Leveraging Human-Centered Design and Culturally Relevant Engineering Pedagogy to Strengthen STEM Self-Efficacy Among High School Students and Undergraduate Trainers

Ella Brissett, Duke University

Ella is a Post-baccalaureate Fellow in the Center for Global Women's Health Technologies in Duke University's Biomedical Engineering Department. Ella works with Ignite, a human centered design-based engineering program that links engineering and local, community-based issues to encourage participation in engineering. She is very interested in design pedagogy and curriculum to broaden engineering participation for pre-college students.

David Knudsen

At the Museum of Life and Science, I specialize in science communication projects, program evaluation, and developing tinkering and technology curriculum. Science communication and videography are valuable tools for connecting and sharing the amazing science that is happening in our community! Before joining the team as an Associate Program Manager, I was a part of the Museum's Summer Camp Program and Fellowship Program. I earned my bachelor's degree in political science and journalism from North Carolina State University. While my degree is not in STEM fields, working at the Museum has provided me with numerous opportunities for learning through STEM activities and programs.

Nirmala Ramanujam, Duke University

Nirmala (Nimmi) Ramanujam is the Robert W. Carr Professor of Biomedical Engineering, Professor of Cancer Pharmacology and Cancer Biology, and Global Health at Duke University. She founded the Center for Global Women's Health Technologies (GWHT) in 2013 to reshape women's health through technology innovation. Her translation program in cervical and breast cancer has brought together multiple partners across U.S. and international academic institutions, hospitals, companies, non-governmental organizations, and ministries of health. Prof. Ramanujam values co-creating solutions with those that are at the level of the problem. This led to the creation of a global education program Ignite in 2013 that intersects engineering design thinking, STEM concepts, and the U.N. Sustainable Development Goals.

Megan Madonna, Duke University

Megan Madonna is an Assistant Research Professor in Biomedical Engineering at Duke University, studying human-centered design and student resilience and identity. She serves as the Director of Ignite, a human-centered design-based engineering program that links engineering and local, community-based issues to encourage empathic and creative thinkers and broaden participation in engineering. Additionally, she serves as the Assistant Director of Education for the Center for Global Women's Health Technologies at Duke University.

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Abstract

Background: Students from diverse and often underrepresented backgrounds bring strong curiosity and creativity to STEM, but access to sustained, hands-on programming remains uneven due to structural disparities. Community-university partnerships provide critical opportunities to expand access to early STEM engagement, which is linked to improved academic performance, problem-solving, and collaboration skills. This study examines Ignite, an eight-month hybrid design program in which high school "Makers" are supported by undergraduate "Trainers" through virtual and in-person design activities. The program emphasizes human-centered design aligned with the UN Sustainable Development Goals to connect local action with global impact. The curriculum is organized into the three phases of human-centered design adapted from IDEO: "Hear," "Create," and "Deliver." *Methods:* We analyzed pre- and post-program survey data from 2021–2025 that incorporated the validated Carberry et al. Engineering Design Self-Efficacy instrument to measure confidence, motivation, and anxiety throughout the design process. *Results:* Results show significant increases in design confidence for both Makers ($n = 65$, $p < 0.001$) and Trainers ($n = 76$, $p < 0.001$). Trainers also report a significant decrease in overall anxiety following the program ($p < 0.01$). Across the Carberry design steps, confidence was lowest during the conducting/constructing phases (Makers: $p < 0.001$; Trainers: $p < 0.001$). Anxiety peaked during the constructing phase (Makers: $p < 0.01$; Trainers: $p < 0.001$). Taken together, these findings highlight the potential of culturally responsive and equitable design (CRED) programs to strengthen engineering identity, self-efficacy, and confidence while identifying critical phases and subgroups where additional support is needed. By combining human-centered design, peer mentorship, and culturally relevant pedagogy, Ignite offers a scalable model for broadening participation in STEM and reducing persistent equity gaps.

Introduction and Background

Students from underrepresented backgrounds face persistent structural barriers to sustained, hands-on learning, despite strong interest and creativity [1]. Early and meaningful STEM engagement is widely associated with increased academic performance, stronger problem-solving and communication skills, and greater persistence in STEM pathways [2]. Informal and hybrid learning environments–such as community programs, museums, and university partnerships–play a critical role in broadening participation by offering flexible, low-barrier opportunities for students who may be excluded or underserved in traditional classroom settings [2], [3].

The Ignite program, led by the Duke University Department of Biomedical Engineering in Durham, NC in partnership with the Museum of Life and Science in Durham, NC, was developed to address these disparities. Over eight months, high school participants ("Makers") work through the engineering design process while working with undergraduate "Trainers" who serve as near-peer mentors and co-designers of the curriculum. Through this structure, Makers receive individualized mentorship and consistent academic support–two factors known to strengthen persistence in STEM for historically marginalized groups [4].

Ignite emphasizes human-centered engineering and encourages students to address locally relevant challenges in human health and its intersection with water, energy, and sustainability, such as improving access to clean water, reducing environmental exposures, and addressing community wellness needs. Each project is aligned with the United Nations Sustainable Development Goals (SDGs), enabling Makers to situate their designs within broader social and environmental contexts and recognize the global relevance of local problem solving [5]. Within this model, the interactions between undergraduate Trainers and high school Makers are central. Trainers help guide Makers through complex design tasks, model engineering mindsets, and support students as they navigate unfamiliar concepts. Because near-peer mentorship has been shown to foster belonging, confidence, and persistence in STEM pathways, particularly for students from underrepresented groups (for example, [6], [7]), we sought to understand how Ignite's mentorship structure influences both the Makers' and the Trainers' perceptions of the engineering design process.

The pedagogical design of Ignite is grounded in complementary learning and motivation theories that emphasize the social, cultural, and affective dimensions of STEM learning. Social Learning Theory and Self-Determination Theory together emphasize that motivation grows when learners feel competent, autonomous, and socially connected [8], [9]. These frameworks highlight how Ignite's emphasis on feedback and collaboration, modeled with the Ignite Trainers, contributes to persistence in STEM learning environments. Within Social Learning Theory, self-efficacy–the belief in one's ability to complete a specific task–plays a central role [10]. Unlike self-esteem or outcome expectancy, self-efficacy is context-specific and directly influences motivation, persistence, and achievement [11], [12]. Bandura identified four primary sources of self-efficacy: mastery experiences, vicarious experiences, social persuasion, and affective states [10]. Together, these sources form a feedback loop through which learners evaluate and build confidence in their abilities [13].

- Mastery Experiences: Direct success on challenging tasks strengthens self-efficacy, while repeated failure may weaken it. However, it is the learner's interpretation of these outcomes that matters most; attributing success to effort or strategy produces more substantial gains in confidence than attributing it to luck or external help [8].
- Vicarious Experiences: Observing peers or mentors succeed can reinforce a sense of possibility, particularly when the model shares similar characteristics or challenges [11].
- Social Persuasion: Encouragement and feedback from trusted figures can raise self-efficacy, especially when coupled with authentic opportunities to succeed [8].
- Affective States: Emotional and physiological cues also shape perceived capability; high self-efficacy learners interpret arousal as readiness, whereas low-efficacy learners perceive it as anxiety [10].

These sources interact dynamically across developmental and social contexts. Mastery experiences tend to dominate in early learning, while social and vicarious influences become stronger in adolescence. Gender and cultural factors also shape efficacy beliefs–female students often respond more to modeling and feedback in male-typed fields like engineering, and learners from collectivistic cultures rely more on group mastery and social support [4], [10], [13]. Across decades of research, self-efficacy has emerged as one of the most potent predictors of motivation and performance, linking cognition, emotion, and behavior to explain how educational interventions enhance confidence, persistence, and emotional regulation in design-based learning (For example, [13], [14]). In Ignite, the Makers connect engineering design to topics that their community, family, and themselves deem important to work on.

Culturally relevant pedagogy (CRP) provides a complementary framework for fostering both academic success and cultural competence among diverse learners. Grounded in Ladson-Billings' foundational theory, CRP emphasizes that effective teaching requires not only promoting achievement but also affirming students' cultural identities and developing their critical consciousness [15]. Rather than simply accommodating cultural differences, CRP integrates students' lived experiences into classroom learning to challenge inequities and empower marginalized students. Building on this foundation, research on culturally responsive and equitable design (CRED) shows that such approaches enhance teacher self-efficacy and increase student engagement, particularly among female and previously disengaged students [16]. By valuing students' cultural knowledge and embedding it within collaborative learning environments, Ignite Trainers foster both cognitive growth and social connection–key motivational dimensions aligned with Social Learning and Self-Determination Theories.

Constructivist theory further underpins this approach by positioning learning as an active, reflective, and collaborative process in which students build understanding through interaction and inquiry. Rooted in the work of Piaget, Vygotsky, and Bruner, constructivism emphasizes that knowledge is co-created through experience, dialogue, and problem-solving rather than transmitted from teacher to learner. Ignite Trainers act as facilitators who guide exploration, pose open-ended questions, and design environments that connect prior experiences to new concepts, enabling students to construct meaning through experimentation and reflection [17]. This means coupling the basics of biology taught in their high school science and health classes with problems that students witness firsthand in their experiences outside of school. This student-centered approach provides the pedagogical foundation for frameworks like CRED, which emphasize equitable participation, contextual relevance, and learner agency.

Finally, resilience theory in STEM education highlights adaptability, persistence, and self-efficacy as critical capacities that enable students and educators to thrive amid challenges [18]. Within Ignite, resilience supports sustained engagement by helping Makers regulate emotions, maintain motivation, and develop optimism when confronting demanding or uncertain situations. Communication and social interaction play key roles in this process, as supportive peer and mentor relationships foster belonging and provide interactive resources to navigate adversity. Notably, resilience is particularly salient for underrepresented and minority students, who often encounter additional structural and social barriers. Research indicates that inclusive pedagogies, mentorship, and community networks can strengthen resilience by enhancing self-efficacy and promoting long-term persistence in STEM pathways [18]. This is particularly relevant for Ignite, which intentionally serves students from historically underrepresented backgrounds.

Theory

The Ignite program is grounded in a multi-theoretical foundation to support students' and Trainers' cognitive and identity development in engineering, particularly those from historically underrepresented backgrounds. Drawing from Social Learning Theory, Self-Determination Theory, Resilience Theory, and Constructivist Theory, the curriculum is structured around three core phases: "Hear," "Create," and "Deliver." Each phase leverages theory-aligned strategies to promote student engagement, engineering identity, and community connection (Figure 1).

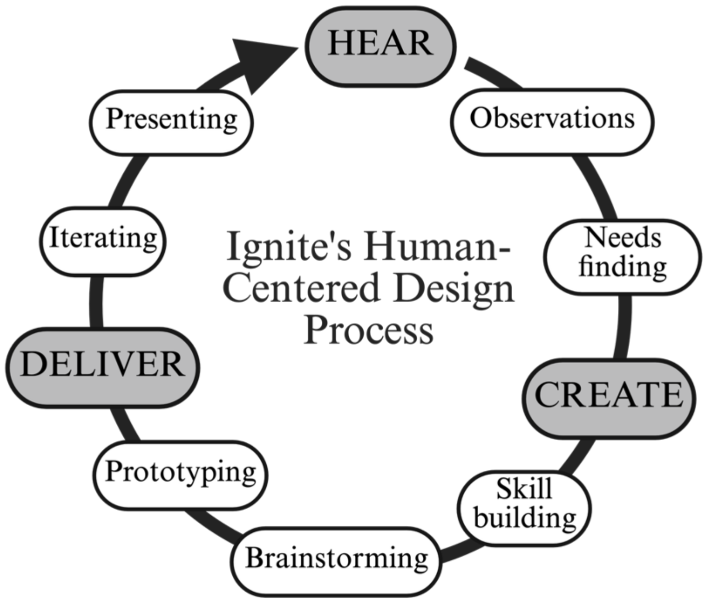

Figure 1: Ignite's Human-Centered Design Process. This cyclical model emphasizes human-centered, hands-on learning, and supports identity development through consistent mentorship and reflection.

Hear / Deliver Phase: Fostering Identity and Belonging

Bandura's four sources of self-efficacy are woven throughout Ignite's Hear and Deliver phases, which emphasize observation, feedback, and early skill-building:

- Mastery Experiences: Students build competence through structured lesson delivery, reflective discussions, and guided implementation of the engineering design process.
- Vicarious Experiences: Undergraduate Trainers serve as peer mentors, modeling perseverance and success.
- Social Persuasion: Consistent, constructive feedback from Trainers and peers reinforces students' developing confidence.
- Affective States: Positive emotional experiences–such as collaboration, encouragement, and accomplishment–help students reframe challenges as growth opportunities.

These experiences directly engage the three psychological needs outlined in Self-Determination Theory–competence (through mastery and feedback), relatedness (through mentorship and teamwork), and autonomy (through student-led exploration), cultivating intrinsic motivation and a sustained sense of agency in learning.

Ignite's curriculum also aligns with Culturally Relevant Pedagogy (CRP), operationalized through the Culturally Relevant Engineering Design (CRED) framework. Students are guided to "identify" community needs, "describe" problems with cultural and place-based understanding, "generate" solutions rooted in local knowledge, "embody" those ideas in prototypes, and "finalize" them with a focus on social impact.

Create Phase: Building Engineering Identity through Practice

The hands-on, design-based Create phase is supported by Constructivist Theory, positioning students as active problem-solvers who learn by experimenting, reflecting, and collaborating. This approach fosters growth in:

- Engineering identity and sense of belonging in STEM
- STEM abilities and design experience
- Awareness of local and global issues
- Community pride and social responsibility

Resilience Theory informs this phase as students learn to persist through iteration, uncertainty, and design setbacks. Mentorship and peer collaboration serve as protective factors that reinforce resilience, helping students maintain motivation and emotional balance in the face of complex, open-ended problems. This process mirrors findings in resilience research that highlight the role of social support and reflective problem-solving in sustaining engagement and well-being within STEM education [18].

These theoretical frameworks and their integrated application within the Ignite curriculum are illustrated in Figure 2, which highlights how each phase and pedagogical approach contribute to students' growth in engineering identity, STEM ability, and community identity.

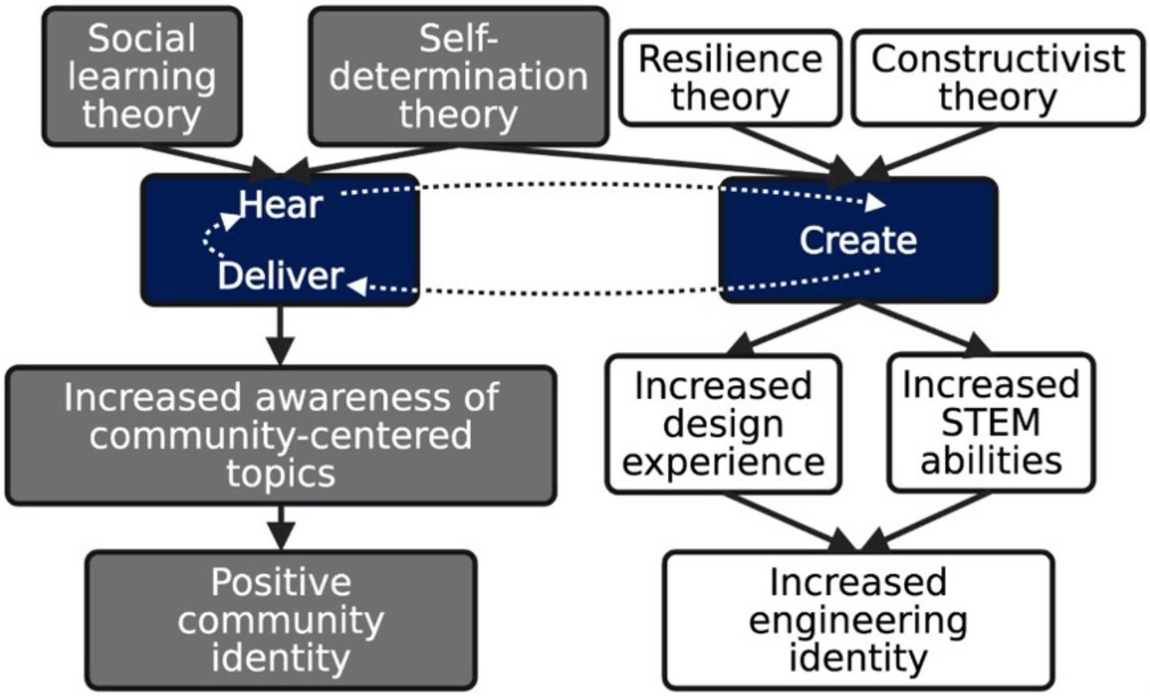

Figure 2: Theoretical Foundations and Outcomes of the Ignite Program. Ignite aims to strengthen engineering identity through hands on design while maintaining, legitimizing, or increasing a student's connection to their community.

Operationalizing the Framework: The Carberry Model

To evaluate these outcomes, the Ignite Makers program employs the validated Engineering Design Self-Efficacy instrument developed by Carberry, Lee, and Ohland [19]. This instrument assesses the cognitive and affective components central to engineering learning:

- Self-Efficacy (Confidence): Belief in one's ability to complete design tasks
- Motivation: Willingness to engage in design activities
- Outcome Expectancy: Belief that effort leads to success
- Anxiety: Emotional or affective barriers to participation

These constructs are mapped onto the Massachusetts Department of Education's (2006) nine-step engineering design process: Conduct engineering design → Identify a design need → Research a design need → Develop design solutions → Select the best possible design → Construct a prototype → Test and evaluate a design → Communicate a design → Redesign.

Together, these frameworks ensure that Ignite not only cultivates technical engineering design proficiency but also promotes confidence, resilience, and community identity–establishing a learning environment where students see themselves as capable, connected, and empowered engineers.

Methodology

Makers participate in an eight-month, project-based engineering program that combines weekly 1-hour synchronous virtual sessions and 2-hour in-person design workshops structured around Ignite's human-centered design (HCD) process (Figure 1). Program content and activities are aligned with state science, mathematics, and technology standards, the Next Generation Science Standards (NGSS), and the AE3 engineering education standards. Consistent with the *Hear* phase of the HCD model, students begin each project by engaging in observation and needs-finding activities to understand the social, environmental, and contextual dimensions of the problem space. These problem spaces center on biomedical and environmental health contexts, including clean energy and local water systems, human interactions with environmental resources, and the roles of both chemical and non-chemical factors in shaping human health. Students explore the Durham County Health Report and other primary public health literature to understand the most pressing health concerns of the community and are encouraged to interview members of their community to begin to understand areas where innovation may be needed. Further, the program emphasizes culturally responsive problem framing and supports students in identifying community needs and constraints prior to solution development. During the *Create* phase, teams participate in guided brainstorming and ideation sessions, build foundational technical and fabrication skills, and translate identified community and health needs into initial design concepts. Students then progress through multiple cycles of prototyping, testing, and feedback, emphasizing iteration. The *Deliver* phase includes refinement and preparation of final prototypes for presentation. Makers conclude the program by presenting their final designs, communicating their design rationale, and explaining the anticipated health, environmental, and community impacts of their solutions during a public showcase event. This culminating experience brings together families, community members, museum partners, and university faculty and staff, providing students with an opportunity to communicate their design process, justify design decisions, and reflect on the societal and community impact of their solutions. Figure 3 illustrates the Hear–Create–Deliver process through a student project–the ThermoChill knee brace–showing how community needs and health evidence identified during Hear (3A) informed concept generation and prototyping in Create (3B), and culminated in a user-centered biomedical design in Deliver (3C).

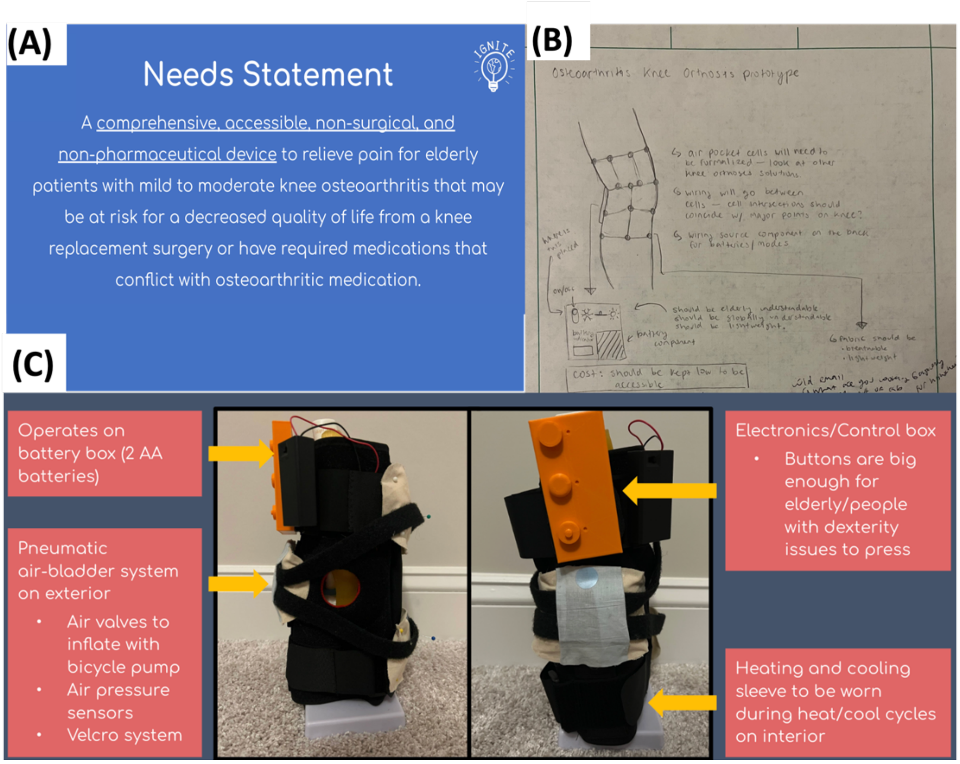

Figure 3: Example Makers project illustrating the Hear–Create–Deliver human-centered design process for a ThermoChill knee brace. (A) Hear: community-informed needs statement identifying an accessible, non-surgical, and non-pharmaceutical intervention for individuals with knee osteoarthritis. (B) Create: early concept generation and sketch-based prototyping, translating identified user and health needs into preliminary design features. (C) Deliver: refined functional prototype incorporating biomedical design considerations for a public showcase.

Undergraduate Trainers serve as near-peer mentors throughout the program, supporting Makers by facilitating needs-finding and design discussions, guiding students through each stage of the human-centered engineering design process, and providing constructive feedback on both technical implementation and design rationale. In parallel, Trainers develop their own instructional, mentoring, and leadership competencies through teaching responsibilities and reflective practice.

We assessed the impact of our program on Makers (n = 65) and Trainers (n = 76) participating in Ignite's curriculum using survey data collected from 2021 to 2025. Among Trainers, the largest group identified as Asian (60.5%), followed by White (21.1%), Black or African American (13.2%), Other racial identities (3.9%), and Hispanic, Latino, or Spanish origin (1.3%). Among Makers, the majority also identified as Asian (72.1%), with smaller proportions identifying as White (18.0%), Black or African American (4.9%), Hispanic, Latino, or Spanish origin (3.3%), and Other racial identities (1.6%). Across both cohorts, students identifying as female or underrepresented gender groups made up a clear majority. Makers (n = 65) were 72%

female/underrepresented genders (47 students) and 28% male (18 students). Trainers (n = 76) were 57% female/underrepresented genders (43 students) and 43% male (33 students).

The purpose of this study was three-fold: (1) to evaluate how participation in Ignite influenced changes in engineering design self-efficacy–specifically confidence, motivation, and anxiety–among high school Makers and undergraduate Trainers; (2) to examine how these outcomes varied across demographic groups, including race/ethnicity, gender, and grade level; and (3) to identify the phases of the engineering design process in which students experienced the greatest improvements or persistent challenges, in order to guide targeted curricular improvements. To assess these constructs, we used the validated Carberry Engineering Design Self-Efficacy instrument, which asks students to rate their confidence, motivation, and anxiety for each of the nine engineering design steps on a 0–100 scale (0 = cannot do at all, 50 = moderately can do, 100 = highly certain can do) (Table 1).

Table 1. Statements used to assess confidence, motivation, and anxiety around engineering design for Ignite's Makers and Trainers, derived from Carberry (2010) [19].

Categories	Confidence
	Motivation
	Anxiety
Statements	Conduct engineering design
	Identify a design need within the community
	Research a design need
	Develop design solutions
	Select the best possible design
	Construct a prototype
	Evaluate and test a design
	Communicate a design
	Redesign / iterate

All statistical analyses were conducted in R. Pre- and post-program differences in confidence, motivation, and anxiety were assessed within each of the nine Carberry design steps using paired t-tests. To examine how overall program performance varied across steps, averaged pre- and post-program scores were compared using Tukey HSD post-hoc tests to identify significant pairwise differences between steps. Demographic subgroup analyses were conducted using independent t-tests and one-way ANOVA to examine differences in student outcomes by race, gender, and age. We interpreted results using a standard significance threshold of $\alpha = 0.05$; p-values below 0.05, 0.01, and 0.001 are denoted by *, **, and ***, respectively.

To examine long-term academic outcomes, we conducted a retrospective analysis of former Ignite Makers from the 2021–2025 cohorts. First, we obtained each student's intended undergraduate major from their original Ignite application. We then identified students who had since graduated from high school and could be reliably tracked using publicly available information. For these students, we used LinkedIn profiles to determine their current undergraduate major or declared academic program. Students still enrolled in high school or lacking verifiable academic information were excluded. This process yielded 22 trackable alumni.

All procedures were carried out under the Duke University Institutional Review Board protocol #0087.

Results and Discussion

Because Ignite pairs high school Makers with undergraduate Trainers who guide them through every phase of the engineering design cycle, we sought to understand how this mentorship model shapes both groups' experiences. Specifically, we examined shifts in students' confidence, motivation, and anxiety toward the design process before, during, and after the program. Participants had substantial gains in confidence, with both Makers and Trainers showing statistically significant improvements (Makers: Δ +6.1, p = 2.10e-04; Trainers: Δ +11.13, p = 1.37e-07). Motivation remained high across the program, with only small, non-significant shifts (Makers: Δ –1.2; Trainers: Δ +1.14). Anxiety decreased for both cohorts, with Makers showing a modest reduction (Δ –2.4) and Trainers exhibiting a significant decrease (Δ –5.91, p = 9.67e-03) (Figure 4). Of note, these populations included 5–7 Makers who had completed the Makers program more than once and 17–20 Trainers who had worked with Ignite for more than one year. Although there were no significant changes to Makers' and Trainers' baselines between new and returning students, we hope to continue to grow this number to allow for long-term impact quantification using these metrics.

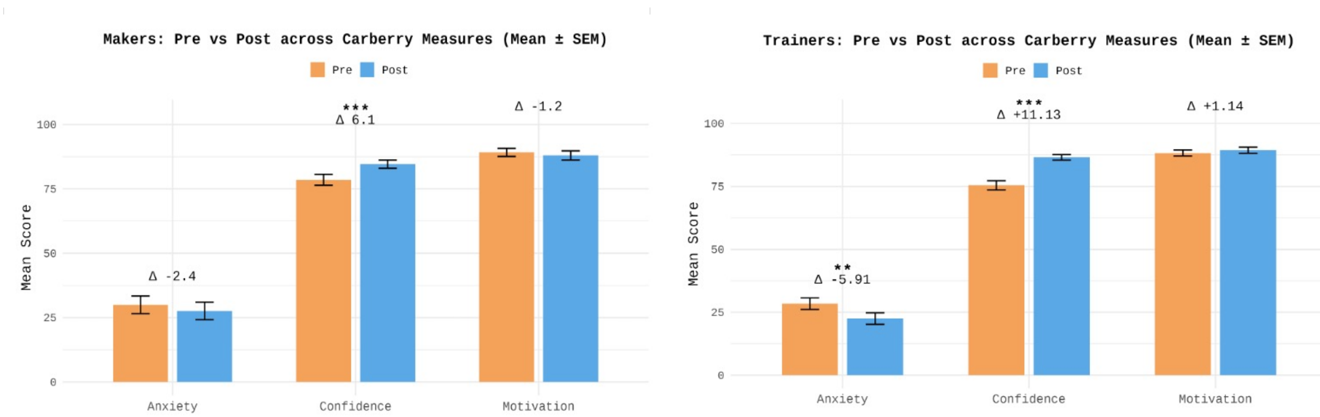

Figure 4: Self-Efficacy Changes in Makers. Pre- and post-program self-efficacy scores for Makers (A; n = 65) and Trainers (B; n = 76) across the three Carberry engineering design measures–confidence, motivation, and anxiety–shown as mean ± SEM. Δ values represent mean pre–post differences, and asterisks denote statistical significance based on paired t-tests.

To analyze Carberry step-level outcomes, we begin by examining Makers' shifts in anxiety, confidence, and motivation. No statistically significant changes in anxiety were observed across the design steps for Makers. The largest decreases in anxiety were observed in the Identify (–5.54), Conduct (–4.98), and Construct (–4.05) phases, suggesting greater comfort with early-stage problem framing, planning approach, and engaging in initial hands-on construction (Figure 5A). Participants entered the program with already high levels of motivation. Post-program changes were minimal and not statistically significant (Figure 5B).

While Ignite may not substantially increase motivation, given that Makers enter the program already highly motivated, longitudinal data suggest that the program may play a meaningful role in shaping students' eventual academic pathways. To examine this, we compared students' intended majors from their first Ignite application to the majors they ultimately pursued in college. After excluding students still in high school, we were able to track 22 former Makers, and remarkably, 20 of the 22 students (91%) went on to pursue STEM fields in college. Furthermore, 11 of the 22 students (50%) matriculated into engineering majors–including Biomedical, Mechanical, Electrical, and Financial Engineering. Although the proportion of engineering majors was similar to the proportion of students who initially expressed interest in engineering, these longitudinal patterns suggest that participation in Ignite may help sustain students' STEM engagement and engineering identity throughout their transition to college.

Maker participants reported significantly higher confidence after participating in the Ignite program. Statistically significant increases were observed across six of the nine Carberry steps, particularly in steps like Conduct (+11.07, $p = 5.83e{-}05$), Identify (+6.97, $p = 7.25e{-}04$), and Construct (+8.93, $p = 4.02e{-}04$) (Figure 5C). These gains suggest that the program effectively built engineering self-efficacy, especially in phases requiring ideation, hands-on building, and decision-making.

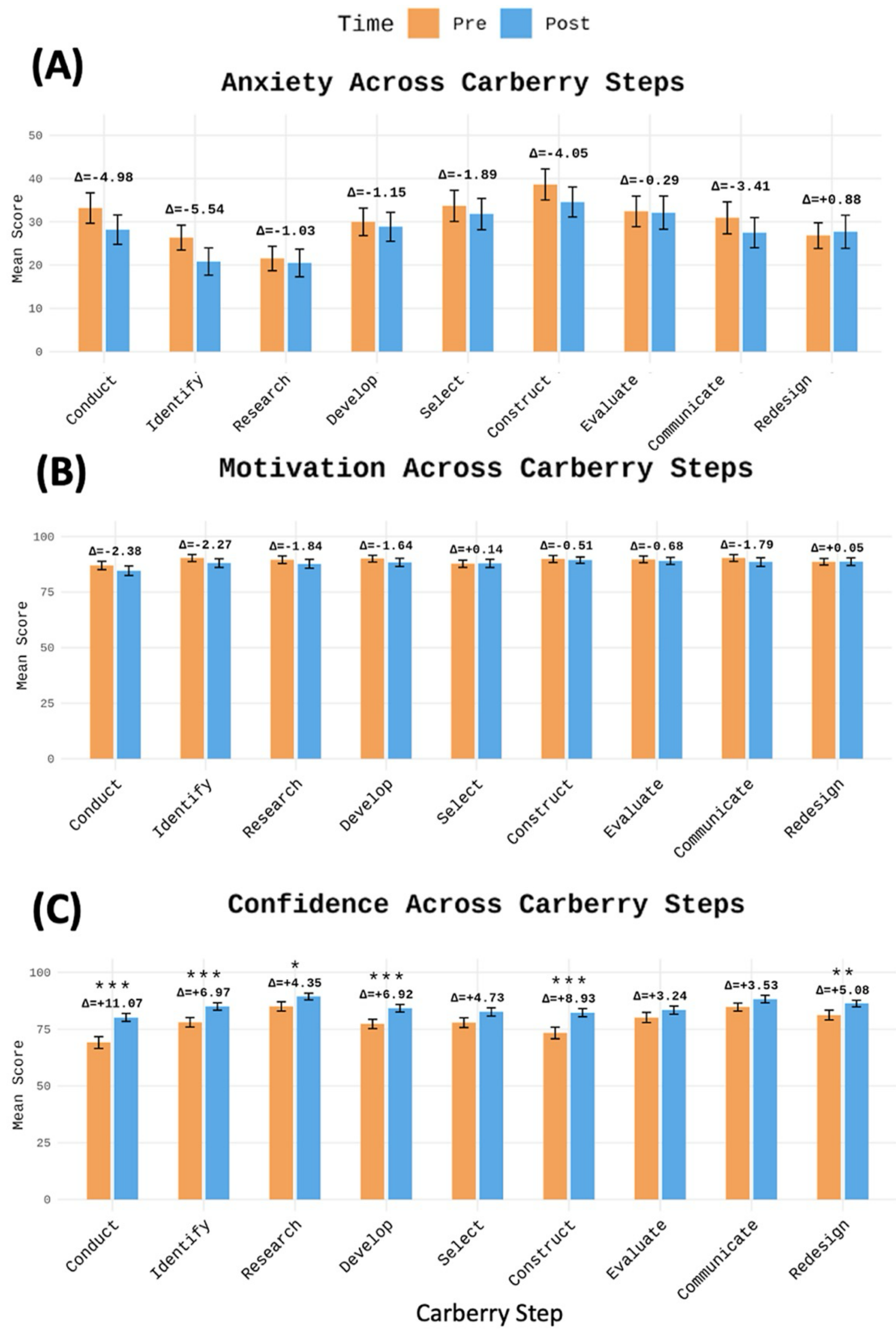

Figure 5: Changes in Self-Efficacy Across Design Steps. Pre- and post-program mean self-efficacy scores for Maker participants (n = 65) across the nine Carberry engineering design steps. Panels show (A) anxiety, (B) motivation, and (C) confidence. Δ values represent Post–Pre changes, and confidence scores are presented as mean ± SEM. Asterisks indicate statistical significance based on paired t-tests.

When examining whether outcomes varied across demographic groups among Makers, White Makers showed the largest overall confidence gain (Δ = +13.32, p = 0.04, n = 11). Asian Makers also demonstrated a significant increase in confidence (Δ = +4.62, p = 9.04e–04, n = 44–43). For both Asian and White students, changes in motivation and anxiety were small and not statistically significant. Statistical comparisons were not conducted for Black/African American (n = 3), Hispanic/Latino (n = 2), and Other (n = 1) Makers due to insufficient sample sizes (Table 2).

Table 2. Makers' Pre/Post Confidence, Motivation, and Anxiety by Ethnicity. Significance thresholds: $p < 0.05$*, $p < 0.01$**, $p < 0.001$***. Note: for Asian students, n was 44 for confidence and 43 for motivation and anxiety.

Ethnicity	Metric	Pre Mean	Post Mean	Δ (Post–Pre)	p-value
Asian (n = 44–43)					
	Confidence	81.21	85.83	4.62	**0.000904*** **
	Motivation	90.15	89.12	-1.03	0.488656
	Anxiety	27.65	23.75	-3.90	0.309274
Black or African American (n = 3)					
	Confidence	74.97	75.56	0.59	—
	Motivation	87.41	78.52	-8.89	—
	Anxiety	48.89	48.61	-0.28	—
Hispanic, Latino, or Spanish origin (n = 2)					
	Confidence	60.56	67.78	7.22	—
	Motivation	85.14	78.33	-6.81	—
	Anxiety	27.22	26.11	-1.11	—
White (n = 11)					
	Confidence	69.81	83.13	13.32	**0.043969***
	Motivation	85.05	86.16	1.11	0.853981
	Anxiety	30.33	41.01	10.68	0.419564
Other (n = 1)					
	Confidence	94.44	93.33	-1.11	—
	Motivation	100.00	96.67	-3.33	—
	Anxiety	5.56	33.33	27.77	—

In examining Trainers' shifts in anxiety, confidence, and motivation across the Carberry step-level analysis, we observed both significant reductions in anxiety and gains in confidence.

Trainers showed statistically significant decreases in anxiety across several design steps, with the largest reductions–similar to Makers–occurring during Conduct (Δ = –10.73, p = 0.000423) and Construct (Δ = –12.11, p = 0.001194). These reductions suggest that Trainers became more comfortable guiding students through phases that involve uncertainty, developing potential solutions, and iterating on early prototypes (Figure 6A).

Similar to Makers, Trainers entered the program with already high motivation. While motivation remained stable across most design steps, Trainers demonstrated a statistically significant increase specifically in the Conduct phase (Δ = +4.63, p = 0.031), suggesting that leading the initial investigative and research activities of the design process may have been particularly engaging for them (Figure 6B).

Confidence increased significantly and consistently across every phase of the design process, with the greatest gains observed in the Conduct and Construct steps (Δ = +15.91, p = 2.71e-9 and Δ = +15.57, p = 1.61e-8, respectively) (Figure 6C). Notably, these are also the two phases in which Makers showed the largest increases in confidence after participating in Ignite. These parallel improvements suggest that Trainers developed a stronger sense of mastery in both initiating the design process and supporting hands-on construction–two phases that require leadership, applied engineering skills, and adaptability.

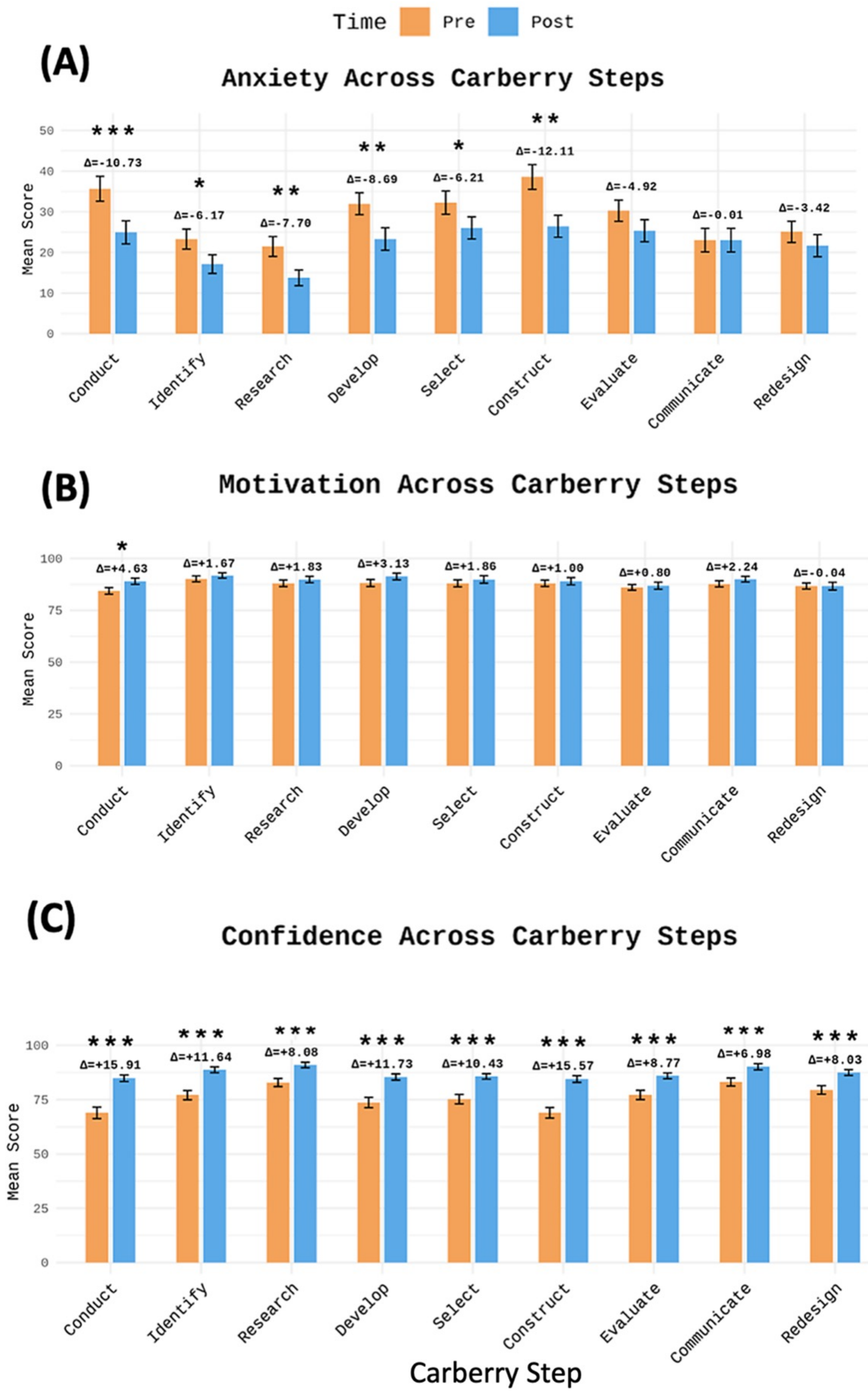

Figure 6: Self-Efficacy Changes in Trainers. Pre- and post-program mean self-efficacy scores for Trainer participants (n = 76) across the nine Carberry engineering design steps. Panels show (A) anxiety, (B) motivation, and (C) confidence. Δ values represent Post–Pre changes, and scores are presented as mean ± SEM. Asterisks indicate statistical significance based on paired t-tests.

When examining Trainers' subgroup differences by grade level, clear patterns emerged across constructs. Pre-program anxiety displayed a steady downward trend from 35.59 (Freshman) to 27.14 (Sophomore), 24.62 (Junior), and 21.24 (Senior), with a statistically significant difference between Freshmen and Seniors (Figure. 7A). In terms of pre–post change, younger Trainers showed the largest reductions: Freshmen decreased by −5.00, compared to −1.14 among Seniors–suggesting that Ignite may offer the greatest anxiety reduction for younger undergraduate students (Figure 7A).

Motivation remained high across all grade levels, with minimal variation and no statistically significant differences between groups (Figure 7B). All grades demonstrated positive pre–post gains (ranging from +1.38 to +2.80), indicating that Trainers enter the program highly motivated and maintain this strong motivation throughout their involvement (Figure 7B).

Confidence showed the clearest grade-related differences, with pre-program confidence levels increasing steadily from 74.51 (Freshman) to 83.39 (Sophomore), 85.97 (Junior), and 90.39 (Senior), with statistically significant differences between Freshmen and all older grade-level groups (Figure 7C). All grades also demonstrated meaningful pre–post program gains, with younger students continuing to exhibit the largest improvements, suggesting that Ignite may be particularly impactful for strengthening engineering confidence early in undergraduate education (Figure 7C). These findings are consistent with literature indicating that mastery experiences tend to dominate in early learning [10].

These patterns may also reflect Ignite's multi-year participation model. Because many Trainers return for multiple years, older students may have already experienced their most substantial improvements in both confidence and anxiety reduction during earlier cycles, resulting in smaller observable changes among older students.

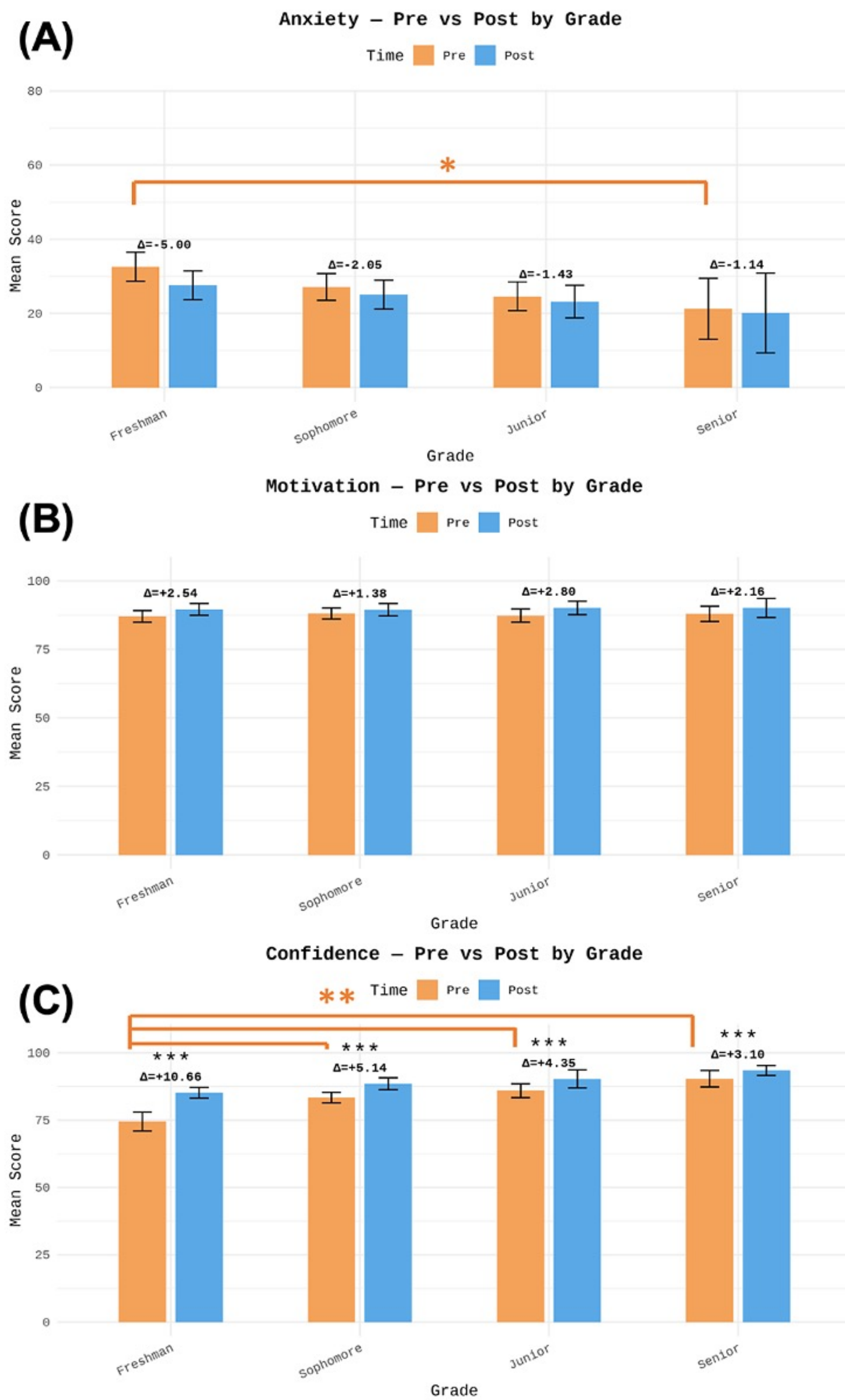

Figure 7: Grade-level Carberry outcomes among Trainers. Panels illustrate grade-level patterns in anxiety, motivation, and confidence across the Carberry engineering design framework. Sample sizes were Freshman (n = 30), Sophomore (n = 23), Junior (n = 16), and Senior (n = 7). Δ values represent Post–Pre changes, and error bars represent SEM. Tukey-adjusted pairwise comparisons were conducted on pre-program scores across grade levels.

When examining pre–post outcomes across ethnic groups among Trainers, Asian Trainers, similar to the Makers, demonstrated the largest reductions in anxiety (Δ = –8.66, p = 0.000632, n = 46). Asian Trainers also exhibited a substantial confidence gain (Δ = +12.33, p = 0.0000698). White Trainers showed a smaller but still significant increase in confidence (Δ = +7.41, p = 0.0144, n = 16). However, pre–post changes among Black Trainers (n = 10) were not statistically significant. Statistical comparisons were not conducted for Hispanic/Latino (n = 1) and Other (n = 3) Trainers due to insufficient sample sizes (Table 3).

Table 3. Pre/Post Confidence, Motivation, and Anxiety Scores for Trainers by Ethnicity. Pre-program means, post-program means, pre–post change (Δ), and overall pre/post mean for each metric across ethnic groups. Significance thresholds: $p < 0.05$*, $p < 0.01$**, $p < 0.001$***.

Ethnicity	Metric	Pre Mean	Post Mean	Δ (Post–Pre)	p-value
Asian (n = 46)					
	Confidence	73.44	85.78	12.33	**0.0000698*** **
	Motivation	88.55	90.39	1.83	0.223663
	Anxiety	29.55	20.88	-8.66	**0.000632*** **
Black or African American (n = 10)					
	Confidence	77.99	89.26	11.27	0.328
	Motivation	89.01	88.09	-0.92	0.671752
	Anxiety	41.63	39.35	-2.29	0.880704
Hispanic, Latino, or Spanish origin (n = 1)					
	Confidence	46.67	84.44	37.78	—
	Motivation	80.00	85.56	5.56	—
	Anxiety	35.56	8.89	-26.67	—
White (n = 16)					
	Confidence	80.19	87.59	7.41	**0.014396***
	Motivation	87.81	89.35	1.54	0.536574
	Anxiety	15.93	16.15	0.22	0.928783
Other (n = 3)					
	Confidence	76.94	81.39	4.44	—
	Motivation	88.33	81.11	-7.22	—
	Anxiety	13.33	15.56	2.22	—

Demographic trends were similar across Makers and Trainers. Asian and White participants, who had the largest sample sizes, showed statistically significant gains in confidence and reductions in anxiety, while smaller groups showed similar but non-significant trends due to limited statistical power. These findings highlight not only the program's overall effectiveness, but also the need for continued efforts to support equitable participation.

When examining outcomes by gender, results were similar for male and female participants in both cohorts, with only small differences in average confidence, motivation, and anxiety. Among Makers, female and male students showed nearly identical average pre/post confidence (81.47 vs. 80.86) and motivation levels (89.21 vs. 87.15), with only small differences in anxiety levels (31.59 vs. 26.57). Trainers showed the same pattern: female and male participants reported comparable overall pre/post confidence levels (81.88 vs. 79.79), consistently high motivation (89.18 vs. 85.80), and similar anxiety levels (26.36 vs. 23.72).

Limitations and Future Directions in Program Development

A limitation of the present study is that we examined changes in Makers' self-efficacy without directly reporting students' technical proficiency and ability following participation. Discrepancies between perceived ability (self-efficacy) and demonstrated ability warrant further investigation. Future work would benefit from examining the alignment between Makers' self-efficacy and objective indicators of design performance to better characterize the relationship between confidence and competence. Nevertheless, a substantial body of prior research supports the use of self-efficacy as a meaningful and independent outcome in educational contexts. Studies have shown that self-efficacy is positively and significantly associated with academic performance and academic persistence, and that these relationships are often even stronger for lower-achieving students than for students already performing well [14]. This is particularly relevant given Ignite's focus on broadening access to engineering learning opportunities for students who have been historically underserved in STEM. Moreover, self-efficacy has been shown to be one of the strongest predictors of students' persistence and performance in learning activities, particularly in applied and problem-based learning environments [13]. In this context, self-efficacy alone represents an important outcome, effectively capturing students' beliefs in their capacity to successfully engage in and carry out engineering design tasks.

A notable finding is that Trainers often showed even larger self-efficacy gains than Makers, despite starting with higher baseline confidence. This is consistent with research demonstrating that teaching others deepens understanding and strengthens self-efficacy through repeated mastery experiences and reflection [7]. Future work should complement these self-efficacy findings with academic outcomes for Trainers, particularly given their central role in the program model. While academic records were not available under the current IRB protocol, a future expanded IRB-approved study could link Trainers' self-efficacy measures with institutional academic records to more comprehensively characterize Ignite's impact on academic outcomes.

Several logistical and institutional factors may influence the feasibility and fidelity of implementing this model at other institutions. The Ignite program relies on sustained partnerships between high schools, community organizations (e.g., a local science museum), and universities, which require coordination of space, transportation, time, and staff, student, and trainer availability. Recruiting high school students and recruiting, training, and retaining undergraduate trainers is resource-intensive and depends on institutional capacity and student availability. In addition, the hybrid format assumes reliable access to technology and internet connectivity, which may vary across local contexts and could influence participation and engagement. Implementation may also vary depending on institutional support for culturally responsive pedagogy. Finally, because Ignite is delivered over eight months, sustained student participation and institutional buy-in are critical and may present challenges in settings with competing demands. These logistical constraints should be considered when adapting or scaling the model to new contexts.

Conclusion

Despite their different ages, backgrounds, and roles, both high school Makers and undergraduate Trainers experienced meaningful growth through Ignite's human-centered, culturally relevant approach to biomedical engineering design. Students in both groups demonstrated significant gains in confidence, reductions in anxiety, and consistently high motivation–particularly in the Conduct and Construct phases, which are among the most cognitively demanding steps of engineering design. These results highlight the value of Ignite's near-peer mentorship structure, where Trainers developing leadership directly support Makers' growth, and both groups benefit from repeated mastery experiences, social persuasion, and collaborative problem-solving. Taken together, the findings suggest that Ignite not only strengthens self-efficacy and resilience in the short term but also contributes to a scalable model for broadening participation and fostering engineering identity among students historically underrepresented in STEM.

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