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Enhancing rural students' perceived relevance and career interest in engineering through 3D printing

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Introduction: Engineering education has the potential to create meaningful career pathways for rural students by empowering them to address local challenges and contribute to their communities. However, rural students remain underrepresented in engineering, often due to a perceived disconnect between traditional curricula and their lived experiences. To bridge this gap, integrating 3D printing to connect learning with local context may be a viable solution.

Methods: This convergent mixed methods study examined the impact of engaging in 3D printing practices on rural students' perceived relevance of engineering and their interest in pursuing engineering careers. The study engaged students in hands-on making practices that reflected their personal and community contexts. Quantitative data (e.g., surveys) and qualitative data (e.g., semi-structured interviews) were collected and analyzed separately and then integrated to provide a comprehensive finding.

Results: Quantitative results showed significant increases in students' perceived authenticity and career interests after engaging in 3D printing sessions. Qualitative findings extended and explained quantitative results by discussing how 3D printing connected learning to students' lived experience and career aspirations. The integrated findings underscored the potential of 3D printing for supporting rural students' perceived relevance to learning and career interests in engineering.

Discussion: This study demonstrated that 3D printing allowed students to engage in making practices closely relevant to their experience and community. When students recognize the relevance, they tend to engage in engineering and align it with their career aspirations. The findings underscore the importance of providing contextually meaningful learning experiences to support rural students' participation in STEM and foster interest in STEM careers.

KEYWORDS

rural education, STEM education, engineering career interests, perceived relevance, 3D printing

Introduction

Engineering education holds significant importance for rural students (Baldwin, 2021; Gillen et al., 2017), as it opens pathways to careers that can address local challenges and drive community growth (Schilling and Grohs, 2024). Rural areas often face unique issues that require locally tailored engineering solutions. By participating in engineering education, rural students can obtain core engineering concepts and problem solving skills that empower them to contribute meaningfully to their communities (Crain and Webber, 2021; Saw and Agger, 2021). Moreover, engineering careers can provide stable, well-paying jobs that help retain talent to stay in rural areas, reducing the "brain drain" phenomenon where skilled individuals leave in search of opportunities elsewhere (Petrin et al., 2014). Access to engineering education thus not only supports the personal and professional growth of rural students but also contributes to the broader economic and social resilience of rural communities.

However, rural students are underrepresented in engineering education (Carrico, 2013; Harris and Hodges, 2018). Research has shown that rural students often perceive engineering education as disconnected from their personal background or the needs of their rural community, making it difficult for rural students to envision themselves as future engineers (Schilling and Grohs, 2024). Particularly, critics argue that mandated curricula, developed from a middle-to-upper-class, White suburban perspective, often decontextualize learning and disengage rural students (Gruenewald, 2003; Peine et al., 2020).

By fostering a hands-on, tangible connection to science, technology, engineering and math (STEM) education, 3D printing allowed students to perceive engineering as both accessible and relevant to their future (Buechley and Ta, 2023; Kit et al., 2022; Saorín et al., 2017). In line with the rural-reimaged approach, this method adapted a universally applicable technology to a unique educational context, illustrating how career aspirations in STEM can be cultivated when learning is contextualized in students' lived experiences. While 3D printing is broadly applicable in STEM education (universality), this study situated it within the context of rural education to address the unique aspirations, needs, and career pathways of rural students, providing a dual perspective that reinforces both universal applicability and place-based specificity. The following research questions (RQ) were answered in this study:

RQ1. To what extent and in what ways does a 3D printing curriculum impact rural students' perceived authenticity of engineering education?

RQ2. To what extent and in what ways does a 3D printing curriculum impact rural students' career interests in engineering jobs?

Literature review

Rural STEM education

Rural students are underrepresented in STEM workforce. The National Center for Education Statistics show that over 9.3 million K-12 students, about one in every five students, attend rural schools (Johnson et al., 2021), but they have lower STEM achievement and lower likelihood of pursuing STEM careers (Crain and Webber, 2021; Saw and Agger, 2021). Rural students are facing a severe gap in access to STEM education, including a lack of resources, funding, teachers, and infrastructure. For instance, the *Ending the Double Disadvantage* report (Change the Equation, 2017) shows that eighth graders in rural schools have much less access to science labs and materials than their non-rural peers. Providing rural students with access to high-quality STEM education is thus urgently needed.

Noteworthy, implementing STEM education in rural areas must account for their unique sociocultural and socio-economic contexts that shapes rural education (Harris and Hodges, 2018). Research emphasizes the importance of integrating local environmental, cultural, and workforce knowledge into STEM curriculum to enhance rural students' perceived authenticity of learning experiences and strengthen their connections to their communities (Schilling and Grohs, 2024; Starrett et al., 2022; Tang et al., 2024; Zimmerman and Weible, 2017). For instance, Zimmerman and Weible (2017) found high school students investigating water quality in a three-week watershed unit recognized its critical role in community health and the environmental impact of local economic and recreational activities. Starrett et al. (2022) found STEM workforce development relevant to local context positively predicted rural students' motivation, STEM career interest, and their rural community aspirations.

A particularly effective approach for rural education is place-based learning, which situates educational content within students' lived experiences and ensure learning is meaningfully applicable to their surroundings (Howley et al., 2011; Smith and Sobel, 2014). By embedding STEM content into local contexts, place-based learning empowers students with a deep conceptual understanding and a sense of agency in addressing community challenges (Starrett et al., 2022; Zimmerman and Weible, 2017). This approach reinforces rural students' emotional attachment to their communities, which in turn shape their career aspirations closely tied to local development (Howley et al., 2011; Irvin et al., 2019). Overall, place-based learning equips rural students with knowledge and skills needed for STEM careers while inspiring them to apply these competencies to improve their communities.

3D printing in rural STEM education

3D printing, also referred to as additive manufacturing, is a technology that creates three-dimensional objects by layering material incrementally (Bicer et al., 2017). It has gained increasing attention in education, particularly in STEM fields, as it provides students with hands-on opportunities to engage in iterative cycles of designing, prototyping, and revising that mirror real-world STEM practices (Tyler-Wood et al., 2018). The technology has been incorporated into K-12 school curricula to support STEM education, especially in enhancing students' motivation (Avendano et al., 2019) and design skills as well as cultivating their spatial abilities (Huang and Lin, 2017).

One of the key benefits of 3D printing in STEM education is its ability to create a sense of authenticity in student learning experiences (Maiden et al., 2024). Research suggests that when students engage in design and fabrication activities using 3D printing, they are more likely to see their learning as relevant to real-world engineering and scientific practices (Maiden et al., 2024; Saorín et al., 2017). Additionally, integrating 3D printing in STEM education can strengthen connections between classroom learning and professional engineering careers as they gain exposure to real-world product design and manufacturing processes (Tyler-Wood et al., 2018).

In rural education, 3D printing and makerspaces offer students valuable opportunities to engage with STEM concepts through hands-on, contextually relevant experiences that traditional, decontextualized instruction often lacks (Murai and Juan, 2024; Nixon et al., 2021). By embedding learning within tangible, real-world contexts, making and tinkering through 3D printing have been recognized as promising tools for fostering grassroots STEM innovation in rural communities (Murai and Juan, 2024). For example, Nixon et al. (2021) found that training rural teens as maker-mentors in a mobile makerspace enhanced their engagement in pre-college engineering and also empowered them to take on leadership roles in addressing community-based issues.

Methodology

This study employed a convergent mixed methods design (Creswell and Clark, 2017) to examine the impact of the Maker experience driven by the use of 3D printing on rural students' perceived authenticity of learning and career interests in engineering. The quantitative research assessed changes in students' perceptions of authenticity and career interests before and after participating in the Maker sessions, while the qualitative study explored students' experience with the 3D printing sessions. The integration of findings from the two complementary data sources provided a holistic understanding of how 3D printing influences rural students' perceived authenticity of learning and career aspirations in engineering.

Participants and contexts

The study was conducted at a high school makerspace session in the rural areas of the southeastern United States. To define the rural context of this study, the National Center for Education Statistics (NCES) locale classifications were used (Thier et al., 2021). The school area was classified as Rural, Distant (code 42), referring to schools located in rural areas more than 5 miles but less than 25 miles from an urbanized area. These schools serve communities that are geographically separated from urban centers and usually have limited access to STEM learning resources. For the school in this study, all the students were eligible for the free and reduced-price lunch program.

An Institutional Review Board (IRB) approval was received from the University of South Carolina (Pro00139961) before recruiting participants. A total of 11 high school students, at the age of 16–18 years old, voluntarily participated in the study, including six female and five male students. About a half of them ($n = 7$) were minority, including three from multi-racial groups. All the participants have no prior experience of working on 3D printing.

Makerspace

The makerspace session was scheduled every week for a group of students to engage in making and tinkering practices to learn about 3D printing and its relevant concepts. Students self-selected into the makerspace sessions and were generally highly motivated to pursue STEM degrees in college. Considering the expertise of participants, a teacher from this school was invited to serve as facilitator who offered students orientation on the use of 3D printers and relevant software (e.g., AutoCAD and TinkerCard) as well as provided technical help in the making and tinkering process.

Participants engaged in making and tinkering activities that involved the use of 3D printers to design and prototype artifacts that is relevant to their life and the community. Participants were introduced to AutoCAD and TinkerCard applications where they built 3D models and then used the 3D printing machines to bring their ideas to life. Their projects ranged from practical items (e.g., recyclable water bottles, personalized coasters, and portable containers) to cultural heritage and personal identity (e.g., Aztec whistles or miniature room models). Some students also designed prototypes of assistive (e.g., prosthetic components) or health-related devices (e.g., fidget toy). For instance, one student created a fidget toy to support children with anxiety.

While working on their designs, participants used individual laptops, and the facilitator present in the classroom to provide continuous support. Meanwhile, peer support was allowed as participants frequently turned to one another for feedback, troubleshooting support, or suggestions on improving their designs.

Data collection

Quantitative data was collected via self-reported surveys to assess the participants' perceived authenticity of learning and career interests in engineering jobs. Survey items were adapted from the Authenticity section of the Personal Creativity Index (McKlin et al., 2018) and the Engineering section of the STEM Career Interest Survey (STEM-CIS) (Kier et al., 2014). The Authenticity section included eight Likert-type scale items following a five-point scale, ranging from 1 (Strongly Disagree) to 5 (Strongly Agree) to indicate their agreement with the authenticity of learning in the Maker sessions. Sample items included "3D printing allows me to work on projects that are based in the real world" and "3D printing helps me explore and think about real world issues." In addition, eleven five-point Likert-type scale items were adapted from STEM-CIS to evaluate participants' career interests in engineering. Sample items included "I plan to use engineering in my future career" and "I would feel comfortable talking to people who are engineers." To evaluate the reliability of the survey, Cronbach's alpha coefficient was calculated. The result ($\alpha = 0.87$) confirmed that the survey showed an acceptable level of internal consistency.

Qualitative data was collected through semi-structured interviews with purposively selected participants. A maximum variation criterion (Tang, 2020; Tang et al., 2020, 2021) was used to guide the selection of the interviewed participants by considering students' attendance, engagement, and performance in the makerspace sessions. A semi-structured protocol was used to inquire about participants' experiences with the 3D printing and leave flexibility of attending to emerging questions during the interview (Gikas and Grant, 2013). Sample interview questions included "How do you describe your overall experience of working on 3d printing projects?" Each interview was scheduled in advance to perform individually with each interview participant at the end of the project. The length of each interview was between 25 and 40 min which was recorded and transcribed with each participant's permission.

Data analysis

Descriptive statistics about participants' perceived authenticity of learning and career interests in engineering was determined. Shapiro–Wilk test was used to determine if the data satisfied the normal distribution assumption. The result indicated that the data for the two variables, the perceived authenticity of learning ($p = 0.75$) and career interests in engineering ($p = 0.21$), was normally distributed. Paired sample t-test was thus used to determine whether the participants' change in the two variables was significant.

Inductive analysis (Creswell and Creswell, 2017) was conducted to analyze qualitative data. Two cycles of coding were completed. The first cycle focused on generating and refining the codes (Saldaña, 2021). *In vivo* coding, which used direct quotations of participants' utterances to make sense of their experience (Saldaña, 2021), was employed for this cycle, generating a total of 65 codes such as "challenging" and "thinking of solutions." Before the second cycle, all the codes from the first cycle were reviewed to establish an initial structure and develop a basic understanding. The second cycle, featuring pattern coding, aimed at organizing codes into cohesive patterns, categories, and themes derived from the data (Saldaña, 2021). In the end, two themes emerged from the data. To ensure the rigor and trustworthiness of the themes, member checking was performed with the interviewed participants, who all confirmed that the themes reflected their experience with the 3D printing intervention. In addition, rich, direct quotes from the participants' interview were provided as a measure to assess the rigor of the findings.

Results

Quantitative findings

Descriptive statistics showed that participants' perceived authenticity of learning increased from pre-test ($M = 2.97$, SD = 0.51) to post-test ($M = 3.33$, SD = 0.66). Paired sample t-test result indicated that the change was statistically significant, $t(10) = 2.22$, $p = 0.04$, with a medium effect size (Cohen's $d = 0.55$). Their engineering career interest also significantly increased from pre-test ($M = 3.00$, SD = 0.56) to post-test ($M = 3.27$, SD = 0.55), $t(10) = 1.78$, $p = 0.04$, with a medium effect size (Cohen's $d = 0.48$). Overall, participants felt their learning was more connected to their real-life experiences and developed a stronger interest in pursuing engineering-relevant careers in the future after participating in the makerspace sessions.

Qualitative findings

Theme 1

The first theme, *3D printing impacted rural students' career aspirations towards engineering*, articulated that the experience of participating in 3D printing projects influenced participants' career aspirations, particularly in fields related to engineering and design. The makerspace session provided them with foundational skills and inspired them to consider pursuing engineering careers. Two categories subsumed this theme including "exploring engineering basics" and "reinforcing engineering career pathways."

For the category of "exploring engineering basics," participants emphasized how 3D printing provided them with a foundational understanding of engineering principles, particularly the iterative process of constructing models, refining designs, and creating artifacts on the 3D printer. For many, this hands-on experience served as an introduction to engineering concepts that they had not previously encountered in traditional classroom settings. By physically creating artifacts, participants were able to see firsthand how 3D models were translated into solid artifacts and how their design choices influenced functionality or esthetics of the artifacts.

> *It will give me a base model to see as an overview, being able to actually see the structure of what I would be designing, or why I will be engineering and being able to make further modifications.*
>
> *Engineering itself is based on building and structure, and 3d printing is the basic building blocks, and learning how to do that. So having something like 3d printing on your belt help you work with the machines and blueprints, and it will help you build something bigger.*

For the category of "reinforcing engineering career pathways," participants who already had an interest in engineering or related technical fields, 3D printing reinforced their aspirations and solidified their desire to pursue careers in these areas. Many participants described how their experiences with 3D printing connected to their existing interests in building and design and strengthened their confidence in choosing engineering-related career paths. This category highlighted the value of integrating 3D printing into STEM education, as it introduced students to engineering concepts and cultivate their career commitment to the field.

> *I think for my future, I plan to do a lot of computer and engineering. I think with 3d printing, it helped me with my modeling skill.*
>
> *I have been thinking about pursuing an engineering degree…the use of the software would definitely help me be able to use the use of shapes, geometric as well as other different types of uses that can be used in the field that I am trying to go into.*

Theme 2

The second theme, *3D printing connected classroom learning with real-life contexts*, described participants' perception of their learning as more relevant and applicable to their life and community. Rather than viewing abstract concepts as disconnected from their daily lives, students found that 3D printing allowed them to create tangible, functional objects that had personal and practical value. The theme consisted of two categories such as "connecting learning to authentic life" and "prototyping solutions to everyday problems."

For the category of "connecting learning to authentic life," participants highlighted how 3D printing allowed them to bridge the gap between theoretical knowledge and real-world applications, reinforcing the relevance of their classroom learning. Unlike traditional instruction that often remains abstract, 3D printing provided an opportunity for students to create tangible, functional objects that could be used in their daily lives. This hands-on engagement reinforced the idea that STEM skills have direct applications beyond academic settings. In addition, 3D printing not only enhanced technical skills but also fostered a sense of relevance and authenticity, motivating students to see their learning as meaningful and impactful.

> *When you make something, no matter what it is, and you create it from your hand and you are proud of that accomplishment, and you want to make more. So that's basically what three printing is. So it is meaningful, very meaningful.*

> *If you go to a museum and you were to see that, you will be like, 'Oh, what was this used for?' And since you learned about it, then you might think about what it might sound like, or something like that. So, you just create one, just having a replica in your room somewhere.*
>
> *It is always something new to learn, something new to create, and this could help benefit the future.*

For the category of "prototyping solutions to everyday problems," participants described how they leveraged 3D printing to prototype solutions to everyday challenges. This aspect of 3D printing encouraged students to identify specific needs in their lives and design custom solutions. These experiences highlight the role of 3D printing in empowering students to approach real-world problems with a STEM solution. By enabling students to prototype and iterate on their own ideas, 3D printing fosters an innovative spirit and a proactive approach to addressing real-world issues.

> *I would say that would benefit me daily. I recently made a 3D print[ed] bottle I use daily, I would say that really ties back into the environment, how it is eco-friendly, where it does not actually waste materials, and how that is saving up on expenses as well as other materials.*
>
> *I think my latest one is the one. It is like a portable cup holder, or portable container where you could put, like a small cup, or just like any small object. I thought that was a cool idea to have a little container you could just carry in your pocket.*

Integration of findings

Quantitative results and qualitative findings were integrated at the end of data analysis to formulate a comprehensive understanding of how rural students' participation in community-relevant 3D printing sessions affected their perceived authenticity of learning and their interest in engineering careers. Quantitative data revealed a statistically significant increase in students' perceptions of authentic learning and engineering career interests, both with medium effect sizes. Qualitative data explained and extended quantitative results by illustrating how students perceived 3D printing as a personally meaningful learning experience. By creating tangible artifacts rooted in their lived experiences within rural communities, students were able to connect classroom learning to real-life contexts and address authentic problems, which helped explain the observed increase in their perceived authenticity of learning. Furthermore, students' quotes showed that 3D printing engaged them in iterative design and prototyping processes that mirrored the professional practices of engineers. This experience allowed rural students to explore engineering principles and began to envision how these principles could translate into future engineering careers, which likely contributed to their increased interest in pursuing engineering pathways. Overall, 3D printing sessions helped bridge the gap between abstract STEM concepts and rural students' everyday lives, thereby empowering rural students to see themselves as capable of contributing meaningfully to their communities and future engineering professions.

Discussion

The study confirmed that incorporating 3D printing in STEM education for rural students significantly enhanced their perceived authenticity of learning and bolstered their interest in engineering careers, echoing prior studies (Murai and Juan, 2024; Nixon et al., 2021). Specifically, students reported a heightened sense of relevance as 3D printing projects connected meaningfully with their personal interests and community. The tangible aspect of 3D printing and its alignment with place-based learning increased students' perceived relevance of STEM education to themselves.

Additionally, students expressed a marked increase in interest in pursuing careers in engineering. By designing and producing items with practical value, students saw firsthand the impact of engineering skills on their local environment, which reinforced the value of STEM careers, reiterating the findings of prior studies (Maiden et al., 2024; Saorín et al., 2017; Tyler-Wood et al., 2018). This outcome highlights how rural-focused approaches can foster engineering aspirations by emphasizing practical relevance and local impact. Notably, students' enhanced career interest in engineering has implications for building a rural engineering talent pipeline, addressing a critical need for more STEM professionals in underserved regions.

Furthermore, the dual focus on uniqueness and universality is central to understanding the transformative potential of 3D printing in rural STEM education. The results indicated that while 3D printing is universally applicable, its integration within rural-specific contexts—grounded in students' local culture and community—elevates its effectiveness as an educational tool. The universal principles of STEM education become deeply meaningful to rural students when coupled with culturally relevant applications, fulfilling both unique and universal educational goals.

Implications for rural STEM education

This study illustrates the potential of rural-focused educational methods, such as place-based 3D printing, to transform STEM education by fostering both unique and universally valuable skills. Our findings suggest that when rural students engage in STEM learning that connects with their lives, they are more likely to see value in pursuing related careers. Furthermore, this rural-reimaged application of 3D printing suggests that even well-established technologies can be meaningfully adapted to suit rural needs, offering a model for similar adaptations in other STEM fields.

The impact of culturally and geographically relevant STEM education extends beyond immediate learning outcomes. By aligning curriculum with rural students' interests and community contexts, educators can cultivate a sense of ownership in learning, thus building a foundation for sustainable engagement in STEM fields. The study underscores the importance of designing STEM educational experiences that honor rurality while being adaptable to broader educational environments, ultimately contributing to a more diverse and resilient STEM workforce.

Limitations

This research had several limitations, including a small sample size and the absence of a control group, which may limit the generalizability of the findings. Future studies should address these limitations by implementing more rigorous, school-based research designs with larger and more diverse participant pools. Additionally, while the NCES locale code was incorporated to classify the rurality of the participating school, this study could have improved the trustworthiness of the findings by fully engaging in rural definition triangulation (Grant et al., 2024). Rural definition triangulation recommends using multiple data points to define "rural," including definition reliance, participant definition checking, site definition checking, and personal description definition (Grant et al., 2024). Future research focused on rural schools may seek to develop a more authentic understanding of "rurality" by intentionally incorporating participant perspectives, validating context at the site level, and including researchers' personal reflections to deepen contextual insight. Another limitation was the extent to which place-based learning principles were embedded in the 3D printing curriculum. A more intentional integration of place-based approaches could have further enriched students' connections between their projects and their local communities. Future research can build upon this study by designing and evaluating place-based 3D printing curricula or makerspace sessions to examine their impact on rural students' engagement, learning outcomes, and career aspirations in STEM fields.

Conclusion

This study aligns with the special issue's focus on bridging the uniqueness and universality of rural STEM education by demonstrating the potential of 3D printing as a tool for culturally relevant, engaging, and career-relevant STEM education. Through a rural-focused, place-based approach, we found that 3D printing not only increased the perceived relevance of STEM education for rural students but also enhanced their interest in engineering careers. These results highlight the value of integrating rural-specific educational practices within universal STEM frameworks, offering a blueprint for how educational technologies can be adapted to meet the unique needs of rural students while yielding insights valuable across diverse contexts.

By contributing to the discourse on rural-focused and rural-reimaged STEM education, this study offers actionable insights for educators and policymakers seeking to foster STEM career pathways in rural settings. As rural education continues to evolve, embracing place-based, culturally relevant methodologies alongside universally applicable technologies like 3D printing will be crucial to equipping the next generation with the skills and inspiration to excel in STEM fields.

Data availability statement

The datasets presented in this article are not readily available due to the IRB requirement. Requests to access the datasets should be directed to Hengtao Tang, htang@mailbox.sc.edu.

Ethics statement

The study involving humans was approved by the Institutional Review Board at the University of South Carolina (#Pro00139961). The study was conducted in accordance with the local legislation and institutional requirements. Written informed consent (assent) for participation in this study was provided by the participants and/or their parents or legal guardians.

Author contributions

HT: Conceptualization, Data curation, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. YQ: Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that Generative AI was used in the creation of this manuscript to revise grammar and improve the choice of words for writing.

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