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Research article

Fostering global STEM engagement: Evaluating the impact of a youth development program on students' affinity and aspirations

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Abstract: Fostering engagement and persistence in science, technology, engineering, and mathematics (STEM) among adolescents is critical for preparing future professionals in a rapidly evolving technological landscape. This study evaluated the impact of the Youth Development Program (YDP 2025), a cross-cultural STEM initiative involving high-achieving middle and high school students from the United States (n = 21) and South Korea (n = 13). The program provided immersive experiences, including mentorship, collaborative projects, research presentations, coding challenges and robotics workshops, and interactions with leading scientists, including Nobel Laureates. A mixed-methods approach was employed to examine program outcomes. Quantitative measures assessed students' STEM affinity before and after the program using Likert-scale surveys, analyzed with descriptive statistics and Welch's t-tests; effect sizes were calculated to estimate the magnitude of change. Unequal pre- and post-survey response rates limited the feasibility of paired analyses. Qualitative data from open-ended post-survey responses were analyzed thematically to capture participants' perceptions of learning outcomes, confidence, and future STEM aspirations.

Results indicated minimal overall change in STEM affinity. U.S. students demonstrated a moderate increase (Cohen's d = 0.55), while Korean students showed little improvement. However, qualitative findings revealed substantial gains in practical skills (robotics programming, coding challenge, oral research presentations), confidence in STEM tasks, and motivation toward STEM careers. Participants emphasized mentorship, hands-on activities, and exposure to STEM professionals as particularly influential. Findings suggest that experiential STEM programs can enhance skills, confidence, and career-oriented motivation. Future iterations should expand hands-on challenges, integrate structured career exploration, and address language accessibility to maximize impact.

Keywords: STEM education, youth development, cross-cultural program, mentorship, coding, career aspirations, iDRONE program

1. Introduction

Developing sustained interest, skills, and confidence in science, technology, engineering, and mathematics (STEM) during adolescence is widely regarded as critical for cultivating a strong STEM identity and long-term engagement, which are predictive of future STEM persistence and career choices [1,2]. However, despite numerous efforts to promote STEM education at the K-12 level, studies indicate that many students, particularly those from underrepresented backgrounds, struggle to maintain interest, self-efficacy, and identification with STEM disciplines throughout middle and high school [3,4].

Large-scale international and national assessments highlight persistent cross-national differences in STEM achievement, participation, and attitudes [5–7]. Data from assessments such as the Programme for International Student Assessment (PISA), Trends in International Mathematics and Science Study (TIMSS), and the National Assessment of Educational Progress (NAEP) consistently show that students in East Asian countries, including South Korea, outperform their U.S. peers in STEM achievement and demonstrate stronger academic preparation in mathematics and science.

However, these achievement advantages do not always translate into comparable levels of STEM interest, confidence, or long-term career participation, particularly when cultural, educational, and motivational factors are considered [8–10]. These patterns underscore the need to move beyond achievement comparisons to examine how contextual and cultural factors shape students' STEM engagement, identity, and aspirations across countries [11,12].

Theoretical models of STEM identity development suggest that meaningful engagement with hands-on activities, mentorship, and social role models can reinforce students' sense of belonging and self-efficacy [13,14], shaping their motivation and persistence in STEM pathways.

Programs that integrate collaborative, project-based learning, such as robotics and coding challenges, are associated with fostering computational thinking, problem-solving skills, and positive attitudes toward STEM [15,16]. Such approaches align with motivation theories, including the self-determination theory, which emphasize the importance of autonomy, competence, and relatedness in sustaining engagement and intrinsic motivation [17,18]. Empirical evidence indicates that participation in these activities enhances not only practical skills but also increases self-efficacy, which has been linked to greater persistence and continued pursuit of STEM careers [19,20].

The Youth Development Program (YDP) 2025 was designed to provide high-achieving middle and high school students from the United States and South Korea with immersive experiences in STEM through mentorship, collaborative projects, research presentations, coding challenges and robotics workshops, and interactions with leading scientists, including Nobel Laureates. By integrating theories of identity formation and motivation, this study aims to explore the mechanisms through which multifaceted, cross-cultural STEM initiatives influence students' engagement, self-efficacy, and career aspiration. Using both quantitative (pre- and post-surveys) and qualitative (open-ended responses) methods, the study seeks to critically examine not just the outcomes but also the processes and perceptions underlying students' development of STEM-related attitudes and skills.

2. Literature review

Research on youth development programs (YDP) targeted at STEM education consistently demonstrates their potential to influence students' interest, skills, and long-term engagement in science, technology, engineering, and mathematics [21,22]. However, to deepen our understanding of *how* these programs exert their influence, it is essential to anchor empirical findings within robust theoretical frameworks that elucidate the mechanisms driving change. Importantly, a growing body of research also highlights limitations and mixed outcomes of experiential STEM programs, including uneven gains across diverse student populations, short-term effects that dissipate over time, and challenges in translating increased interest into sustained STEM participation (e.g., [19,20]; see also critiques of pipeline models and contextual barriers). These mixed findings suggest that program effects are not uniform and are shaped by the complex interaction of individual, social, and cultural factors.

2.1. Theoretical foundations of STEM identity and self-efficacy

Central to STEM engagement are constructs such as *identity* and *self-efficacy*, which previous research has shown to predict persistence in STEM fields [21,22]. This study adopts Bandura's [21] social cognitive theory and identity development perspectives as the guiding conceptual framework. Bandura's [21] social cognitive theory posits that self-efficacy beliefs—one's confidence in their ability to execute specific tasks—serve as key motivators for sustained engagement. In the context of STEM, programs that provide mastery experiences, vicarious learning, social persuasion, and emotional regulation can strengthen these beliefs, resulting in increased interest and persistence.

Similarly, the development of a scientific and engineering identity—a sense of belonging and recognition within STEM communities—is influenced by exposure to authentic practices and role models [22]. When students see themselves as capable contributors, their motivation shifts from extrinsic to intrinsic, fostering resilience against challenges.

2.2. Mentorship, role models, and cross-cultural influences

Mentorship and interactions with STEM professionals, especially role models like Nobel Laureates, are hypothesized to influence identity development and long-term career aspirations by providing vicarious experiences and social persuasion—key pathways outlined in Bandura's framework [21].

These interactions can serve to:

- Broaden students' perceptions of who can succeed in STEM,

- Reinforce perceptions of legitimacy and belonging,
- Stimulate aspirations through exposure to exemplars of success.

However, research also highlights potential limitations of mentorship-based interventions. For example, mentorship effects can be uneven depending on the quality of the mentor-mentee relationship, the degree of continuity, and the extent to which mentoring is culturally responsive. Moreover, in some cases, mentoring may unintentionally reinforce stereotypes or create unrealistic expectations if students cannot see pathways to similar success in their local contexts.

Cross-culturally, these mechanisms may vary. For example, Hofstede's [23] cultural dimensions theory suggests that individualistic versus collectivist orientations shape how mentorship influences identity. In collectivist cultures (e.g., South Korea), emphasis on group harmony and recognition may intensify the role of social persuasion and community belonging, whereas in individualistic cultures (e.g., the U.S.), personal achievement and autonomy may be primary pathways. Empirical evidence supports this; studies indicate that mentorship leads to greater self-efficacy and career motivation [24,25], yet the manifestation of these effects may depend on cultural context, shaping how identity and confidence are constructed.

2.3. Hands-on engagement and skill development

Practical, hands-on activities such as robotics, coding challenges, and research presentations activate mastery experiences, a core component of self-efficacy development [21]. These opportunities allow students to successfully apply their knowledge, which strengthens their belief in their capabilities, fosters problem-solving skills, and promotes deep learning. Empirically, such experiential learning correlates with increased motivation, confidence, and positive attitudes toward STEM [16,26].

However, the literature also identifies challenges related to experiential STEM learning, including uneven access to resources, varying levels of instructional support, and disparities in prior knowledge. These factors can lead to unequal outcomes, particularly across different cultural and educational systems. For instance, some studies suggest that hands-on programs may produce strong skill gains but limited long-term identity changes when not coupled with sustained support and culturally relevant contexts.

2.4. Anticipated pathways in a cross-cultural context

Integrating these theories within a cross-cultural framework, the pathways through which mentorship, experiential activities, and social interactions influence STEM identity and self-efficacy are moderated by cultural values:

- In collectivist settings, peer recognition, group success, and interpersonal bonds may be particularly influential in fostering a sense of belonging and professional identity.
- In individualistic settings, personal achievement, autonomy, and self-referenced competence may predominate [23].

Thus, the mechanisms of influence—whether through mentorship, mastery experiences, or social recognition—are not universal but contextually mediated. Recognizing these nuances allows programs to tailor interventions that activate pathways optimized for each cultural setting.

2.5. Conceptual framework summary and study hypotheses

Drawing on Bandura's [21] self-efficacy theory and identity development perspectives, this study hypothesizes that (1) hands-on experiences and mentorship will increase self-efficacy and STEM identity, (2) these gains will translate into higher STEM interest and persistence, and (3) the magnitude and nature of these effects will differ across U.S. and Korean contexts due to cultural differences in how competence, recognition, and belonging are experienced.

2.6. Connecting literature to YDP 2025

The existing literature supports the integration of hands-on learning, mentorship, and networking in STEM youth programs to enhance students' skills, confidence, and motivation. The findings from YDP 2025 complement this evidence, demonstrating that such multifaceted programs can effectively foster practical STEM competencies, engagement, and career-oriented aspirations among gifted students from diverse cultural backgrounds. However, the current study also acknowledges that such outcomes may be shaped by cultural norms, program continuity, and the quality of mentorship, which may explain differences in quantitative versus qualitative outcomes across groups.

3. Materials and methods

3.1. Research questions

This study was guided by the following five research questions, which aim to illuminate both observable outcomes and underlying STEM mechanisms within a cross-cultural context:

1. To what extent did participation in the Youth Development Program (YDP 2025) influence students' STEM affinity scores, both overall and by country (the U.S. vs. Korea)?
2. How did students perceive changes in their practical STEM skills, including robotics programming, coding, and research presentation abilities, as a result of the program?
3. In what ways did participation in the program affect students' confidence and self-efficacy in engaging with STEM tasks and hands-on activities?
4. How effective and feasible did participants find the activities—such as robotics, coding challenges, and research presentations—in enhancing their understanding of STEM?
5. What are students' overall perceptions of the program, and what recommendations do they have for future iterations?

3.2. Participants and setting

The study involved 34 high-achieving middle and high school students (18 males, 16 females; ages 13–18) from the United States (n = 21) and South Korea (n = 13), purposefully selected based on demonstrated motivation, academic excellence in STEM, and prior engagement in related research or competitions. Participants were recruited through national STEM competitions, gifted student programs, and application interviews, ensuring a cohort with strong foundational knowledge and interest in STEM fields.

Participants' backgrounds varied in terms of gender, socio-economic status, prior STEM experiences (e.g., participation in robotics clubs, coding courses, or research projects), and language proficiency, particularly among Korean students, some of whom had varying levels of English fluency. Selection criteria emphasized academic motivation, prior achievement, and a demonstrated ability to collaboratively engage with challenging STEM tasks. Prior exposure to robotics, programming, or research was documented through self-report surveys upon enrollment, allowing analysis of their influence on outcomes.

3.3. Program design and procedure

YDP 2025 was a multi-day, immersive STEM program designed to provide experiential learning aligned with disciplinary core ideas and practices outlined in the Next Generation Science Standards (NGSS) [27]. The program's content integrated disciplinary ideas such as systems and engineering, energy, and information flow, with practices including designing, building, and testing prototypes, coding and programming, scientific communication, and collaboration. Crosscutting concepts like stability and change, cause and effect, and models were explicitly emphasized.

Key activities included:

- Robotics workshops: Participants designed, built, and programmed autonomous vehicles using hardware components such as Arduino microcontrollers, sensors, and motors. These activities reinforced engineering principles, systems thinking, and computational modeling.
- Coding challenges: Students developed algorithms for real-time obstacle navigation and autonomous decision-making, fostering computational thinking, algorithmic reasoning, and systems analysis.
- Research presentations: Participants prepared and delivered research posters and oral presentations on scientific topics, aligning with scientific practices of hypothesis formulation, data analysis, and communication.
- Mentorship and professional interactions: Students engaged with STEM professionals, including Nobel Laureates, through seminars and networking sessions, promoting understanding of scientific inquiry and the interdisciplinary nature of STEM.
- Cross-cultural activities: The program facilitated intercultural exchanges, team-building, and collaborative projects to foster global perspectives and social skills.

All activities were explicitly linked to NGSS disciplinary ideas and science practices, providing opportunities for students to engage in authentic STEM inquiry and engineering design processes. The overall program schedule is presented in Table 1.

Table 1. YDP 2025 schedule.

Date	Main activities
August 6 (Wed)	- Pre-survey - Pre-meeting between students and mentors
August 7 (Thu)	- Opening ceremony, plenary session/symposium - Special meeting with Nobel Laureate(s) - Distinguished sponsor forums: the Korea Foundation for Science and Creativity and the Korean-American Scientists and Engineers Association (KOSAC-KSEA) joint forum on fostering scientific talent - STEM talk: Professors Young-Kee Kim (University of Chicago) and Michael Choi (University of

	Illinois) serve as speakers, with Professor Gloria Kim (University of Florida) as the moderator.
August 8 (Fri)	- Field trip to the Georgia Institute of Technology - Oral presentations - Poster session setup and presentations - Networking dinner - Coding challenge
August 9 (Sat)	- Closing ceremony/final plenary session: awards ceremony for outstanding youth presentations awards - Post-survey

The detailed breakdown schedule is as follows:

- On Wednesday, August 6, a pre-meeting between students and mentors was held, serving as an initial orientation to introduce participants to their mentors and prepare them for the upcoming program activities.
- On Thursday, August 7, the morning session began with an opening ceremony, followed by a plenary session and symposium. A highlight of the morning was a special meeting with a Nobel Laureate, providing students with the opportunity to engage directly with a leading figure in scientific research. In the afternoon, participants attended distinguished sponsor forums, including a joint forum organized by KOSAC and KSEA focused on nurturing scientific talent, followed by a STEM talk delivered by professors from the University of Chicago and the University of Illinois, moderated by a University of Florida faculty member, addressing key topics in contemporary STEM fields (Figure 1).

Figure 1. STEM talk with a STEM scholar.

- On Friday, August 8, the morning included a field trip to the Georgia Institute of Technology, offering participants valuable exposure to a leading technological institution. The afternoon and evening featured oral presentations (Figure 2), a poster session where students presented and discussed their research findings (Figure 3), and the STEM coding challenge (Figure 4). Outstanding research presentations were recognized with awards to acknowledge students' excellence in scientific communication, creativity, and depth of inquiry. During the hands-on coding challenge, teams of 2–4 students built autonomous robot cars using provided hardware, including Arduino boards, sensors, and motors. Participants assembled and tested their robots using example codes and developed autonomous programs to navigate an obstacle course, incorporating line-following, obstacle detection, signaling with LEDs, beeping, and playing a short melody. Teams were evaluated on performance, including smooth movement, obstacle avoidance, and completion time, with up to three attempts allowed. The highest-scoring team received the President's Award.

Figure 2. Oral presentation.

During the oral and poster sessions, ten student teams—five from South Korea and five from the United States—presented their research findings. The topics reflected each country's distinct research strengths. Korean teams investigated diverse STEM fields such as mathematics, chemistry, materials science, environmental engineering, and astronomy, whereas U.S. teams focused mainly on drone- and artificial intelligence (AI)-based applications for environmental monitoring and engineering design. Table 2 presents the representative research topics from both groups.

Table 2. Research topics presented by Korean and U.S. teams.

No.	Research title	Country
1	The Range of a Generalized Affine Index Polynomial Invariant	Korea
2	Morphology and Size Control of HKUST-1 via Vapor-assisted Conversion Method	Korea
3	Analysis of the Physicochemical Properties of Ulva Australis Biochar at Different Cooling Rates and Its Use as a Soil Salinity Remover	Korea
4	Photometric Observations of Open Clusters Using Mobile Phone Cameras	Korea
5	Various Mathematical Discoveries Regarding the Number of Divisors	Korea
6	SkyLink: IoT-Based Sensor Triggered Temporary Drone Network	U.S.
7	Aerial Enforcement Guidance and Intelligence System	U.S.
8	BlueShield: Detecting Eutrophication with AI-Enhanced Hyperspectral Drone Imaging	U.S.
9	Real-time Multi-label Wildfire Classification with AI-enabled Drone	U.S.
10	Preventative Early Building Inspection and Treatment Through Drones	U.S.

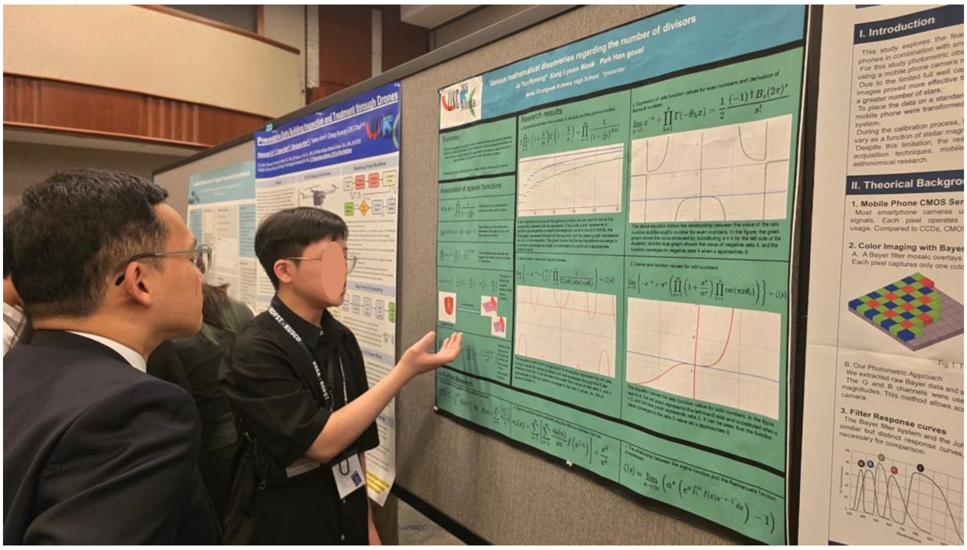

Figure 3. Poster presentation by a Korean student.

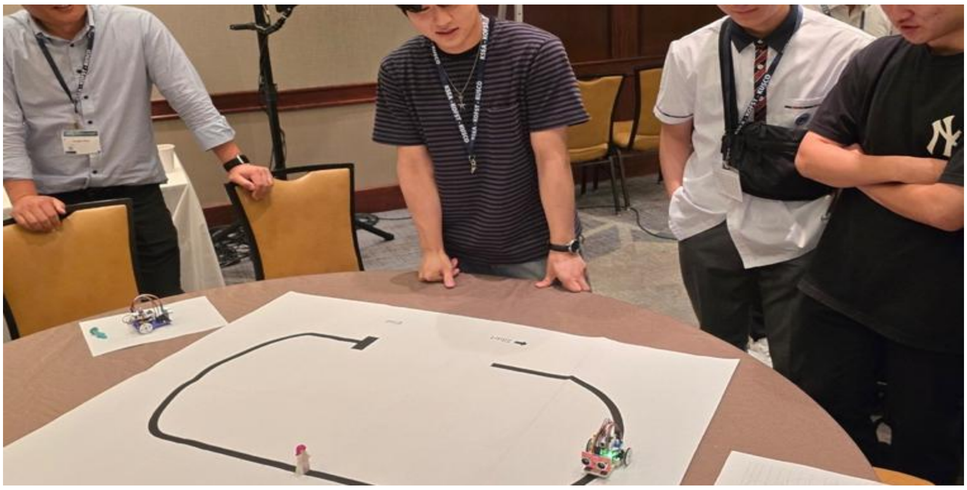

Figure 4. Coding challenge.

- The program concluded on Saturday, August 9, with a closing ceremony and final plenary session from 10:00 AM to 1:00 PM, which included an awards ceremony recognizing outstanding youth presentations and program achievements.

3.4. Measures

Given the small and uneven sample sizes, particularly the limited number of participants who completed both pre- and post-surveys (six from the United States and three from South Korea), statistical analyses were conducted with caution, and findings are interpreted as exploratory.

3.4.1. Quantitative measures

The primary quantitative instrument was a pre- and post-program survey assessing STEM affinity, comprising 15 Likert-scale items (1 = strongly disagree to 5 = strongly agree). Constructs measured included interest in STEM subjects, perceived competence, self-efficacy, and aspirations for future STEM careers (adapted from Tyler-Wood et al. [28]). Sample items included:

- "I am confident in my ability to solve STEM problems."
- "I am interested in pursuing a STEM career."
- "I understand how engineering principles are applied in real-world situations."

For Korean participants, the survey was translated into Korean employing a forward-translation/back-translation process conducted by bilingual experts [29,30]. Pilot testing and expert review supported the instrument's validity and reliability within this context.

While formal psychometric validation across cultures was limited due to the program's scope and timeframe, pilot testing aimed to establish content validity and linguistic accuracy [31]. Future iterations should include more rigorous validation, such as testing for measurement invariance [32].

3.4.2. Qualitative measures

Open-ended survey questions explored participants' perceptions of their learning outcomes, confidence development, and future plans related to STEM. Example questions included:

- "Describe how participating in the program affected your understanding of STEM."
- "What activities did you find most valuable, and why?"
- "Do you see yourself pursuing a STEM career in the future? Please explain."

These responses aimed to complement quantitative data by capturing nuanced insights into student experiences and attitudes.

3.5. Data analysis procedures

3.5.1. Quantitative data analysis

Descriptive statistics, including means, standard deviations, and medians, were used to summarize the data. Due to unequal pre- and post-survey response rates (pre: 13 Korean, 6 U.S.; post: 3 Korean, 9 U.S.), paired *t*-tests were not feasible. Consequently, inferential comparisons were conducted using Welch's *t*-tests as preliminary, exploratory analyses to identify potential trends [33]. Effect sizes (Cohen's *d*) were calculated to estimate the magnitude of observed changes [34]. Statistical significance was evaluated at $p < 0.05$. All results are interpreted with appropriate caution, with an emphasis on descriptive patterns rather than definitive inferential conclusions.

3.5.2. Qualitative data analysis

Open-ended responses were analyzed using Braun and Clarke's [35] six-phase thematic analysis:

- Familiarization with data: Reading responses repeatedly for immersion.
- Generating initial codes: Line-by-line coding of meaningful segments.
- Searching for themes: Grouping codes into overarching themes aligning with research questions.
- Reviewing themes: Refining themes to ensure internal coherence.
- Defining and naming themes: Clarifying the essence of each theme.
- Producing the report: Synthesizing themes and illustrative quotations.

To ensure coding reliability, two researchers independently coded 20% of responses, achieving an intercoder reliability of 85%, with discrepancies discussed and resolved.

3.6. Trustworthiness and validity measures

To enhance the credibility and dependability of findings, researchers employed multiple strategies:

- Member checking: Participants received summaries of qualitative findings for validation [36].
- Triangulation: Combining quantitative scores with rich qualitative data provided corroboration [36].
- Intercoder reliability: Independent coding with resolutions improved coding consistency [37].
- Reflexivity: Researchers maintained reflective logs to monitor biases and assumptions throughout analysis [38].
- Bilingual validity: Translations of survey items and responses were carefully checked by bilingual experts to ensure semantic equivalence and cultural appropriateness [29].

4. Results

The mixed-methods analyses yielded nuanced insights into the impact of the Youth Development Program (YDP 2025). Quantitative analyses indicated largely nonsignificant changes in STEM affinity, whereas qualitative findings revealed perceived gains in skills, confidence, and motivation toward STEM. This divergence likely reflects the small sample size, uneven response rates, limited statistical power, and the short duration of the intervention. Taken together, the findings underscore the value of integrating quantitative and qualitative evidence when evaluating intensive, short-term youth STEM programs.

4.1. Quantitative findings

4.1.1. Descriptive statistics

Table 3 presents pre- and post-survey STEM affinity scores for all participants and by country. Overall, mean STEM affinity scores remained relatively stable from pre-survey (M = 4.01, SD = 0.90) to post-survey (M = 3.90, SD = 0.71), with identical medians (Md = 4.00).

Table 3. Pre- vs. post-survey results (Welch's t-test and effect sizes).

Group	Pre-mean (SD)	Post-mean (SD)	Welch's t (df)	p-value	Cohen's d	Interpretation
All students (34)	4.01 (0.90)	3.90 (0.71)	0.38 (27.4)	0.71	–0.13	No meaningful change
Korean students (13)	4.28 (0.81)	4.22 (1.10)	0.09 (2.5)	0.94	–0.07	Stable, no change
U.S. students (21)	3.41 (0.85)	3.79 (0.58)	–0.96 (8.1)	0.37	+0.55	Moderate improvement (ns)

Among U.S. participants, mean scores increased from 3.41 (SD = 0.85, n = 6) to 3.79 (SD = 0.58, n = 9). In contrast, Korean participants exhibited minimal change (pre: M = 4.28, SD = 0.81, n = 13; post: M = 4.22, SD = 1.10, n = 3). Although these descriptive trends suggest modest subgroup variation, interpretation is constrained by small and uneven subsample sizes. Figure 4 illustrates the pre- and post-survey mean scores by group.

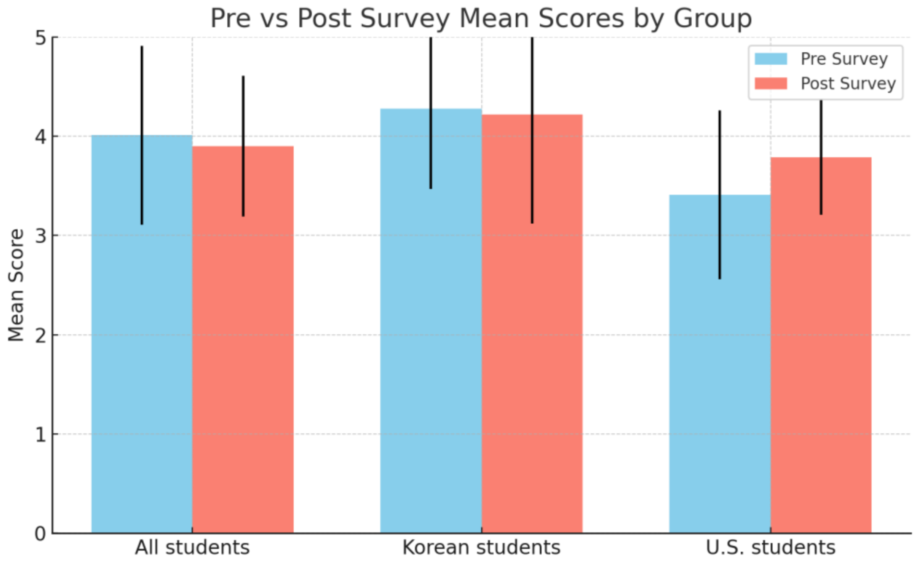

Figure 5. Pre- and post-survey mean scores by groups.

4.1.2. Inferential analysis (Welch's t-test)

Because pre- and post-survey responses did not involve matched pairs and participation rates were uneven, paired analyses were not feasible. Welch's *t*-tests were therefore conducted as exploratory analyses. No statistically significant differences were observed for the full sample [$t(27.4) = 0.38$, $p = 0.71$] or for Korean participants [$t(2.5) = 0.09$, $p = 0.94$].

For U.S. participants, the difference between pre- and post-survey scores was also not statistically significant [$t(8.1) = -0.96$, $p = 0.37$]. However, the corresponding effect size was moderate ($d = 0.55$), suggesting a potential positive trend that warrants cautious interpretation.

4.1.3. Effect sizes (Cohen's d) and power considerations

Effect size estimates indicated a negligible change for Korean participants ($d = -0.07$), a very small negative effect for the overall sample ($d = -0.13$), and a moderate positive effect for U.S. participants ($d = 0.55$). Given the small and uneven sample sizes, particularly in the post-survey, these estimates should be interpreted as exploratory rather than confirmatory. Overall, the quantitative findings suggest that detectable changes in STEM attitudes may be difficult to capture within short-term interventions characterized by limited statistical power.

4.2. Qualitative findings

In contrast to the quantitative results, qualitative analyses revealed consistent thematic patterns related to participants' perceived learning, confidence, and engagement in STEM. Responses were synthesized into four analytically salient themes aligned with the study's research questions.

4.2.1. Development of practical skills and conceptual understanding

Participants frequently reported gains in applied STEM skills and a deeper understanding of how theoretical concepts translate into practice. Hands-on activities—particularly coding, robotics, and engineering design—were perceived as effective in strengthening problem-solving abilities and systems thinking. Students described STEM as an interconnected and applied field, noting that exposure to research posters, design challenges, and discussions with scientists broadened their perspectives and clarified future academic interests:

> *"Through the conversation with the Nobel Prize Laureate, I was inspired in my STEM studies. By viewing the diverse research posters, I was able to broaden my perspective and develop insights that allow me to look further ahead toward my career path."*
> *"The program really opened my eyes as to how big the STEM field is."*
> "*Talking with the Nobel Laureate inspired me in my STEM studies. Viewing diverse research posters helped me see the many possibilities in STEM and consider my future path."*
> "*Developing ideas for hardware comes hand in hand with coding."*

These experiences helped participants articulate a clearer understanding of STEM as an interconnected and applied field.

4.2.2. Growth in confidence and self-efficacy

A prominent theme across reflections was increased confidence in engaging with STEM tasks. Participants described feeling more capable of addressing complex problems, presenting ideas, and discussing technical concepts. Several students explicitly noted reduced self-consciousness about their STEM abilities, attributing this change to hands-on learning experiences:

> *"I gained confidence in learning STEM through hands-on activities,"*
> *"I feel less self-conscious about my STEM skills, partly because I feel a bit more confident."*

These accounts align with constructs of self-efficacy, suggesting that experiential engagement supported perceived competence even when such changes were not captured by survey measures.

4.2.3 Broadening of STEM career awareness and aspirations

Participants reported expanded awareness of STEM career pathways following exposure to diverse disciplines, research practices, and professional role models. Rather than expressing immediate career decisions, students described increased clarity regarding interests and motivation to pursue further STEM opportunities. For example, engagement in drone-related activities influenced aspirations toward aviation-related careers, while observation of data analysis and experimental design during poster sessions inspired interest in scientific research. Several participants characterized the program as both challenging and enjoyable, emphasizing its role in shaping emerging academic and professional goals. Notably, over half of the U.S. teams continued collaborative research following the program and submitted their projects to additional national and international conferences:

> *"Participating in the Youth Development Program was an experience that I would definitely go through again. It was a fun experience to learn more about STEM."*

> *"My strong passion to participate in the program was ignited. I have a strong conviction that I should go into engineering."*

4.2.4 Social and cross-cultural engagement in STEM contexts

Students emphasized the importance of peer collaboration and cross-cultural interaction, reporting that working with peers from different national and linguistic backgrounds enhanced both learning and engagement. Despite language barriers, participants maintained communication beyond the program, highlighting sustained social and academic connections. Both students and mentors described the collaboration as supportive and meaningful, underscoring the role of inclusive, cross-cultural mentorship in fostering sustained interest and participation in STEM.

4.3. Synthesis and critical interpretation

These findings reveal a divergence between quantitative and qualitative outcomes. While survey-based measures detected minimal change in STEM affinity, qualitative evidence suggests that YDP 2025 supported participants' skill development, confidence, and motivational orientation toward STEM. This discrepancy likely reflects limitations in measurement sensitivity, statistical power, and program duration rather than an absence of meaningful impact.

These results highlight the importance of mixed-methods approaches when evaluating short-term STEM interventions, particularly for constructs such as identity, confidence, and motivation that may develop gradually and be more readily articulated through reflective narratives than Likert-scale instruments. Future research employing larger samples, longitudinal designs, and culturally responsive measures is needed to more robustly assess how experiential and cross-cultural STEM programs shape developmental trajectories over time.

5. Discussion and conclusions

This study provides contextualized and theoretically grounded insights into the effects of a short-term, immersive STEM youth development program for high-achieving adolescents from the United States and South Korea. Although quantitative analyses revealed largely nonsignificant changes in STEM affinity, these findings must be interpreted in light of limited statistical power, potential ceiling effects associated with a high-achieving sample, and the brief duration of the intervention. In contrast, qualitative findings revealed perceived gains in practical skills, confidence, and motivational orientation toward STEM, suggesting that certain developmental outcomes may be more readily captured through reflective and experiential indicators than through pre–post survey measures alone.

5.1. Scope, sampling, and generalizability

The scope of the present findings is bounded by the characteristics of the participant sample. Students were purposefully selected based on demonstrated achievement, motivation, and prior interest in STEM, and participation was voluntary. Accordingly, the findings are not intended to generalize to broader or more heterogeneous student populations, including students with limited prior exposure to STEM or those from historically underrepresented groups. The absence of statistically significant quantitative change may reflect ceiling effects within this highly prepared cohort rather than an absence of program influence.

Despite these limitations, the study offers insight into how intensive, enrichment-oriented programs function within advanced-learning contexts. Generalization beyond this group is therefore best conceptualized in terms of underlying mechanisms rather than direct outcomes. Specifically, the findings highlight how particular program features—such as experiential learning, mentorship, and authentic engagement with STEM practices—may support learning and motivation when thoughtfully adapted to different populations and educational settings.

5.2. Implications for program design, evaluation, and policy

Several elements of the program demonstrate relevance across contexts, particularly the role of hands-on experiential learning, sustained mentorship, and opportunities for authentic participation in STEM practices. These components consistently emerged in participants' reflections and align with prior research emphasizing mastery experiences and social persuasion as central mechanisms for fostering self-efficacy and persistence in STEM pathways [21,23,26]. Program designers may therefore consider these elements as foundational features of effective STEM enrichment initiatives.

At the same time, other aspects of YDP 2025—such as its intensity, selectivity, and access to high-profile role models—are context-specific and may not be readily scalable. From a policy perspective, broader implementation efforts should prioritize adaptation rather than replication, ensuring that comparable mechanisms of engagement, recognition, and support are embedded within inclusive and culturally responsive environments. From an evaluation standpoint, the findings underscore the importance of mixed-methods approaches that extend beyond short-term attitudinal measures to capture developmental processes such as confidence, identity formation, and evolving aspirations.

5.3. Theoretical contributions and cross-cultural insights

This study contributes to theory by illustrating how self-efficacy and STEM identity frameworks operate across cultural contexts. Consistent with social cognitive theory, participants' qualitative accounts underscore the importance of mastery experiences, vicarious learning, and social affirmation in shaping confidence and motivation [21]. While these mechanisms appeared robust across both national contexts, their expression and salience varied culturally.

Differences observed between U.S. and Korean participants suggest that cultural norms influence how developmental gains are perceived, articulated, and measured. For instance, collectivist orientations may foreground peer relationships and social belonging, whereas more individualistic orientations may emphasize personal confidence and self-referenced growth. Integrating these insights with integrated STEM frameworks [15] and culturally responsive pedagogies [29] extends existing models by emphasizing that STEM development is not solely cognitive but also socially and culturally mediated.

5.4. Conclusions and future directions

In conclusion, this study demonstrates that short-term, immersive STEM youth programs may exert meaningful influences on students' skills, confidence, and motivation, even when such changes are not readily detectable through conventional quantitative measures. The findings reinforce the importance of theoretically grounded, culturally attentive, and methodologically pluralistic approaches to evaluating STEM education initiatives. Future research should examine these mechanisms longitudinally, with more diverse samples and culturally sensitive instruments, to further elucidate how experiential STEM programs support developmental trajectories across contexts.

6. Limitations and future research

Several limitations should be considered when interpreting the results of this study. First, the small sample limits statistical power and reduces the ability to detect modest or nuanced changes in attitudes, particularly in quantitative analyses. Uneven pre- and post-survey response rates further constrain inferential interpretation and raise the possibility of nonresponse bias. Second, response bias may have influenced the qualitative findings, as participants who experienced the program more positively may have been more likely to submit detailed reflections, potentially amplifying favorable themes. Third, measurement validity presents an additional limitation. The use of brief Likert-scale items, while appropriate for exploratory research, may not have fully captured the multidimensional nature of constructs such as STEM identity, self-efficacy, and motivation. Although survey instruments were adapted from established measures [31], self-reported data remain sensitive to interpretation differences, particularly across cultural contexts. Fourth, ensuring cultural equivalence poses an inherent challenge in cross-national research. Despite careful translation and review procedures [31], variations in language, educational norms, and culturally shaped response styles may have influenced how items were understood and how experiences were reported. Finally, the short duration of the program and the absence of longitudinal follow-up preclude conclusions about the durability of observed gains or their translation into long-term outcomes such as sustained interest, academic persistence, or STEM career trajectories [22]. As such, findings should be interpreted as indicative of short-term experiential and perceptual changes rather than enduring developmental effects.

6.1. Future directions

Future research can strengthen empirical rigor and extend the contribution of this work in several ways. Studies employing larger, more diverse, and randomly selected samples would improve generalizability and enable more robust statistical analyses across demographic and cultural groups. Longitudinal designs that follow participants over multiple years would allow researchers to examine the persistence of changes in attitudes, skills, and STEM pathways, providing insight into how early program experiences influence longer-term educational and career outcomes [20].

Methodologically, incorporating performance-based assessments—such as evaluations of project artifacts, research presentations, or demonstrated technical competencies—would complement self-reported measures and offer more objective indicators of learning and skill development [35–37]. Additionally, further cross-cultural validation of survey instruments, coupled with mixed-methods or ethnographic approaches, could deepen understanding of how STEM identity and self-efficacy are constructed and expressed within different cultural contexts [30,32].

In sum, while this study offers evidence that experiential, mentorship-driven STEM programs can foster meaningful skill development and motivation among high-achieving youth, broader and more rigorous investigation is needed. Such efforts are essential to informing scalable program designs and equitable policies that support sustained STEM engagement across diverse student populations.

Author contributions

Jiyoon Yoon: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing; Jae Hyeon Ryu: Conceptualization, Funding acquisition, Project administration, Resources, Software, Supervision, Validation, Writing – review & editing; Oksu Hong: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing; Byoungho Jung: Project administration, Supervision, Writing – review & editing; Yungjun Yoo: Conceptualization, Project support, Student mentoring, Writing – review & editing; Hannah Ziegler: Writing – review & editing, Project support; Heeju Hong: Writing – review & editing, Project support.

Use of Generative-AI tools declaration

In the development of this manuscript, the authors utilized ChatGPT (a generative AI language model by OpenAI) to assist with language refinement, grammar correction, and suggestions for clarity and structure. All content, ideas, and interpretations presented in this manuscript are solely the authors' own work. The use of ChatGPT was limited to editorial support and did not influence the research design, data analysis, results interpretation, or conclusions. The authors have reviewed and verified all content generated or revised using the AI tool to ensure accuracy and integrity.

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Conflict of interest

The authors declare that they have no known competing financial or personal interests that could have appeared to influence the work reported in this manuscript.

Ethics declaration

This study was conducted in accordance with ethical standards and approved by the Institutional Review Board (IRB) of the University of Texas at Arlington (Protocol Review #2023-0207.1). All participants provided informed consent prior to participation, and the study procedures adhered to guidelines for the protection of human subjects.

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