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The Role of Need for Cognition in Enhancing Innovation Capacities among Interdisciplinary Graduate Students: An Equity-Focused Approach

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Abstract

Innovation Capacities (IC) is a critical skill for addressing complex global challenges, and higher education institutions play a pivotal role in cultivating this capacity. This study investigates how Need for Cognition (NFC) – the tendency to enjoy and engage in effortful thinking – relates to IC among STEM graduate students, with a focus on examining whether an interdisciplinary training program that overlays disciplinary Ph.D. degree programs moderate the association between NFC and IC. Using a quasi-experimental design, this study collected data from Ph.D. students who are also participating in the *Ohio State EmPOWERment Program* – an interdisciplinary National Research Traineeship funded by the U.S. National Science Foundation – along with a control group of Ph.D. students who only participate in their disciplinary Ph.D. programs. NFC and IC were measured at the beginning and end of the academic year using validated instruments, and sequential regression models were used to investigate the predictors of IC development. The results support the argument that participation in the *Ohio State EmPOWERment Program* significantly enhanced NFC and highlight the role of this program as a catalyst for cognitive engagement and intellectual curiosity. Participation in the *Ohio State EmPOWERment Program* also appeared to support IC development across cognitive, intrapersonal, and interpersonal domains. Furthermore, interdisciplinary training moderated the relationship between NFC and specific innovation capacities, with particularly pronounced benefits for students experiencing moderate increases in NFC. These findings highlight the potential interdisciplinary education in fostering innovation and cognitive growth while also emphasizing the importance of refined classification criteria in future research to better capture interdisciplinary influences.

1 Introduction

Innovation is a critical skill for addressing the complex challenges of the global economy. Higher education institutions can foster innovation by developing students and graduates into innovators who address complex problems and generate novel and contextual ideas through intentional educational practices e.g.,[1],[2]. Reflecting those potentials, in recent years the National Science Foundation (NSF) has funded several interdisciplinary training programs aimed at preparing undergraduate and graduate students in Science, Technology, Engineering, and Mathematics (STEM) disciplines for the complexities of modern research and industry. Despite growing research on innovation capacities among undergraduates in monodisciplinary settings nationally and globally e.g., [3],[4]. Mayhew et al. [5] highlight the lack of knowledge regarding innovation capacities in the graduate population, especially in interdisciplinary settings.

Innovation capacities encompass a range of cognitive, intrapersonal, and social domains, including creative cognition, persuasive communication, and intention to innovate, which enable individuals to generate and apply novel ideas in diverse contexts [6]. The development of these capacities is not a uniform process; this development is shaped by individual traits [7],[8]. educational environments [1],[9],[5],[2],[10],[11], and socio-demographic factors [12],[8].

Building upon this foundation, Need for Cognition (NFC) is an individual trait that may influence the development of innovation capacities. Defined as an intrinsic motivation to engage in and enjoy effortful cognitive activities [13], NFC has been studied for its impact on problem-solving, critical thinking, and creative cognition, all of which are integral components of innovation capacities [14],[15]. Students with high NFC are more likely to embrace intellectual challenges, persist in solving complex problems, and actively seek novel perspectives, aligning closely with the demands of interdisciplinary innovation [16],[17].

In the context of graduate education – particularly in interdisciplinary programs – NFC may be a cognitive catalyst and enhance the ability of students to integrate diverse knowledge domains, communicate persuasively across disciplines, and generate actionable ideas. Yet, while NFC has been extensively studied in relation to cognitive engagement [14], academic achievement e.g., [15] and problem-solving e.g., [16], there is a need to investigate its role in interdisciplinary graduate education. Interdisciplinary training may moderate how NFC contributes to innovation by shaping students' access to resources, experiences of inclusion, and opportunities for intellectual engagement. Thus, this work investigates the research question: *How does Need for Cognition influence the development of Innovation Capacity among graduate students, and to what extent do interdisciplinary training programs moderate this relationship?*

2 Interdisciplinary Training Program

The *Ohio State EmPOWERment Program*, a U.S. National Science Foundation National Research Traineeship, is an interdisciplinary convergent training program designed to develop Ph.D. students to exercise leadership in the workforce of sustainable, decarbonized energy systems. This program was created through collaboration between faculty from six colleges within the university and several external stakeholders from industry, national laboratories, and non-profit organizations. Together, they identified core competencies and attitudes to achieve three goals:

1. Prepare a diverse cohort of versatile graduates with the innovation capacity, self-efficacy, and collaborative capacity to influence positive change in the transition to environmentally, economically, and socially benign energy systems.
2. Leverage and catalyze convergent research for sustainable energy solutions with energy sector partners, using the campus of the university as a testbed; and
3. Refine this new convergent traineeship model through continuous evaluation and disseminate replicable best practices and lessons learned.

The *Ohio State EmPOWERment Program* follows a cohort-based model and is to open to all Ph.D. students at the university conducting research in energy. Participants complete their departmental Ph.D. requirements while engaging in distinctive program elements designed to enhance their expertise without extending their time to graduate. The program offers well-rounded, interdisciplinary opportunities that equip trainees with the skills, knowledge, and professional connections essential for success in the energy sector.

Incoming *EmPOWERment* trainees participate in a two-week Bootcamp, which serves as an intensive onboarding experience. The Bootcamp introduces them to data analytics through a challenge problem sponsored by an external industrial partner. New trainees work in interdisciplinary teams guided by faculty and returning trainees, who serve as mentors. This immersive experience enhances their analytical and collaborative skills, preparing them for the demands of the program. The Graduate Interdisciplinary Specialization (GIS) in Data-Driven Sustainable Energy Systems is the curricular component of the program. Consisting of six courses, the GIS includes a foundational sustainable energy course, a capstone on energy innovation, and four elective courses selected from five thematic areas: (1) energy system modeling; (2) information systems; (3) energy policy, regulation, and economics; (4) energy-business modeling; and (5) energy technologies, components, and subsystems. The GIS allows trainees to tailor their learning to align with their research interests and professional goals.

Beyond coursework, trainees participate in a bi-weekly Sustainable Energy Student Community of Practice and Engagement (SCOPE). The co-curricular Energy SCOPE offers skills-building workshops and networking opportunities with energy professionals. Additionally, each trainee receives guidance from their primary Ph.D. advisor, another mentor internal to Ohio State, and an external mentor. These mentors provide academic support, professional development insights, academic and industrial networking, and career guidance.

To track progress and set goals, trainees complete an Individual Development Plan, which they update annually, and sign a Participation Agreement that outlines program expectations. These components ensure accountability and continuous growth throughout the program. This integrated approach is intended to equip Ph.D. students with the skills and connections to lead sustainable energy initiatives while developing a scalable model for interdisciplinary graduate training.

3 Conceptual Framework

Kegan's [17],[18] constructive developmental theory of adult psychological and epistemological evolution provides a relevant framework for this study, particularly the fourth plateau: self-authorship. This stage enables individuals to navigate and critique social-cognitive systems and transcend external expectations [19]. For first-year STEM Ph.D. students, self-authorship is essential as they adapt to new environments and develop the professional capacities to address cutting-edge research questions. Several studies have applied Kegan's theory in higher education context [10]. Here, we used Kegan's theory as a foundation to design the outcomes and programmatic elements of the *Ohio State EmPOWERment Program*.

In this study, Kegan's theory complements the NFC framework and provides another lens through which to understand how graduate students' developmental trajectories influence their ability to innovate. NFC operates as a motivational construct and as a cognitive predisposition, which provides the internal drive to seek out and process complex information. When combined with the transformative potential of self-authorship, NFC can illuminate how students navigate intellectual challenges and develop innovation capacities in interdisciplinary contexts.

4 Literature Review

4.1 Innovation Capacities in Graduate Education

Numerous studies have underscored the advantages of interdisciplinary exposure in enhancing the innovation capacities of graduate students e.g., [20],[21],[22],[23]. These studies highlight that interdisciplinary exposure fosters creativity and critical thinking and equips students with the diverse skill sets necessary to address complex, real-world problems. O'Meara and Culpepper's [23] insights on scaffolding highlight a crucial aspect of effective interdisciplinary education for graduate students. They emphasize that structured support, feedback, and reflection are essential to guide students through the complexities of interdisciplinary work and minimize challenges that can arise during collaborative efforts. Burt et al. [21] echoed and emphasized the significance of structured interactions in promoting effective interdisciplinary interactions among team members. Swayne et al. [24] emphasized that the project-based learning (PBL) approach effectively facilitates interdisciplinary exposure, which is crucial for developing innovation capacities among graduate students.

4.2 Need for Cognition in Higher Education

Need for Cognition enhances students' abilities to engage in critical thinking, problem-solving, and creative ideation, which are central to innovation e.g., [25],[26],[14]. It has evolved not merely a psychological tendency but developmental construct [26]. For example, Liu & Nesbit [15] found that graduate students with high NFC exhibit greater persistence in tackling intellectually demanding tasks, which is a trait crucial for interdisciplinary research. Additionally, Bruinsma and Crutzen [27] argued that NFC plays a significant role in fostering intellectual curiosity and openness to novel perspectives, key attributes in navigating the complexities of modern research environments. Mayhew et al [26] suggested that instruction incorporating reflection, active learning, and perspective-taking enhance students' NFC and fosters an orientation toward lifelong learning.

Yet the role of NFC in interdisciplinary contexts is under-investigated. Graduate students in interdisciplinary programs encounter unique challenges, such as integrating knowledge across domains and navigating collaborative dynamics. Need for Cognition may provide an advantage by enabling students to process diverse information, adapt to novel challenges, and generate innovative solutions. These abilities are particularly critical in STEM fields, where interdisciplinary approaches are increasingly essential for addressing global challenges (e.g., sustainability, healthcare, technological innovation).

5 Methodology

5.1 Data Source and Sample

This study used a quasi-experimental design to examine the impact of NFC and interdisciplinary training program on the development of Innovation Capacity (IC) among STEM graduate students. Participants were recruited from the *Ohio State EmPOWERment Program*, along with a control group of Ph.D. students who did not participate in the program. Survey participation was limited to students who were beginning their first year of Ph.D. studies. Data were collected at two time points: the beginning of the academic year and the end of the academic year. Participants in the experimental group received $20 gift cards as an incentive for completing the surveys, while control group participants were entered into a raffle for a chance to win one of five $100 gift cards. The experimental group included 24 Ph.D. trainees; 21 consented and 19 completed the entire research process. The control group comprised first-year Ph.D. students from various disciplines, including both STEM and non-STEM Ph.D. degree programs; 124 consented and 116 completed the process.

5.2 Measures

The two primary measures used in this study are theoretically grounded, reliable, and valid instruments designed to assess the key constructs: Need for Cognition (NFC) and Innovation Capacity Scale (ICS). Additionally, demographic factors and program participation were included as moderators to evaluate their influence on the relationship between NFC and ICS.

5.2.1 Need for Cognition (NFC).

The NFC is a psychometric measure that refers to the engagement in and enjoyment of effortful thinking. It is measured using an 18-item scale that evaluates preferences for cognitive engagement. Items are rated on a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), with higher scores indicating a greater NFC. Examples include, "I would prefer complex problems instead of simple problems" and "I prefer my life to be filled with puzzles that I must solve."

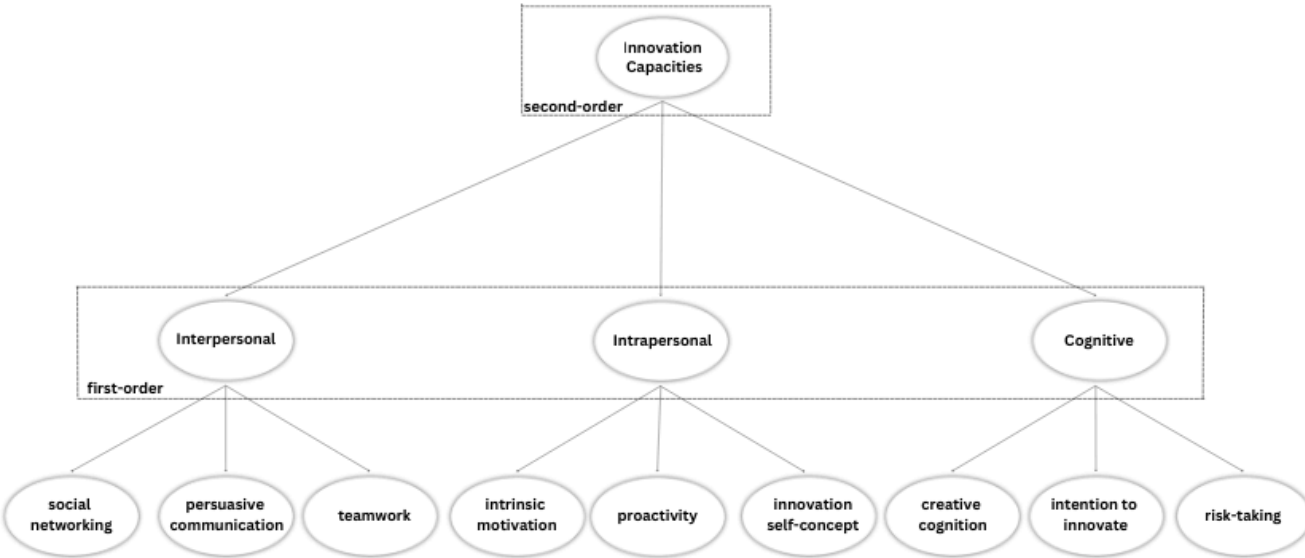
The NFC scale has consistently demonstrated robust psychometric properties. Studies reported high internal consistency, with Cronbach's alpha values typically exceeding 0.85, which indicates strong reliability across diverse populations e.g., [28], [14]. In terms of validity, the NFC scale has shown strong construct validity and often treated as a unidimensional construct. Confirmatory Factor Analysis (CFA) supports this structure with good model fit indices. For example, Liu and Nesbit [15] reported a CFI of 0.92 and a Root Mean Square Error of Approximation (RMSEA) of 0.06. In this study, NFC scores were derived using factor analysis to compute factor scores, which represent the latent construct of NFC. We also investigated whether NFC scores varied across groups and tested for changes over time. To do so, we used *post-test* NFC scores to explore the relationship with Innovation Capacity Scale (ICS) and its sub-capacities under ICS model.

5.2.2 Innovation Capacities Scale (ICS).

ICS is measured using a survey instrument that integrates nine multi-item constructs into a single metric using a second-order CFA. These constructs are grouped into three domains: intrapersonal (*motivation*, *proactivity*, and *self-confidence*), interpersonal (including *persuasive communication*, *teamwork across differences*, and *networking*), and cognitive (intention *to innovate*, *creative cognition*, and *risk-taking*) [6]. The ICS has been validated by Selznick and Mayhew [9] for an undergraduate population and has shown robust confirmatory fit indices (*CFI* = 0.989, *RMSEA* = 0.060, 90% CI [0.044, 0.076]), which indicates a strong structural validity for assessing innovation capacities. Similar to NFC, factor scores were computed for ICS using factor analysis, which allows for the construction of a composite score and domain-specific scores. These factor scores captured the latent dimensions of ICS while addressing the multidimensional nature of the construct.

Instead of using a second-order model to assess the IC, we used a repeated sequential regression approach so that we can have a detailed examination of the individual contributions of the nine competencies. This approach allows us to investigate the influence of each of the constructs independently and provide a nuanced understanding of their distinct roles in fostering innovation capacities. Figure 1 shows the constructs and the scales that they comprise.

Figure 1
Framework for Evaluation of Innovation Capacities in the Training Program.



The Intrapersonal Scale assesses an individual's self-awareness, self-perceptions, and capabilities in fostering creative ideation and execution in the context of innovation and entrepreneurship. This measure encompasses constructs including *intrinsic motivation*, *proactivity*, and *innovation self-concept*. The *intrinsic motivation* construct assesses individuals' persistence, resilience, and sustained effort toward achieving long-term goals, overcoming setbacks and challenges, and maintaining commitment despite uncertainty or discouragement. The *proactivity* construct assesses individuals' ability to initiate actions and gather diverse information to positively transform situations for themselves and others, contributing to broader societal improvement. The *innovation self-concept* construct tests individuals in performing specific tasks related to their beliefs about their creative problem-solving abilities, generating original ideas, and contributing beneficial innovations to themselves and others.

The Interpersonal Scale pertains to the measurement of social aspects and interactions that influence innovation and entrepreneurship among students in higher education. It includes constructs such as *social networking*, *persuasive communication*, and *teamwork across differences*. These constructs reflect students' perceptions of the social domain and their ability to engage in social experiences that support innovation and career development within the college environment. *Networking* measures an individual's ease in establishing and maintaining mutually advantageous new connections. *Persuasive communication* assesses the perceived effectiveness of one's capacity to convey new ideas and action plans clearly to others. *Teamwork across differences* gauges the perceived effectiveness of one's ability to collaborate within a group comprising diverse individuals to accomplish a shared objective.

The Cognitive Scale refers to the measurement of cognitive abilities and processes associated with innovation and entrepreneurship. It includes constructs such as *creative cognition*, *intention to innovate*, and *risk-taking* or *tolerance*. These constructs reflect the cognitive dimensions that are essential for generating novel ideas, bridging gaps between knowledge domains, and functioning effectively in scenarios where new opportunities present themselves. *Creative cognition* assesses consensus on the pleasure derived from and the capability to engage in generating contextually advantageous novel concepts. *Intention to innovate* gauges the perceived effectiveness in identifying new opportunities, strategically planning, securing resources, and organizing efforts to effectively realize and leverage innovations. *Risk-taking* or *tolerance* assesses individuals' willingness and ability to critically engage with others' ideas by confidently suggesting improvements, challenging perspectives, and expressing differing viewpoints in various educational and co-curricular contexts.

5.2.3 Control Variables

In this study quasi-experiment design, one of our primary control variables is the treatment variable for which we used binary coding to divide participants into two groups, control and experimental.

5.3 Analytic Approach

Before conducting the regressions, changes in NFC were examined to understand group-level differences and trends over time. Paired t-tests assessed NFC changes within the treatment and control groups. A robust variance equality test confirmed that the assumption of equal variances was met and supported the validity of the t-tests. Then, we employed a sequential regression framework to examine predictors of post-test innovation capacity (IC) scores among graduate students. This approach also enabled the evaluation of continuous variables and time-varying covariates, which are critical for understanding longitudinal changes (Cohen et al., 2003). The analysis focused on the contributions of four key predictors: pre-test IC scores, changes in NFC across the academic year (NFC Change), participation in an interdisciplinary training program (Treatment), and the interaction between NFC Change and Treatment. Sequential regression models were constructed to evaluate the unique and combined contributions of these predictors, allowing for a stepwise assessment of their influence on post-test IC scores. Four models were tested sequentially:

Model 1: Baseline Model

The model controlled for baseline IC scores (pre-test) to establish a foundation for detecting changes in other models,

$$Y = \propto + \beta_1 X_1$$

where Y and X_1 are respectively the *post-test* and *pre-test* IC scores for the measure being investigated.

Model 2: NFC Model

$$Y = \propto + \beta_1 X_1 + \beta_2 X_2$$

In the NFC Model, we added NFC Change as an independent variable. This variable, X_2, facilitates the investigation of whether changes in NFC influence the development of innovation capacities, controlling for *pre-test* IC scores in the model. By including the change of NFC scores, this model allowed for an investigation of how cognitive engagement at the end of the academic year contributed to training program outcomes and provides insight into the role of NFC as a predictor of IC development.

Model 3: Treatment Model

$$Y = \propto + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3$$

For a third model, we added a binary variable X_3 to the NFC Model to represent participation in the *Ohio State EmPOWERment Program.* This Treatment Model allows us to differentiate results from those in the broader population of Ph.D. students at the university.

Model 4: Interaction Model

$$Y = \propto + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4$$

The Interaction Model expanded the Treatment Model by introducing an interaction term (X_4) for the product of NFC Change and Group Participation Treatment. This interaction term allowed us to investigate whether the relationship between NFC Change and post-test IC differs based on participation in the *Ohio State EmPOWERment Program*. The Interaction Model was included to test whether the effect of NFC Change on innovation capacity may be moderated by participating in the *Ohio State EmPOWERment Program*, and the Interaction Model allowed us to capture differences in how changes in cognitive engagement influence innovation outcomes for participants versus non-participants in the *Ohio State EmPOWERment Program*. Each model's fit was evaluated using *adjusted* R^2 and Akaike Information Criterion (AIC), with changes in R^2 indicating the incremental contribution of each predictor. The Variance Inflation Factor (VIF) was assessed for all predictors to ensure no significant multicollinearity, with all VIF values below the threshold of 5.

To enhance the robustness of the findings, we applied bootstrapping with 1,000 replications to validate the regression coefficients, standard errors, and confidence intervals [29]. This approach minimized the potential impact of sampling variability and provided a robust basis for interpreting the results. To provide a more nuanced understanding, separate sequential regression analyses were conducted for IC sub-constructs within the intrapersonal, interpersonal, and cognitive domains. This step allowed for an investigation of specific pathways through which NFC Change and program participation influenced distinct innovation capacities (e.g., motivation, teamwork, creative cognition). The same sequential framework was applied to each sub-construct, controlling baseline scores to isolate changes due to intervention and cognitive engagement.

6 Results

6.1 The Role of NFC

A robust variance equality test was conducted to ensure that the variability in *NFC Change* between the treatment and control groups was not significantly different. The treatment group had a higher mean *NFC Change* ($M = 0.450$, $SD = 0.684$, $n = 19$) than the control group ($M = -0.093$, $SD = 0.611$, $n = 116$), yet the difference was not statistically significant at the 5% level. This lack of statistical significance indicated that the assumption of equal variances was met and supports the use of paired t-tests to investigate changes in NFC over time between the groups. Overall, NFC remained stable, with no significant change observed across all participants ($M = -0.017$, $SD = 0.65$, $t(134) = -0.30$, $p = 0.762$). However, group-level analyses revealed contrasting trends. The control group had a marginally significant decrease in NFC ($M = -0.093$, $SD = 0.61$), which was almost significant at the 5% level ($t(115) = -1.65$, $p = 0.051$). In contrast, the treatment group had a statistically significant increase (at the 5% level) in NFC ($M = 0.450$, $SD = 0.68$, $t(18) = 2.87$, $p = 0.010$). These results suggest that participation in the *Ohio State EmPOWERment Program* enhanced cognitive engagement. Our findings challenge the common assumption that NFC remains stable over time and highlight the potential impact of structured educational interventions.

Table 1
Paired t-Test Results for NFC Change Across Groups

Group	*M*	*SD*	*95%CI*	*t*	*df*	*p*
Overall	-0.017	0.650	[-0.139, 0.105]	-0.30	134	0.762
Control (0)	-0.093	0.611	[-0.187,0.001]	-1.65	11	0.051
Treatment (1)	0.450	0.684	[0.129,0.771]	2.87	18	0.010

6.2 Robustness and Multicollinearity

Over the four sequential regression models, Variance Inflation Factor (VIF) values for all predictors were below 5 (mean VIF = 1.11), and no correlations between predictors exceeded 0.8. These results indicated no significant multicollinearity in the models. Bootstrapping with 1,000 replications was applied to validate the robustness of the coefficients, standard errors, and confidence intervals. The bootstrapped results closely aligned with the observed values (see Table 2) and indicated that the findings are robust to sampling variability. For instance, in Model 3, the observed coefficient for *Initial IC* ($\beta = 0.676$, 95% CI [0.559, 0.792]) was nearly identical to the bootstrapped coefficient ($\beta = 0.676$, 95% CI [0.63, 0.789]). A similar consistency was observed for *NFC Change* and *Treatment*, plus other models.

Table 2. Bootstrapped Coefficients and Confidence Intervals for Predictors of Post-Test Innovation Capacity

Variable	**Model 1**		**Model 2**		**Model 3**		**Model 4**	
	Obs	Boot	Obs	Boot	Obs	Boot	Obs	Boot
Initial IC (β_1)	**0.654*** **	0.654	**0.706*** **	0.706	**0.676*** **	0.676	**0.693*** **	0.693
NFC Change (β_2)			**0.357*** **	0.357	**0.248***	0.248	**0.357** **	0.357
Treatment (β_3)					**0.613** **	0.613	**0.867***	0.218
Interaction (β_4)							**-0.656** **	-0.656

Note: * indicates $p < .05$, ** indicates $p < .01$, *** indicates $p < .001$. Significant relationships are bolded.

6.3 Sequential Regression Analysis of Innovation Capacities

Table 3 summarizes the results of the sequential regression analyses. In terms of model fit, each sequential model improved upon the previous model, as indicated by decreases in Akaike Information Criterion (AIC) and increases in R^2. The Baseline Model (Model 1) accounted for 42.5% of the variance in post-test IC (Table 3: *Adjusted* $R^2 = 0.425$, $p < 0.001$, AIC = 301.732). Adding *NFC Change* in Model 2 improved the explained variance to *Adjusted* $R^2 = 0.484$, with a change in R^2 *of* $R^2_{change} = 0.059$ and reduced the AIC to 267.022. Model 3 further incorporated *Treatment* as a predictor and the *Adjusted* R^2 increased to 0.526 ($R^2_{change} = 0.042$) and reduced the AIC to 257.266. Finally, Model 4 included the interaction term between *NFC Change* and *Treatment*, yielding the best model fit with *Adjusted* $R^2 = 0.547$, an additional $R^2_{change} = 0.021$ and the lowest AIC at 252.334. These results indicated that each predictor in Model 4 contributed meaningfully to explaining post-test IC, with the inclusion of the interaction term providing the most comprehensive model.

Table 3
Sequential Regression Results Predicting Post-Test Innovation Capacity

Variables	*β*	t	Sig.	AIC	*Adjusted R^2*	*R^2 Change*
Baseline Model				301.732	0.425	-
Initial IC	0.654	10.44	<0.001			
NFC change Model				267.022	0.484	0.059
Initial IC	0.706	11.70	<0.001			
NFC change	0.357	3.56	<0.001			
Treatment Model				257.266	0.526	0.042
Initial IC	0.676		<0.001			
NFC change	0.248		0.030			
Treatment	0.613		0.002			
Interaction Model				252.334	0.547	0.021
Initial IC	0.693	11.11	<0.001			
NFC change	0.357	3.51	0.001			
Treatment	0.867	4.36	<0.001			
Interaction	-0.656	-2.62	0.010			

6.4 Domain Specific Analysis of Innovation Capacities

The innovation capacities (IC) is not a unidimensional construct [6], it encompasses distinct *intrapersonal*, *interpersonal*, and *cognitive* domains, each with unique sub-constructs (e.g., motivation, networking, creative cognition). To better understand the specific pathways through which NFC and interdisciplinary training contribute to innovation development, we further examined the sub-constructs within each domain, using a similar sequential regression framework.

By analyzing each sub-construct separately, we sought to:

1. Identify whether NFC changes differentially predict scores across sub-constructs.
2. Determine whether the *Ohio State EmPOWERment Program* moderates NFC's influence on specific capacities.
3. Explore whether certain sub-constructs are more sensitive to educational interventions than others.

By controlling baseline sub-construct scores to account for individual starting points, we focused our analysis explicitly on changes rather than initial differences. This method assessed the unique contributions of NFC changes, direct effects of program participation, and interactions between NFC changes and treatment group status, clarifying their combined effects on innovation sub-constructs.

The results for each sub-construct, presented in Table 4 provide a nuanced understanding of how cognitive engagement and interdisciplinary exposure contribute to different domains in IC model. By examining these sub-constructs independently, we uncover domain-specific insights that inform targeted strategies for fostering innovation in graduate education.

6.4.1 Intrapersonal Domain

Motivation Competence

The results in Table 4 show that pre-test motivation scores are statistically significant at the 1% level across all models (Baseline Model: $\beta_1 = 0.652$, $p < 0.001$; NFC Change Model: $\beta_1 = 0.730$, $p < 0.001$; Treatment Model: $\beta_1 = 0.722$, $p < 0.001$; Interaction Model: $\beta_1 = 0.721$, $p < 0.001$). The *Adjusted* R^2 increases from 0.374 in the Baseline Model to 0.476 in the Interaction Model, with R^2 change of 0.074 from the Baseline Model to the NFC Change Model, 0.016 from the NFC Change Model to the Treatment Model, and 0.012 from the Treatment Model to the Interaction Model. Group participation is significant at the 5% level in the Treatment Model ($\beta_3 = 0.387$, $p = 0.028$) and remains significant at the 1% level in the Interaction Model ($\beta_3 = 0.569$, $p = 0.006$). The interaction model is also significant at the 5% level ($\beta_4 = -0.504$, $p = 0.046$), which indicates that participation in the *Ohio State EmPOWERment Program* moderates the relationship between NFC Change and post-test motivation.

Self-Concept Competence

Result shows that pre-test self-concept scores significantly predict post-test scores at the 1% level in all models (Baseline Model: $\beta_1 = 0.543$, $p < 0.001$; NFC Change Model: $\beta_1 = 0.579$, $p < 0.001$; Treatment Model: $\beta_1 = 0.551$, $p < 0.001$; Interaction Model: $\beta_1 = 0.554$, $p < 0.001$). The *Adjusted* R^2 improves from 0.280 to 0.367 across the models, with R^2 change of 0.029 from the Baseline Model to the NFC Change Model, 0.025 to the Treatment Model, and 0.033 to the Interaction Model. While participation in the *Ohio State EmPOWERment Program* is significant at the 5% level in the Treatment Model ($\beta_3 = 0.509$, $p = 0.017$) and at the 1% level in the Interaction Model ($\beta_3 = 0.804$, $p = 0.001$), the interaction term also shows a significant moderation effect at the 1% level ($\beta_4 = -0.821$, $p = 0.006$), which amplifies the relationship between NFC Change and self-concept growth.

Proactivity Competence

Pre-test proactivity scores significantly predict post-test outcomes in all models (Baseline Model: $\beta_1 = 0.446$, $p < 0.001$; NFC Change Model: $\beta_1 = 0.437$, $p < 0.001$; Treatment Model: $\beta_1 = 0.425$, $p < 0.001$; Interaction Model: $\beta_1 = 0.435$, $p < 0.001$). The Adjusted R^2 improves modestly from 0.194 in the Baseline Model to 0.255 in the Interaction Model, with R^2 change of 0.012, 0.047, and 0.002 across models. Participation in the *Ohio State EmPOWERment Program* is significant at the 1% level in the Treatment Model ($\beta_3 = 0.605$, $p = 0.003$) and remains significant in the Interaction Model ($\beta_3 = 0.729$, $p = 0.001$). However, the interaction term is not significant at the 10% level ($\beta_4 = -0.348$, $p = 0.233$), which suggests that NFC Change and participation in the *Ohio State EmPOWERment Program* independently affect proactivity.

6.4.2 Interpersonal Domain

Persuasive Communication Competence

Pre-test scores are strong predictors of persuasive communication in all models (Baseline Model: $\beta_1 = 0.546$, $p < 0.001$; NFC Change Model: $\beta_1 = 0.562$, $p < 0.001$; Treatment Model: $\beta_1 = 0.560$, $p < 0.001$; Interaction Model: $\beta_1 = 0.560$, $p < 0.001$). The Adjusted R^2 increases from 0.272 to 0.302, with R^2change of 0.009 from the Baseline Model to the NFC Change Model, 0.024 to the Treatment Model, and -0.003 to the Interaction Model. While participation in the *Ohio State EmPOWERment Program* is significant at the 5% level in the Treatment Model ($\beta_3 = 0.495$, $p = 0.027$) and at the 1% level in the Interaction Model ($\beta_3 = 0.562$, $p = 0.009$), the interaction term is not significant at the 10% level ($\beta_4 = -0.186$, $p = 0.168$).

Teamwork Competence

Pre-test teamwork scores significantly predict post-test scores across all models (Baseline Model: $\beta_1 = 0.505$, $p < 0.001$; NFC Change Model: $\beta_1 = 0.556$, $p < 0.001$; Treatment Model: $\beta_1 = 0.571$, $p < 0.001$; Interaction Model: $\beta_1 = 0.574$, $p < 0.001$). The Adjusted R^2 improves from 0.243 to 0.301, with R^2 change of 0.032, 0.021, and 0.005. Participation in the *Ohio State EmPOWERment Program* is significant in the Treatment Model ($\beta_3 = 0.462$, $p = 0.027$) and Interaction Model ($\beta_3 = 0.611$, $p = 0.009$). However, the interaction term remains insignificant at the 5% level ($\beta_4 = -0.413$, $p = 0.130$).

Networking Competence

Networking capacity has the highest baseline *Adjusted* R^2 (0.564), with minimal improvement across models (*Adjusted* $R^2 = 0.557$ in the Interaction Model). Pre-test scores are significant predictors at the 0.1% level (Baseline Model: $\beta_1 = 0.755$, $p < 0.001$; Interaction Model: $\beta_1 = 0.761$, $p < 0.001$). Group participation is significant in the Treatment Model at the 5% level ($\beta_3 = 0.368$, $p = 0.026$) but becomes significant only at over 5% level in the Interaction Model ($\beta_3 = 0.365$, $p = 0.056$). The interaction term is not significant ($\beta_4 = 0.006$, $p = 0.978$), which indicates that NFC Change does not moderate the relationship between participation in the *Ohio State EmPOWERment Program* and networking.

6.4.3 **Cognitive Domain**

Creative Cognition Competence

Pre-test scores significantly predict creative cognition at the 0.1% level in all models (Baseline Model: $\beta_1 = 0.453$, $p < 0.001$; Interaction Model: $\beta_1 = 0.464$, $p < 0.001$). The *Adjusted* R^2 increases modestly from 0.187 to 0.259, with R^2 change of 0.021, 0.052, and -0.001. Participation in the *Ohio State EmPOWERment Program* is significant at the 1% level in the Treatment Model ($\beta_3 = 0.671$, $p = 0.002$) and at the 0.1% level the Interaction Model ($\beta_3 = 0.760$, $p = 0.001$). However, the interaction term is not significant ($\beta_4 = -0.260$, $p = 0.397$), which suggests an independent effect of group participation on creative cognition.

Intention to Innovate Competence

Intention to innovate is predicted at the 0.1% level by pre-test scores (Baseline Model: $\beta_1 = 0.578$, $p < 0.001$; Interaction Model: $\beta_1 = 0.636$, $p < 0.001$). The *Adjusted* R^2 improves from 0.314 to 0.445 across models, with R^2change of 0.091, 0.029, and 0.011. Participation in the *Ohio State EmPOWERment Program* is significant at the 1% level in the Treatment Model ($\beta_3 = 0.533$, $p = 0.006$) and in the Interaction Model ($\beta_3 = 0.710$, $p = 0.001$). The interaction term ($\beta_4 = -0.506$, $p = 0.061$) is not significant at the 5% level, which we cannot conclude a moderating effect of NFC Change on participation in the *Ohio State EmPOWERment Program*.

Risk-Taking Competence

Pre-test scores significantly predict risk-taking at the 0.1% level in all models (Baseline Model: $\beta_1 = 0.576$, $p < 0.001$; Interaction Model: $\beta_1 = 0.557$, $p < 0.001$). The Adjusted R^2 increases marginally from 0.319 to 0.310 across models. Group participation is not significant at the 10% level in either the Treatment Model ($\beta_3 = 0.348$, $p = 0.104$) or the Interaction Model ($\beta_3 = 0.388$, $p = 0.119$). The interaction term is also not significant ($\beta_4 = -0.099$, $p = 0.752$).

Table 4

Sequential Regression Results Predicting Post-Test Innovation Capacities Sub-Constructs

Sub-Construct	*Adjusted R^2*	*R^2_{change}*	S.E.	F value	p value
Motivation Competence					
Baseline Model	0.374	-	0.713	88.33	<0.001
NFC change Model	0.448	0.074	0.683	54.99	<0.001
Treatment Model	0.464	0.016	0.673	39.39	<0.001
Interaction Model	0.476	0.012	0.665	31.24	<0.001
Self-Concept Competence					
Baseline Model	0.280	-	0.814	57.44	<0.001
NFC change Model	0.309	0.029	0.815	30.45	<0.001
Treatment Model	0.334	0.025	0.800	23.03	<0.001
Interaction Model	0.367	0.033	0.780	20.13	<0.001
Proactivity Competence					
Baseline Model	0.194	-	0.788	36.11	<0.001
NFC change Model	0.206	0.012	0.791	18.37	<0.001
Treatment Model	0.253	0.047	0.767	16.09	<0.001
Interaction Model	0.255	0.002	0.766	12.47	<0.001
Persuasive Communication Competence					
Baseline Model	0.272	-	0.809	54.89	<0.001
NFC change Model	0.281	0.009	0.819	26.74	<0.001
Treatment Model	0.305	0.024	0.805	20.33	<0.001
Interaction Model	0.302	-0.003	0.807	15.26	<0.001
Teamwork Competence					
Baseline Model	0.243	-	0.798	47.80	<0.001
NFC change Model	0.275	0.032	0.803	26.19	<0.001
Treatment Model	0.296	0.021	0.791	19.67	<0.001
Interaction Model	0.301	0.005	0.789	15.34	<0.001
Networking Competence					
Baseline Model	0.564	-	0.618	188.73	<0.001
NFC change Model	0.567	0.003	0.621	87.50	<0.001
Treatment Model	0.580	0.013	0.611	61.86	<0.001
Interaction Model	0.557	-0.003	0.613	46.04	<0.001
Creative Cognition Competence					
Baseline Model	0.187	-	0.818	34.77	<0.001
NFC change Model	0.208	0.021	0.822	18.54	<0.001
Treatment Model	0.260	0.052	0.794	16.73	<0.001
Interaction Model	0.259	-0.001	0.795	12.70	<0.001
Intention to Innovate Competence					
Baseline Model	0.314	-	0.765	67.91	<0.001
NFC change Model	0.405	0.091	0.733	46.20	<0.001
Treatment Model	0.434	0.029	0.714	35.03	<0.001

Interaction Model	0.445	0.011	0.707	27.68	<0.001
Risk-taking Competence					
Baseline Model	0.319	-	0.788	68.84	<0.001
NFC change Model	0.306	-0.013	0.804	30.13	<0.001
Treatment Model	0.315	0.009	0.798	21.25	<0.001
Interaction Model	0.310	-0.005	0.801	15.84	<0.001

Table 5

Predictors of Innovation Capacity Sub-Constructs Across Sequential Regression Models

	Baseline Model	**NFC change Model**	**Treatment Model**	**Interaction Model**
Motivation Competence				
β (constant)	0.005	0.002	-0.054	-0.047
β_1 (Initial Score)	**0.652*****	**0.730*****	**0.722*****	**0.721*****
β_2 (NFC change)	-	**0.329****	**0.266****	**0.348****
β_3 (treatment)	-	-	**0.387***	**0.569****
β_4 (NFC change x treatment)	-	-	-	**-0.504***
Self-Concept Competence				
β (constant)	-0.011	-0.017	-0.092	-0.078
β_1 (Initial Score)	**0.543*****	**0.579*****	**0.551*****	**0.554*****
β_2 (NFC change)	-	0.075	-0.008	0.128
β_3 (treatment)	-	-	**0.509***	**0.804****
β_4 (NFC change x treatment)	-	-	-	**-0.821****
Proactivity Competence				
β (constant)	0.001	-0.017	-0.104	-0.099
β_1 (Initial Score)	**0.446*****	**0.437*****	**0.425*****	**0.435*****
β_2 (NFC change)	-	0.186	0.091	0.148
β_3 (treatment)	-	-	**0.605****	**0.729****
β_4 (NFC change x treatment)	-	-	-	-0.348
Persuasive Communication Competence				
β (constant)	-0.002	-0.020	-0.093	-0.090
β_1 (Initial Score)	**0.546*****	**0.562*****	**0.560*****	**0.560*****
β_2 (NFC change)	-	**0.164*****	0.083	0.114
β_3 (treatment)	-	-	**0.495***	**0.562****
β_4 (NFC change x treatment)	-	-	-	-0.186
Teamwork Competence				
β (constant)	0.003	-0.012	-0.079	-0.072
β_1 (Initial Score)	**0.505*****	**0.556*****	**0.571*****	**0.574*****
β_2 (NFC change)	-	0.187	0.117	0.185
β_3 (treatment)	-	-	**0.462***	**0.611****
β_4 (NFC change x treatment)	-	-	-	-0.413
Networking Competence				

β *(constant)*	-0.016	-0.003	-0.054	-0.054
β_1 *(Initial Score)*	**0.755*** **	**0.768*** **	**0.761*** **	**0.761*** **
β_2 *(NFC change)*	-	0.044	-0.017	-0.018
β_3 *(treatment)*	-	-	**0.368* **	0.365
β_4 *(NFC change x treatment)*	-	-	-	0.006
Creative Cognition Competence				
β *(constant)*	0.000	-0.010	-0.108	-0.103
β_1 *(Initial Score)*	**0.453*** **	**0.488*** **	**0.451*** **	**0.464*** **
β_2 *(NFC change)*	-	**0.220* **	0.107	0.153
β_3 *(treatment)*	-	-	**0.671** **	**0.760*** **
β_4 *(NFC change x treatment)*	-	-	-	-0.260
Intention to Innovate Competence				
β *(constant)*	0.005	0.016	-0.062	-0.053
β_1 *(Initial Score)*	**0.578*** **	**0.674*** **	**0.627*** **	**0.636*** **
β_2 *(NFC change)*	-	**0.435*** **	**0.334** **	**0.421*** **
β_3 *(treatment)*	-	-	**0.533** **	**0.710*** **
β_4 *(NFC change x treatment)*	-	-	-	-0.506
Risk-taking Competence				
β *(constant)*	-0.006	-0.020	-0.068	-0.066
β_1 *(Initial Score)*	**0.576*** **	**0.558*** **	**0.559*** **	**0.557*** **
β_2 *(NFC change)*	-	0.086	0.030	0.045
β_3 *(treatment)*	-	-	0.348	0.388
β_4 *(NFC change x treatment)*	-	-	-	-0.099

Note: * indicates $p < .05$, ** indicates $p < .01$, *** indicates $p < .001$. Significant relationships are bolded.

7 Discussion

The interdisciplinary *Ohio State EmPOWERment Program* emerged as a statistically significant impact on NFC development, with an increase in mean scores compared to a marginal decline observed in the control group. These results highlight the ability of the program to foster intrinsic motivation for cognitive engagement, which aligns with prior research that links interdisciplinary exposure to intellectual curiosity and persistence [27]. The program's inclusion of problem-based learning, team-based challenges, and interaction with diverse knowledge systems likely played a critical role in this enhancement. Prior research supports that higher NFC is associated with improved critical thinking, orientations toward lifelong learning, and problem-solving [25], [15], [26].

By integrating interdisciplinary learning components such as seminars, mentorship, and applied research opportunities, the program provides students with sustained intellectual stimulation, which contributes to the observed growth in NFC. This finding is particularly important; NFC is not static, and educational interventions, such as interdisciplinary programs, can serve as catalysts for cognitive growth. Mayhew et al. [26] supported this notion by demonstrating that instructional strategies foster NFC development (which they used as a proxy for lifelong learning).

Selznick and Mayhew [6] emphasized that cognitive dimensions of innovation are distinct from general cognitive engagement, such as NFC. Their findings reinforce the notion that while NFC encourages intellectual curiosity, it does not automatically translate into the development of innovation capacities without structured support. This distinction aligns with our findings here, which suggest that interdisciplinary training serves as a critical mechanism in bridging NFC and innovation outcomes. By providing targeted exposure to problem-solving and collaborative environments, the *Ohio State EmPOWERment Program* facilitated the application of NFC toward real-world innovation challenges.

The *Ohio State EmPOWERment Program* also emerged as a significant contributor to the development of IC across the cognitive, intrapersonal, and interpersonal domains. Participants demonstrated notable improvements in sub-constructs such as motivation, self-concept, and intention to innovate. For instance, the inclusion of structured support systems, such as individualized development plans and internal and external mentoring, provided participants with a foundation for self-efficacy and proactive engagement. These components are crucial for innovation development, as highlighted by Selznick and Mayhew [9]. The emphasis on collaboration and teamwork within diverse cohorts further amplified interpersonal capacities such as networking and persuasive communication. These findings align with O'Meara and Culpepper's [23] research, which underscores the role of scaffolded interdisciplinary interactions in fostering creativity and critical thinking. Additionally, the program's focus on real-world applications through industrial challenges and external mentorship facilitated the translation of theoretical knowledge into actionable ideas, a hallmark of innovation [21].

Our study revealed that interdisciplinary training moderated the relationship between NFC and IC, particularly in domains such as motivation and self-concept. The interaction effect suggests that the cognitive engagement reflected by NFC is amplified within the context of interdisciplinary learning environments. These findings are consistent with the transformative potential of interdisciplinary programs in shaping cognitive and professional capacities [22]. By encouraging students to integrate diverse knowledge streams and navigate collaborative dynamics, the program served as a cognitive multiplier, enhancing both the depth and breadth of innovation capacities.

8 Limitations

This study provides valuable insights into graduate education in STEM fields. Specifically, it demonstrates the significant positive effects of participation in the interdisciplinary *Ohio State EmPOWERment Program* on graduate students' innovation capacities. It also highlights how initial innovation capacities and changes in students' NFC influence of these interventions. But the relatively small sample size, particularly in the experimental group, limits the generalizability of the results. Although bootstrapping was used to enhance the robustness of statistical estimates, larger, more diverse, and multiple institution samples would help to validate these findings. Future research could seek to replicate the study with broader populations to assess the scalability and applicability of interdisciplinary programs across various academic contexts.

Additionally, categorizing students into STEM and non-STEM groups presents challenges, as disciplinary boundaries are blurry. This complexity may introduce variability in control group comparisons. Future studies could refine the classification criteria or investigate alternative grouping strategies that account for interdisciplinary overlaps when evaluating the effects of interdisciplinary training on NFC and IC.

The quasi-experimental design introduces the possibility of self-selection bias, as students who chose to participate in interdisciplinary training programs may differ in important ways from those who do not. While efforts were made to control baseline differences, the findings should be interpreted with this limitation in mind. One important avenue for future research is the use of propensity score matching to address potential selection bias in quasi-experimental designs. This approach could ensure that the observed differences in NFC and IC are more likely attributable to the effects of the interdisciplinary training program, rather than pre-existing group differences.

9 Conclusion

The interdisciplinary *Ohio State EmPOWERment Program* worked. Results clearly highlight that participation in the interdisciplinary *Ohio State EmPOWERment Program* significantly enhanced graduate students' innovation capacities. Importantly, these benefits were especially pronounced for students experiencing moderate increases in cognitive engagement (NFC), underscoring the program's critical role as a moderator—transforming cognitive engagement into actionable innovation skills. Not only did it provide structured opportunities for students to develop the internal motivations needed to engage and enjoy effortful thinking, but it also helped students used this motivation as a means for growing their innovation capacities – learn the skills needed to take a new idea and roll it out to execution. Based on the evidence provided for this study, the program should be replicated in other institutions and certainly sustained at its host beyond the NSF funding cycle.

Although the potential for selection bias may compromise potential assertions of causal claims, its use of pretest measures and control groups provide robust evidence of the program's effects: the *Ohio State EmPOWERment Program* could be accentuating initial dispositions towards internal motivations to engage and enjoy effortful thinking and innovation capacities. This idea of accentuation, see [30] – occurring as a result of exposure to and/or participation in effective programs and practices – continues to provide educators with reliable evidence of intervention efficacy, especially among observations of students in their natural albeit non-random environments.

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