanning the years 1989 to 2009. Their findings, particularly within elementary contexts, indicated an increase in student achievement in two out of three studies, leading them to conclude that STEM learning positively impacts students' motivation and achievements.

Further contributing to the discourse, Engelman et al. (2017) reported on the outcomes of STEAM projects in seven high schools, focusing on science and technology subjects. Their study revealed an augmentation of students' creativity and interest in computing, underscoring the potential for STEAM initiatives to enhance students' confidence and creative capacities. This collection of research underscores the multifaceted impacts of STEAM integration on various facets of student learning and engagement.

Within the scholarly discourse, it is acknowledged that the integration of multiple disciplines often unfolds with a particular discipline taking precedence over others (Arpaci et al., 2023; Perignat and Katz-Buonincontro, 2019). Although the literature underscores the benefits of interdisciplinary integration, the absence of conclusive evidence regarding the most advantageous or appropriate integration methods frequently places the onus on educators to make informed decisions (Becker and Park, 2011; Herro and Quigley, 2016). Furthermore, educators assigned to STEAM classrooms often find themselves inadequately equipped for integrative approaches due to limitations in their teacher education programs (Voicus et al., 2023). Kelley and Knowles (2016) emphasize the need for education to address disciplinary boundaries through the STEAM approach, particularly given that 21st-century challenges demand solutions that transcend these traditional boundaries. By explicitly incorporating the creative process into STEM education, STEAM effectively broadens its appeal to a more diverse learning population (Perignat and Katz-Buonincontro, 2019). This approach not only enhances students' interest and deepens their comprehension of science and technology but also aligns with teachers' aspirations to fortify their problem-solving skills (Bush et al., 2016; Guo and Dilley, 2018). Contrary to a perception that the arts merely append an additional letter "A," the arts, as articulated by Perignat and Katz-Buonincontro (2019) and Swaminathan and Schellenberg (2015), function as conduits that enable students to engage more profoundly with the content and practices of science and mathematics.

Despite the absence of empirical research definitively establishing the effectiveness of integrated STEM education, numerous schools express commitment to incorporating the arts within an integrated STEM learning model (Herro and Quigley, 2017; Park et al., 2021). This dedication signals a widespread acknowledgment and adoption of the potential advantages associated with integrating arts into STEM education.

The term "perception" holds diverse interpretations and requires differentiation from interchangeable terms like "conception" and "opinion." In the context of this study, perception is specifically defined as an impression formed based on a collection of experiences (Farland-Smith and Tiarani, 2016). Numerous factors contribute to shaping how learners perceive (Tran, 2018). Scientists utilize the term "perception" to denote a sensory understanding derived from lived experiences (Saptarani et al., 2019). In higher education settings, perceptional data have been employed to gauge college student perceptions of e-feedback (Chong, 2019), specific theories (Hokayem and BouJaoude, 2008), lecture methods (Covill, 2011), and classroom organization (Weaver and Qi, 2005). Although perception is commonly applied to measure student interest, motivation, and attitudinal responses to content and ideas, it is not frequently employed as a valuable teacher feedback instrument (Nelson et al., 2015). Despite the existence of perceptual evaluations, instructors often rely on personal experiences to enhance instruction or delivery methods, potentially neglecting the voices of students associated with evidence-based teaching practices (VanTassel-Baska et al., 2007). Perceptual assessments serve as a valuable source of meaningful, critical feedback for instructors and curriculum designers regarding the student experience (El-Deghaidy and Mansour, 2015; Nelson et al., 2015). While there is no extensive body of empirical literature on students' attitudes in integrated STEAM learning settings, numerous studies explore students' attitudes in STEM learning settings, predominantly at the high school level (Brown et al., 2016; El-Deghaidy and Mansour, 2015; Matsuura and Nakamura, 2021; Roberts et al., 2018; Vennix et al., 2017). The way a student perceives STEM is shaped by their motivations, experiential knowledge, and self-efficacy (Roberts et al., 2018). Additionally, Roberts et al. (2018) underscored that students' academic and social experiences significantly impact their positive perception of learning and, consequently, their approach to learning STEM. Offering all students authentic opportunities for participation and learning in STEM is pivotal for cultivating positive attitudes toward STEM (Roberts et al., 2018). In a qualitative research endeavor, Bush et al. (2020) delved into elementary students' perceptions of STEAM learning experiences, revealing that students found STEAM projects challenging and enjoyable. However, their STEAM experiences were not perceived as meaningful compared to other experiences they described. Tran (2018) observed various factors influencing how students perceive STEM content, including attitudes, self-efficacy, conceptualization, and the learning environment. Therefore, investigating student perception provides a unique perspective and a significant opportunity for enhancing student achievement in STEAM.

3. Theoretical framework

Mezirow's transformative learning theory (Mezirow, 2009) serves as the theoretical framework for this study, aiming to elucidate students' perspectives on STEAM. This section intricately explicates transformative learning and its correlation with STEAM, with particular emphasis on interdisciplinary and transdisciplinary learning experiences. Transformative learning, as posited by Mezirow (2009), entails the conversion of limiting perspectives into more inclusive, open, and reflective ways of perceiving the world. In this context, these perspectives are delineated as frames of reference, encompassing habits of mind, cognitive processes, and perspectives on meaning—a lens through which learners interpret their surroundings. Mezirow contends that culture and language contribute to the shaping of these frameworks as learners seek to make sense of their experiences. Once established, these frames of reference persist throughout an activity, unit, or class. A transformative learning experience is one that fundamentally alters how learners perceive their environment, subsequently influencing their beliefs, expectations, and goals (Cranton and King, 2003; Mezirow, 2009). However, Mezirow acknowledges the inherent challenge of integrating new ideas into existing frames of reference. To foster cognitive shifts and broaden learners' frames, it is essential to provide opportunities for novel learning experiences that either expand or challenge their preconceptions (Cranton and King, 2003; Mezirow, 2009).

Instrumental learning and communicative learning represent distinct categories of transformative learning experiences. Habermas (1984) delineated instrumental learning as the enhancement of practical skills, encompassing abilities like bridge building, multiplication, plant identification, and time-telling. Communicative learning, on the other hand, involves the accurate interpretation and understanding of others' expressions, as well as effective self-expression. Both instrumental and communicative learning have the potential to bring about transformation in students. However, it is noteworthy that instrumental learning primarily impacts a limited subset of frames of reference for comprehension. For instance, when a child acquires a novel method for adding two numbers, their cognitive framework undergoes expansion. However, this expansion is confined to the realm of mathematics and is specific to the adopted addition strategy. Instrumental learning, occurring within the context of interdisciplinary studies, provides students the chance to broaden their frames of reference, albeit within the confines of the designated learning context. Conversely, communicative learning revolves around comprehending individuals and the surrounding world, constituting a student-centric approach. This form of learning, characterized by its expansive scope and integration of self-reflection, serves as a focal point for more profound transformations. Such educational opportunities are meticulously designed to intentionally reshape perceptions or cognitive habits. Choi and Pak (2006) characterized this form of learning as interdisciplinary in nature, positing its heightened transformative potential due to its emphasis on both students and the investigated inquiry. The students' objective extends beyond the acquisition of a mere skill set; rather, it involves a commitment to contributing to the betterment of the world. Transformative learning necessitates a student-centered approach that centers on existing frames of reference, recognizing that students are limited in their ability to expand or alter these frames to encompass ideas or perceptions beyond their current understanding (Kegan, 2000).

4. Methodology

This study employed a case study approach using qualitative research methods. A case study is a detailed description and involves the exploration of an issue through one or more cases within a specific context or setting (Creswell and Creswell, 2018). A qualitative case study design was preferred because of the opportunity to discover college students' perspectives on STEAM in detail, starting from the experiences of the college students who had experiences with STEAM, resulting in an extensive and holistic account of how undergraduates perceive their STEAM learning experience (Creswell, 2007). This qualitative case research study provides findings from a thematic analysis of college students' perceptions that can expand educators' and researchers' understanding of the practices, advantages, and challenges of STEAM. This section describes the participants and environment of the study, the data source and collection, the thematic analysis, the findings, and conclusion.

4.1. Participants and settings

This study was carried out with college students in a comprehensive university in Jiangxi province. This university was chosen because it has STEAM lab and regular STEAM programs offered to students. 108 students, 68 female and 40 males from four different school years were enrolled to participate in this study. The sample is composed of college students who engaged STEAM education. Purposeful sampling was used in this study because the primary consideration is whether they are directly related to the research topic rather than whether they are representative of the universe or not when selecting participants (Neuman, 2012). Purposive sampling gives us the opportunity to study cases that are believed to be rich with information (Yıldırım and Şimşek, 2008). This study is aimed at analyzing the perceptions of those involved in this study.

4.2. Data source and collection

A qualitative survey was used to gather college students' perceptions of their STEAM experiences. The survey was administered to a total of 108 college students in the case university who participated with STEAM, which included the following seven open-ended questions:

1) Describe your experiences with STEAM.
2) What do you like of the STEAM programs that provided to you and why?
3) What was the most unforgettable STEAM experience for you and why?
4) Describe how STEAM has influenced your learning.
5) What other aspects does STEAM affect you (i.e., mindset, cognition, understanding)?
6) In your eyes, what is the difference between STEAM instruction and traditional instruction?
7) What was the challenge(s) you have encountered when you engaged with STEAM?

All 108 participant students were allowed to anonymously respond to all seven open-ended questions, making for up to 756 student responses. The surveys were administered on campus in daytime during the school day. All the responses were transcribed by MAXQDA software and collated into eight documents, one per question. Students' consent of participation was collected before the survey and enabled collection and analysis of their handouts copies of STEAM program. All the information that may identify student or teacher was removed.

4.3. Thematic analysis

This study conducted a thematic analysis. At the beginning of our analysis, a list of emergent codes was created on the basis of the first impressions of common themes as transcribed. Feedback and adjustments were provided to adjust the codes to better define the individual codes. We used random number generation to determine which student responses were coded as a starting point. From four different school years, we randomly selected one student response from each of the seven questions. Each of these 28 student responses (7 responses from four school years) was independently coded by researchers. Subsequently, the coding of researchers was merged in a common document, and the researchers met to discuss the similarities and differences from this initial round of coding. The researchers discussed and refined the coding listings through collaboration to ensure clarity and to eliminate gaps and overlapping codes. This process was repeated with two student responses for each school year, meaning that the researchers independently coded the same 56 student responses in round two. The next discussion was devoted to further distinguishing the similarities and differences and refining the coding lists. We chose a flexible coding list to capture college students' perceptions of STEAM in an authentic and organic way because there is lack of research on undergraduate perceptions of STEAM. As the researchers coded independently and discussed student responses in teams, several themes emerged which required refining the existing codes or creating a new code to reflect the situational awareness the researchers gained through this process. For example, the Effective Group Works, Real-world Problems, Challenging Process, and Creative Problem-Target Solving codes clearly embodied this. These four codes were eventually developed into a hierarchy to capture the different types of STEAM perceptions that were described by college students. This allowed researchers to examine various STEAM experiences as they were perceived by undergraduates.

Next, researchers equally coded the remaining student responses. An equal number of college student responses were coded with each of the researcher. All coding was done autonomously, with each researcher coding in her own file to prevent them from seeing each other's codes. Upon completion of all independent coding, we met to combine the individual codes into one master file. If we fully agreed on how to code a student's answer, no further discussion would be needed and the response would be considered fully coded. The pairs of coders reached complete agreement on 68% (Q1), 62% (Q2), 56% (Q3), 52% (Q4), 63% (Q5), 68% (Q6), and 65% (Q7) of the initial coding, which was reasonable considering the complexity of the flexible coding list. Because this concordance was less than 80%, in line with Creswell and Poth's (2018) suggestion, we chose consistent meetings, resulting in 100% concordance. Thus, if we coding one student's response identified conflicting coding, the student's answer and the conflicting coding associated with it would be discussed together. To discuss any coding disagreements, both researchers met as a regularly via Zoom video call once a week for about 6 months. Any discrepancies in coding were discussed until a consensus from researchers could be reached. At the end of the coding procedure, 100 % agreement was achieved between the coders for all responses. The final list of codes and their definitions are presented in **Table 1**. Upon completion, the codes were examined for duplication and redundancy and then grouped into broad themes (Creswell, 2013). Triangulation was carried out across participants from different colleges, taking care to maintain an audit trail back to the original data. The researchers shared their scientific, mathematical, and STEAM content expertise through the collaborative coding process.

5. Results

The themes that emerged as a result of the data analysis have been presented in tables. **Table 1** displays the basic information of participants, including their gender, major, grade, and age. STEM-related majors include science, technology, engineering, and mathematics while arts include fine arts and liberal arts; others refer to the rest majors that are excluded to STEM and Arts.

Table 1. Demographic of participants.

Content		Number
Gender	Male	40
	Female	68

Table 1. (*Continued*).

Content		Number
Grade	Year 1	21
	Year 2	46
	Year 3	34
	Year 4	7
Major	STEM-related majors	67
	Arts	23
	Others	18
Age	Less than 18	1
	19–20	63
	21–22	41
	23–25	3
	Above 25	0

Our thematic analysis focuses on key findings related to undergraduates' perceptions of STEAM, which emerged both internally (recurring themes) and across codes, in order to build an understanding of undergraduates' STEAM experiences to inform the field. **Table 2** shows the codes we have drawn from the transcripts with some examples to elaborate on the code. We put all the codes into different categories: general description of STEAM (include definition, positive attitude, negative attitude, and fun, challenging experience, and transdisciplinary learning); STEAM process (include instructions, content knowledge, integration); and benefits and challenges (include thinking ability, helpful on career, time, multiple perspectives, and well-rounded student attributes). We cross-referenced all the codes and concluded three themes to the examination of student responses: (1) exciting and challenging difficulties, and transdisciplinary learning in STEAM; (2) STEAM activities are gradual process, problem-oriented instruction, and creative problem solving; and (3) STEAM benefits the metacognition development.

Table 2. List of codes.

Codes	Explanation	Example
STEAM: Definition (Content area)	Perceive STEAM as two or more than two of the disciplines that the acronym represents. For example, the student indicates that STEAM is all about math and science.	STEAM combines subjects like math and science to solve problems. (S2) STEAM involves both engineering and technology to create innovative solutions. (S10)
STEAM: definition (Singular)	The student perceive STEAM as an independent subject, like a math-related subject. The student indicates STEAM as a compound singular discipline.	To me, STEAM is a selective course, mainly about math. (S27) For me, STEAM is mainly about technology and how it can be applied to different areas. (S50)
STEAM: definition (Acronym)	The student indicates a transdisciplinary or cross-disciplines of all the subjects for which STEAM stands. The student notes what the acronym stands for.	STEAM stands for five different subjects and it integrates all these areas. (S56) In STEAM, we learn how different subjects like art and science work together to solve real-world problems. (S6)

Table 2. (*Continued*).

Codes	Explanation	Example
STEAM: fun, challenging experience	Explains STEAM as fun and exciting approach that encourages creative solutions for problems, deeper understanding of each involved subject and requires more attention in classroom; includes challenging but overcoming in describing STEAM experience.	STEAM projects are really fun because they let you be creative and solve real problems, even though they can be challenging. (S36) I find STEAM exciting because it makes learning hands-on and interactive. (S72) STEAM activities are challenging but enjoyable because they push us to think differently. (S13)
STEAM: authentic Problem Solving	Highlights authentic/real-world problem-solving; Includes real-world problems in describing STEAM experiences. The student is interested in finding solutions for these authentic problems.	In STEAM, we worked on creating a water filtration system for a real village in need. (S33) Our STEAM projects often tackle real-world issues, like designing sustainable energy solutions. (S61) STEAM activities focus on solving real-life problems, making the learning experience more meaningful. (S15)
STEAM Attitude P	Indicates a positive experience with STEAM.	I really enjoyed the STEAM programs because they were engaging and educational. (S4) STEAM projects are my favorite part of school because they are so interactive and fun. (S11) I have a positive outlook on STEAM because it makes learning exciting and relevant. (S84)
STEAM Attitude N	Indicates a negative experience with STEAM.	I found the STEAM projects are challenging, so sometimes I feel frustrated and difficult to understand. (S36)
Content Knowledge	Identifies content knowledge involved more than one subject. STEAM helped to break the boundary between subjects (i.e., student learned more than one subject). Note the subject.	The project helped me learn both science and math concepts simultaneously. (S26) In STEAM, we integrated technology and art to create our final project. (S41) STEAM activities combine knowledge from multiple subjects, like engineering and mathematics. (S79)
Well-rounded Student Attributes	Highlights behavior consistent with "a well-rounded student" (e.g., focus, pay effort, persistence).	STEAM projects made me more persistent and focused, as they required a lot of effort to complete. (S55) Engaging in STEAM activities has helped me develop better time-management and organizational skills. (S13) STEAM challenges have taught me the value of persistence and hard work. (S46)
Multiple Perspectives	Indicates how to look at problem through different perspectives in STEAM process, which help or aid with thinking ability.	STEAM taught me to look at problems from different angles and come up with creative solutions. (S17) In STEAM, we learn to approach issues from various perspectives to find the best solution. (S51) The multidisciplinary nature of STEAM encourages us to think outside the box. (S102)

Table 2. (*Continued*).

Codes	Explanation	Example
Helpful in Career or Future	Explains STEAM will help or aid with job-hunting or future goals (i.e., skills learned, more knowledge content acquisition).	The skills I learned in STEAM, like coding and problem-solving, will be really useful in my future career. (S67) STEAM projects give us practical skills that can be applied in various careers. (S54)
Scientific Content +	A lot Scientific content in STEAM.	Our STEAM project involved a lot of biology and chemistry to create an eco-friendly garden. (S23) We used scientific principles to design and test our STEAM models. (S8)
Mathematics Content +	A lot Mathematics content in STEAM.	We used a lot of geometry and algebra in our STEAM project to design a model city. (S82) Mathematics played a key role in solving the problems presented in our STEAM activities. (S62) Our STEAM projects required advanced mathematical calculations and analysis. (S20)
Arts Integration	Indicates various forms of arts are used during STEAM implementation or presented in the final creation.	We incorporated painting and sculpture into our engineering project to make it more aesthetically pleasing. (S17) Our final STEAM project included elements of visual arts and design. (S104)
Technology integration	Highlights teachers' STEAM implementation is carried out through various kinds of technology (e.g., computer, 3D printer, VR).	We used 3D printers and VR technology to create prototypes for our STEAM projects. (S35) We often used advanced technologies like robotics and coding in our STEAM projects. (S85)
Transdisciplinary learning	Highlights the process of transdisciplinary learning that benefits students' academic learning and their thinking.	STEAM projects helped me connect concepts from different subjects and see how they relate to each other. (S25) In STEAM, we learn how to integrate knowledge from various disciplines to solve complex problems. (S57) The transdisciplinary approach in STEAM enhances our overall learning experience. (S104)
Collaboration	Provides experience that requires collaboration during STEAM instruction and highlights the importance of collaboration or teamwork skills in STEAM practices.	Working on STEAM projects required a lot of teamwork and collaboration with my classmates. (S32) STEAM activities often involve group work, teaching us how to cooperate and communicate effectively. (S54) Collaborating with peers on STEAM projects has improved my teamwork skills. (S102)
Independence	Explains the student needs to do everything on their own, including producing new ideas, finding solutions, making the product, etc.	STEAM projects required me to come up with ideas and solutions independently, which was challenging but rewarding. (S33) In STEAM, we are encouraged to work independently and take ownership of our projects. (S57)

Table 2. (*Continued*).

Codes	Explanation	Example
STEAM: Metacognition P	STEAM positively influenced metacognitive thinking skills or self-reflection.	STEAM projects helped me reflect on my learning process and improve my problem-solving strategies. (S16) I learned to think about how I think through STEAM activities, which has improved my learning. (S25) STEAM encourages self-reflection and helps me understand our own learning processes. (S89)
STEAM: Metacognition N	STEAM negatively influenced metacognitive thinking skills or self-reflection.	I found that STEAM projects sometimes made it hard to reflect on my learning because they were too complex. (S41) STEAM's fast pace sometimes leaves little room for metacognitive thinking. (S63)
STEAM: Activities	Student indicates projects or programs that are either too easy or too difficult for them; includes devoid of content knowledge or connection with all STEAM subjects in describing STEAM instructional practices.	Some STEAM activities were too easy and didn't challenge me enough, while others were too difficult to understand. (S37) There are STEAM projects that seem disconnected from the actual subjects they are supposed to integrate. (S44)
STEAM: Process	Explains STEAM is more of process focused.	STEAM education is more about the process of problem-solving and experimentation rather than just the final product. (S9) The focus in STEAM is on the steps we take to reach a solution, not just the solution itself. (S74)
Materials	Indicates that there is too many materials to use, which also cause confusion.	There were so many materials involved in the STEAM project that it sometimes became confusing to manage them all. (S16) Handling numerous materials in STEAM activities can lead to confusion and disorganization. (S85)
Time	Indicates it needs more time to engage with STEAM; Projects or programs in STEAM requires more time to find a better solution or get a better outcome; time-consuming is a challenge in STEAM.	We often need more time to thoroughly engage with STEAM activities and find the best solutions. (S55) Time management is a significant challenge in completing STEAM projects effectively. (S93)
Problem-based instruction	Explains the STEAM instructions are mainly problem-based or project-based instruction, which is quite different from the traditional instruction.	We did a STEAM project where we had to design a bridge using limited materials. It was very hands-on and project-focused. (S4) In STEAM, we take the lead in our learning, which is different from the teacher-led traditional approach. (S59) STEAM projects often involve building or creating something practical. (S85)
Understanding	Indicates the student has a deeper understanding towards STEAM.	Through STEAM, I gained a much deeper understanding of how different subjects can work together to solve real-world problems. (S37) I now have a better grasp of how STEAM subjects relate to each other. (S93)

Table 2. (*Continued*).

Codes	Explanation	Example
Thinking Ability	STEAM aided in some sort of higher order thinking, including creative thinking, and critical thinking.	STEAM education helped improve my critical thinking and problem-solving skills. (S49) Engaging in STEAM projects has enhanced my analytical thinking abilities. (S67) During the STEAM project, we had to come up with a unique solution to reduce plastic waste. We brainstormed various innovative ideas, eventually creating biodegradable packaging. This activity greatly enhanced our creative thinking skills. (S26) One of the most impressive tasks we did in STEAM was developing an art installation that could also function as a solar panel. Combining art and technology required us to think outside the box and come up with imaginative solutions. (S65)

Note: STEAM = science, technology, engineering, arts, and mathematics.

Finding 1: Exciting and challenging difficulties, and transdisciplinary learning in STEAM.

One of the themes that emerged from our thematic analysis was students' perceptions of STEAM itself. College students commented frequently on STEAM programs they engaged in such as designing a flower bed for school department or making a tool for the disabled. For example:

> One of our assignments this year in the STEAM program was the design of a flower bed. At first, I thought it would be easy to do that. Then I understand that the design must be visually beautiful, feasible within the budget and easy to accomplish. We (the team) tried several ideas and finally discussed a better idea that we all satisfied. We used math, science, arts to find out how to meet these requirements. We all felt excited when we came forward the final idea. (S9).
>
> We made shoes for flatfoot. We need to understand that the shoes for flatfoot should be comfortable and nice to high arches for walking. We tested dozens of people and found a suitable material that fits all requirements. We need to use knowledge from different disciplines and deepen our understanding to those disciplines. It was a memorable curricula. (S21)

In a typical traditional classroom, the subject knowledge is often separated from each other. However, students who participate in STEAM programs are able to apply compound knowledge from various disciplines to solve problems (Allina, 2018; Biffle, 2016; Park and Ko, 2012; Sousa and Pilecki, 2013). The application of compound knowledge requires through learning various disciplines. We know from the literature that STEAM combines at least two subjects with transdisciplinary teaching (Guyotte et al., 2014; Sousa and Pilecki, 2013). Students also mentioned transdisciplinary learning informing their experience. Though college students learn different subjects, the application of different subjects would be a challenging difficulty for them. Although many STEAM questions centered on content and practice from science and math, students mostly talked about engaging with transdisciplinary practice and content in their responses. We noticed this pattern in particular when we analyzed our coding for the sixth survey question (In your eyes, what is the difference between STEAM instruction and traditional instruction?), which were a comparison survey prompt. 46 (42 percent) college students reported student-centered teaching and more technology used in STEAM than traditional instruction, and 76 (70percent) students reported using knowledge from more than two disciplines, especially math and science content, to engage in STEAM in response to the comparison question in Question 6. In addition, 32 (30 percent) college students mentioned arts integration in responses to Question 6. Students' descriptions of how they used their knowledge of multiple disciplines to solve problems included responses such as:

> We needed mechanics to help us because [we] need to make it [machine] moving in water. (S60)
>
> This time we need to know how wheelie lifts objects. We had to use our knowledge of wheelie and mechanics if there was no electricity. (S12)
>
> When we had to built a house in tropical area we had to know the changes in temperature, consider the amount of light indoors, load-bearing of house, aesthetics of the house, the annual rainfall, ventilation, etc., and had to use multiple knowledge to reach the purpose. (S79)

Though question three and six asked students to specifically address the most unforgettable STEAM experience and the difference to traditional instruction, some students provided responses across the various learning opportunities that were ideal for capturing the transdisciplinary nature of inquiry that some students experienced. These students' responses showed the knowledge from one subject used and the seamless connection to the other context, clearly showing the students knew how to combine various knowledge from different subjects. Answers like the ones below represent the kind of collaborative, transformative learning (Mezirow, 2009) that educators want to engage students with:

> Our task is to create prostheses, and we must combine our knowledge of math, body mechanics, and aesthetics in order to design prostheses that meet the needs of the human body. (S48)
>
> When we want to make chairs must also be flexible to use a variety of disciplines, although it seems very simple, but also involves a combination of transdisciplinary content, such as mathematics, ergonomics, aesthetics, mechanics. (S57)
>
> Our task was to design houses suitable for construction in earthquake zones, which also required the application of a great deal of interdisciplinary knowledge, including geology, architecture, aesthetics, math, mechanics, and so on. It was a very complex task, but completed with a new understanding of these disciplines. (S35)

Finding 2: Gradual process, problem-oriented instruction, and creative problem solving.

The descriptions of college students' STEAM learning experiences was another theme that emerged through the coding process. To better describe the experiences described by students, three codes were employed throughout the procedure: Gradual Process, Problem-Oriented Teaching, and Creative Problem Solving. These three codes ultimately represented a hierarchy of college students' STEAM learning experiences, as they correlated with the depth of content and practice development within the STEAM inquiry.

Gradual Process. These STEAM activities were progressively advanced and represented experiences students generally considered exciting and challenging, with a clear connection to transdisciplinary content or practice. Instructional practices designed by teachers as part of the STEAM program required a clear alignment to other disciplines. Answers coded this way excluded empathetic elements or were not a genuine request (for example, to solve a real problem in the college, community, or elsewhere). For example:

> I've had fun STEAM experiences this semester, such as powering up a boat and making it move forward on the water automatically. (S53)

In conjunction with the theoretical framework, STEAM practices align with instrumental learning because these experiences involve problem-oriented learning (Mezirow, 2009). These responses coded as Gradual Process because the STEAM activities were designed to be progressively more difficult, and during this progress, students' learning of transdisciplinary content and practices increased. Due to a large amount of responses connected to learning, experiences coded as Gradual Process might indicate a transform in students' perception about subjects, learning, and application of learning.

Problem-Oriented Instruction. The next code in the hierarchy was Problem-Oriented Instruction. These experiences included responses from students such as the following:

> My experience was challenging. We had to clean the trash and silt in the river at a low cost, we studies mechanics. (S61)

In this particular response, the students mentioned their inquiry activity to study the environmental impact of cleaning up silt, trash and debris. In a recent news story about residents along the river who were affected by trash in the river, students learned that many residents volunteered to help clean up trash in the river. From a real-world context, students were eager to address a similar problem in their classrooms. This code was given when students described an authentic/real-world connection and specific problem. These experiences are also consistent with instrumental learning because of the problem-oriented nature of learning (Mezirow, 2009). Responses coded as Problem-Oriented Instruction represent a more transformative learning experience for students due to the extended frames of reference it enlarged for students regarding specific content or practices. For example, one college student explained that her experience in STEAM involved taking measurements of wind speeds to build a windmill for the Plains.

> We measure wind speed in different places every day. (S31)

This student response demonstrates the connection between inquiry, mechanics and math learning content, and learning applications. The above experience was transformative for students as their frame of reference was expanded to include context-specific content-based experiences. However, these instrumental opportunities are difficult to generalize to other real-world opportunities, the experiences coded as Problem-Oriented Instruction may change students' perceptions of the application of learning and likely to change their perceptions of learning itself. STEAM experiences that are coded as Problem-Oriented Instruction are more meaningful to students because it not only shows the difference to traditional classrooms but also allows students to expand their perceptions of learning and their development of content.

Creative Problem Solving. Creative Problem Solving was the top code in the hierarchy of STEAM learning experiences. Students responded to this code by having experienced the following:

> When making the underwater machine, my team had to find a way to make all parts of the motor waterproof and corrosion-resistant. We designed the paddles and fairings to encapsulate the ESC potting on the bottom of the mounting block to achieve an effective water-cooling add-on. (S52)

College students who responded with this code were highly engaged in their own learning and in their shared STEAM experience. These experiences can be classified as creative learning because of the creative outcome of the learning (Mezirow, 2009; Sousa and Pilecki, 2013). The main difference in the students' responses to this code is that the students articulated how they solved the problem creatively, which represents the ability to innovate. Creativity can be developed through daily experiences (Stein, 1987).

Creative Problem Solving is a powerful transformative force in itself. Students responding to this code demonstrated creative thinking in addressing STEAM issues. Additionally, students' responses indicated that their frames of reference were greatly expanded by finding creative solutions to situations beyond their immediate experience. True transformational experiences change the very way an outcome imagined to happen (Mezirow, 2009). In order for this to happen, students must be exposed to a variety of sociocultural scenarios in which they are able to think divergently and creatively. In the responses coded as Creative Problem Solving, students demonstrated the ability to solve problems in a new way that served as a means of transcending disciplinary boundaries because students did not focus on learning and applying knowledge content for some end, but rather focused on finding a novel idea through multiple content to solve the issue at hand, thereby transcending disciplines.

Finding 3: Metacognition Development in STEAM.

Undergraduates' ability to describe a change in their own thinking was another theme that emerged. Undergraduates demonstrated a level of meta-cognitive understanding through their STEAM experiences. Undergraduate responses indicated that STEAM experiences changed how they perceived learning, thinking, and applying content. For example:

> STEAM helped me change the way I used to think, instead of thinking random, ordinary ideas. STEAM gave me a whole new way of thinking about how my ideas could change the world and make a difference for years to come. (S49)

> STEAM has made me realize that there should be no boundaries between subjects and that the application of knowledge is holistic and flexible. There is more than one solution to a real problem, and this has changed the way I think about things, and STEAM has helped me realize a whole new way of thinking. (S91)

Such responses from undergraduates embody the shift in perception that is necessary to expand the frame of reference of the individual. The theory of transformative learning is a meta-cognitive evaluation of instrumental and dialogical learning and thinking (Mezirow, 2009). In this way, the expansion of frames of reference is a self-reflective process (Mezirow, 2009). It is our belief that undergraduates need to understand how their ideas grow and consequently, how they affect and improve the environment surround them. STEAM experiences provide a robust opportunity for undergraduates to engage in self-reflection and metacognition to verify such a path. Critical reflection on assumptions is necessary for transformative learning to occur (Mezirow, 2009). This study coded 15 (14%) undergraduate responses where they identified STEAM experiences as meta-cognitive journeys that enhanced their ability to reflect on their own thinking. For example:

> STEAM experiences have changed my way of thinking, because now I've learned that I should look into issues from different angles, that I shall try different ways, that I try things out and revise myself, and that I should collaborate with my group. (S52)

The example above illustrates a shift in the habits of mind of undergraduates. This particular undergraduate is the embodiment of the metacognitive shifts that are necessary to spark his or her frame of reference growth. Although the fifth survey question (What other aspects does STEAM affect you (i.e., mindset, cognition, thinking habits)?) directly asks for metacognitive thinking, the responses from the participants reveal a rich and transformative process for the participants through their STEAM learning. For example:

> I used to think that science was just a concept that was far away from me, now I know that science is everywhere in life. (S49)
>
> I used to think that disciplines were very different from each other, but now I know that disciplinary integration is everywhere. (S36)

The responses above clearly illustrate undergraduate's shift in thinking about the value and application of knowledge content. Ultimately, our goal is to empower students to rethink what learning should be and how it should be applied. Undergraduate responses above illustrate how meaningful STEAM experiences can transform undergraduates' frameworks for learning and applying content and practices.

6. Discussion

This study investigates the implementation and impact of STEAM (Science, Technology, Engineering, Arts, and Mathematics) education through the lens of transformative learning theory, focusing on how such educational interventions can facilitate significant shifts in students' understanding and practices. Transformative learning theory, as articulated by Jack Mezirow, provides a framework for understanding how learning experiences can lead to fundamental changes in perspective and behavior, which is particularly relevant in the context of STEAM education.

The findings of this study highlight that STEAM education offers more than just interdisciplinary content; it embodies a pedagogical approach that aligns with the principles of transformative learning. Central to transformative learning is the concept of critical reflection, which is essential for challenging and revising existing frames of reference. In this study, STEAM learning activities, through their integrative and problem-based nature, provided students with opportunities to critically reflect on their own knowledge and perspectives. For instance, students engaged in collaborative projects that required them to apply mathematical theories in real-world engineering problems or to integrate artistic design with scientific experimentation. These activities encouraged students to question traditional boundaries between disciplines and reconsider their preconceived notions about problem-solving and knowledge application.

The data reveal that students who participated in these STEAM activities experienced significant shifts in their understanding of the connections between different fields of study. This is consistent with Mezirow's idea of perspective transformation, where learners reassess and modify their existing cognitive frameworks. The integration of various STEAM components in the curriculum required students to engage in reflective thinking about how different disciplines interact and contribute to comprehensive problem-solving approaches. Such experiences facilitated deeper learning and enabled students to view challenges from multiple angles, thus expanding their cognitive and practical skill sets. Moreover, the study underscores the role of STEAM education in fostering metacognitive development, a crucial aspect of transformative learning. Metacognition involves students reflecting on their thought processes, which can lead to more effective learning strategies and problem-solving techniques. The STEAM projects documented in this study often involved iterative design processes, where students assessed and refined their work based on feedback and reflection. This iterative nature not only enhanced students' technical skills but also promoted a reflective mindset, allowing them to develop greater self-awareness and adaptability in their learning practices.

The transformative impact of STEAM education also aligns with the theory's emphasis on fostering personal growth and empowerment. Students reported increased confidence in their ability to tackle complex problems and a greater appreciation for the relevance of interdisciplinary knowledge. By engaging in STEAM activities that bridge the gap between theoretical knowledge and practical application, students were able to develop a more holistic view of their educational experiences and their future professional roles. This empowerment is indicative of a transformative learning outcome, where students not only gain new skills but also experience a shift in their identity and agency as learners.

In summary, this study illustrates how STEAM education can serve as a powerful catalyst for transformative learning. The integration of disciplines within STEAM curricula provides students with opportunities for critical reflection, metacognitive development, and personal empowerment. These elements are essential for facilitating the perspective transformations central to transformative learning theory. The findings suggest that STEAM education, by promoting interdisciplinary thinking and reflective practice, can effectively contribute to deeper, more meaningful learning experiences that prepare students for complex, real-world challenges. Thus, this study supports the notion that STEAM education aligns well with transformative learning principles, offering valuable insights into how educational practices can be designed to foster significant cognitive and personal growth.

7. Implications and conclusion

This section discusses the implications and conclusions related to each of the three themes that emerged. With regard to the theme of identifying transdisciplinary STEAM learning, the most promising finding was that students could absorb and apply the content and practices they learned in STEAM. It is predictable that students were far more likely to accept transdisciplinary instruction used in STEAM than traditional teacher-centered instruction used in China. Undergraduates can also identify technology integration, arts integration, science-based inquiry, and mathematics content. It is surprising that undergraduates tend to identify mathematics in their STEAM learning rather than science, even though the STEAM inquiries contexts were science-based. Identifying mathematics was typically well defined (e.g., counting, measuring area or volume, finding ratio, multiplying). We remained curious as to whether students articulated science content less because it was more deeply embedded in inquiry. Typically, students receive much more time in math than in science, and perhaps they have more experience with math. Although the answers to these questions lie beyond the scope of this study, there remains one important implication for the field. Clearly, transdisciplinary learning experiences must ensure that students engage in and complete inquiry with clear recognition and identification of multiple disciplines content and practices, especially mathematics and science, they have learned and applied. This allows students to see the relevance and connection of their STEAM learning to authentic problems being solved to improve the world. In addition, we believe that this awareness is important for the expansion of students' frames of reference so that they will be better able to take advantage of their STEAM learning experiences in the future.

The results regarding the STEAM gradual process, problem-oriented instruction, and creative problem solving strongly support the idea that not all STEAM inquires lead to the same type of experience or are of the same quality. High-quality STEAM practices offer opportunities for undergraduates to experience firsthand how key ideas can be used to solve real-world problems, and for them to clearly understand why this practice is important and what it is meant to accomplish (Bush and Cook, 2019). Although many STEAM learning opportunities have the potential to transform learning for learners in different ways, some opportunities are better suited for expanding learners' frames of reference. We believe creative thinking is an essential component in helping undergraduates connect their learning to a larger purpose. Through creative ideas, undergraduates are able to see how their learning can be helpful to a variety of situations and expand their knowledge beyond their own understanding of themselves. These experiences provide a great opportunity for students to broaden the frameworks they use. Since creative thinking is nurtured and developed through creative experiences (Amabile, 2017), the way how STEAM is planned and carried out is important. By including creative thinking, teachers have the opportunity to position students for generalizing their learning to many different situations and generate novel ideas as their frames of reference increase. It is considered that creative thinking is important for making novel ideas, creating new products, and influencing future life (Cohen, 1989). Thus, we found that undergraduates broadened their frames of reference to include more creative ideas about the world and society they would one day shape in the undergraduate responses coded as Creative Problem Solving. In order to ensure that students' frameworks are expanded by experiencing STEAM, we recommend that teachers continually reflect on their own practices and the intended results for any STEAM-based instruction. Teachers need to know and understand the prior experiences of each learner, as the classroom is a multicultural furnace of each growing learner. Only then is it possible to plan STEAM practices within the student's current frame of reference, ensuring equal access to the context as well as to transdisciplinary learning. STEAM education has the potential of cultivating and growing a future society of deeply and critically thinking individuals by intentionally building upon the prior learning of students. This study found that creative thinking was a key outcome of the STEAM learning experience for students to reach the point of having a transformational learning experience. While STEAM can be a powerful tool for providing transformative learning experiences that broaden learners' frames of reference, educating the whole learner, and empowering learners to improve the world, it falls to researchers and practitioners in the field to ensure that STEAM instructions are of the highest caliber, i.e., that they promote creative thinking and focus on core science and math content and practices. STEAM experiences should make clear connections between the content and how it is being learned and applied, and should help learners see how the transdisciplinary content and practices being learned can be used in creative or authentic ways for problem solving.

STEAM learning experiences can show students how their transdisciplinary curricula relate to larger goals and outcomes (such as windmill buildup or garden design) and how they can apply their learning to improve our world. Through this STEAM experience, their understanding of learning and perhaps of school itself may change. Learners can start seeing subject content not as isolated subjects, but as a way of helping the world or ultimately changing undesirable conditions. In order to transform students' perceptions of and learning in the STEAM disciplines, it is essential that students become reflective learners and metacognitive learners.

One possible next step for future research would be to look more specifically at how STEAM is perceived by different schools of undergraduates to see whether patterns emerge in STEAM learning experiences. A second opportunity for future research is to examine how undergraduates perceive STEAM by majors and compare the difference between different majors. Third, we will explore how different settings and educator roles (for example, regular classroom teacher vs. STEAM teacher) affect undergraduates' perceptions associated with integrated STEAM practices. A fourth recommendation is to continue to examine equity and access to STEAM learning opportunities. The review of STEM policy reports (Bush, 2019) indicates significant need to expand participation of underrepresented groups in STEM. STEAM learning experiences may help with this effort.

In sum, the perceptions of undergraduates strongly endorse STEAM learning experiences as places to implement the teaching practices that are important and central to higher education reform efforts. While STEAM learning experiences can provide undergraduates with transformational learning opportunities and expand their frames of reference, STEAM practices must be developed with each student as an individual. This study highlights the characteristics of the most effective STEAM inquiry, including a foundational focus on problem-oriented content and practices, creative thinking, and crossing borders. What we do know from this study is that STEAM learning experiences for college students provide opportunities for them to engage deeply and to make meaning out of their transdisciplinary learning. The higher education community is crucial in the conversation about integrated learning spaces, with STEAM initiatives being implemented worldwide.

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