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Post-award grant collaboration: facilitators and hindrances to cross-disciplinary authorship

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Granting agencies often require cross-disciplinary team composition to be competitive for funding. However, to what extent do research teams have cross-disciplinary authorships after they win an award, given that grants are not contracts? This mixed-method study examined the degree to which cross-disciplinary composition translated into cross-disciplinary authorship in grant-funded teams and the factors motivating cross-disciplinary collaboration. We found that after receiving a grant award, nearly 90% of investigators chose to collaborate across disciplines, with 80% working with researchers from fields very different from their own. Interviews uncovered facilitators and hindrances to continued collaboration. Facilitators included strong interpersonal relationships, shared goals, and openness to new ideas. Common hindrances involved funding shortages and limited face-to-face interactions. What defined success in cross-disciplinary collaboration were not only research outputs but learning opportunities, highlighting the intangible benefits of cross-disciplinary research. Researchers stressed the importance of integration and resource availability for deeper collaboration across disciplines.

KEYWORDS

knowledge integration, research grants, educational diversity, expertise diversity, social identity theory, interdisciplinary teams, multidisciplinary teams, team collaboration

Introduction

Research is increasingly tackling "grand challenges" addressing complex societal, environmental, and public health problems that demand cross-disciplinary solutions (e.g., Allen et al., 2017). Cross-disciplinary teams consist of members from diverse functional backgrounds working interdependently to integrate knowledge and create new ideas or products (De Grandis and Efstathiou, 2016). In response, granting agencies such as the National Science Foundation (NSF), a major granting institution in the United States, often require cross-disciplinary team composition (e.g., social scientists and computer scientists working together) to be competitive for funding. However, to what extent do principal investigators (PIs) and co-PIs engage in cross-disciplinary authorship after they win a grant award? Because awards are not contracts, investigators may choose to work independently or with others within their own discipline without losing the money awarded to fund their work.

Moreover, what factors motivate and detract from continuing cross-disciplinary post-award research productivity? Both benefits and challenges arise from the diversity of educational and functional backgrounds present in cross-disciplinary teams. On one hand, cross-disciplinary collaboration is attractive because the research questions tend to be broader in scope, increasing the potential for greater professional achievement and impact (e.g., Hall et al., 2018). On the other hand, working with team members trained under diverse theoretical and methodological traditions pose numerous difficulties for cognitive and social team integration (e.g., Salazar et al., 2012). An ongoing challenge for cross-disciplinary teams is to harness group members' diverse expertise while avoiding the communication and coordination breakdowns that can result from the differences between fields (e.g., Ávila-Robinson and Sengoku, 2017).

Given these advantages and disadvantages, how successful is cross-disciplinary authorship *after* PIs and co-PIs are awarded grant funding? Would, for example, two computer scientists who needed social science representation (e.g., psychology) during the grant proposal phase continue to collaborate with a psychologist after receiving an NSF award?

Addressing these questions is important because, while cross-disciplinary *composition* is required for grant proposals to be competitive for funding, cross-disciplinary *collaboration* is not enforced. However, a group of experts does not make an expert team (Salas et al., 1997). That is, cross-disciplinary benefits accrue, not merely from team members representing diverse expertise (composition), but from PIs/co-PIs integrating knowledge across fields to build shared understanding and behavioral coordination (collaboration) (Salazar et al., 2012). Considering the millions of dollars at stake in science teams and the critical issues they study (e.g., Stokols et al., 2008), it is imperative to investigate the outcomes of grant funders' efforts to promote cross-disciplinary collaboration. Therefore, the purpose of this study was twofold: (1) to investigate the extent to which cross-disciplinary composition translated into cross-disciplinary authorship in grant-funded teams and (2) to explore the facilitators and hindrances motivating cross- disciplinary collaboration.

We address three broad research questions in this paper. First, how did cross-disciplinary authorship compare to disciplinary authorship after winning a grant award? Second, what factors facilitated and hindered cross-disciplinary collaboration and authorship? Third, to what extent did cross-disciplinary integration influence research productivity? To answer these research questions, we used a mixed-method approach to study the interplay between grant-funded PIs/co-PIs cross-disciplinary composition and cross-disciplinary research productivity. Starting with archival data, we collected and cataloged PI/co-PI research productivity (quantity of presentations, publications, and grants) before and after their NSF award using publicly available information. We then conducted 33 semi-structured interviews with PI/co-PIs who reflected on the factors that facilitated and hindered their cross-disciplinary collaboration. After coding, we quantified different levels of cross-disciplinary integration from interview responses and linked them with archivally collected PI/co-PI research productivity.

This study makes empirical and methodological contributions to the cross-disciplinary team literature. First, while prior studies have focused on the choice to join cross-disciplinary teams in the first place (e.g., Lungeanu et al., 2014; Salazar et al., 2011), we follow that initial decision through to the subsequent choice of whether investigators continue to collaborate with members of different disciplines after being awarded a research grant. As such, we examine if the potential benefits of cross-disciplinary team composition translate into actual collaboration with scholars representing diverse fields, despite its difficulties. Second, whereas extant research has primarily emphasized the challenges experienced by cross-disciplinary teams (e.g., Lovelace et al., 2001; Salazar et al., 2012), our results demonstrate that intrinsic benefits are key to motivating investigators to continue collaborating with those from diverse fields, amid the difficulties. Third, much of the research on cross-disciplinary science teams relies on archival measures such as publications, presentations, and grants (Wagner et al., 2011). While we too adopt an archival approach, the present study also incorporates interviews of cross-disciplinary scholars. In so doing, we answer the call of a recent review of cross-disciplinary research to "prioritize multiple and mixed methods approaches," given that studies rarely combine quantitative and qualitative methods (Laursen et al., 2022, p. 339). In addition to better capturing the nuances of interdisciplinary collaboration, mixed-method studies have also been shown to be more impactful (Molina-Azorin, 2012).

The paper is organized in the following way: We first reviewed the theoretical background and then overviewed our mixed method data collection including archival and interview methods. We then presented results for each of our three broad research questions, followed by our interpretation of results in the discussion section. We conclude by highlighting limitations, future research directions, and practical implications for cross-disciplinary teams.

Theoretical background

"Differences among academic disciplines are profound and extensive" (Braxton and Hargens, 1996, p. 35), as "different clusters of academic disciplines create distinctly different academic environments" (Smart et al., 2000, p. 238). These differences stem, in part, from educational diversity, "diversity in the level of education (e.g., bachelor's degree or master's degree) or the category of education (e.g., electrical engineering or chemistry)" among researchers (Jansen and Searle, 2021, p. 1844). In addition, expertise diversity describes team members representing diverse areas of specialization (Todorova, 2021). Different areas of mastery and educational upbringings among researchers result in diverging terminologies, foci of interests, methods of data collection or analysis, publication styles, and the use of different tools, which create significant challenges for cross-disciplinary collaboration (König et al., 2020). According to Social Identity Theory, individuals within a group identify with the defining characteristics and values of that group (Tajfel and Turner, 2004). At the same time, the significance individuals associate with their group membership can vary, along with their behavioral expressions of an identity (Roberts et al., 2008). For researchers who are more aligned with their educational identity (e.g., "I see everything through the lens of psychology"), stepping outside of disciplinary boundaries may be difficult, hindering cross-disciplinary collaboration. Researchers who identify less with their disciplinary background may be more open-minded to other perspectives, making them better able to consider diverse research approaches from outside of their discipline, compared to researchers with a disciplinary background central to their identity.

Further, cross-disciplinary researchers may hold social stigmas about membership to certain academic disciplines. A stigma is an attribute that is devalued in a particular context and can apply to unobservable attributes, including values and beliefs (Goffman, 1963). Fiore (2020) references the disciplinary disdain scholars can have towards other disciplines, coupled with potential arrogance and pride for one's own. For example, disciplinary arrogance can describe the way scholars in the physical sciences (e.g., physics, chemistry) perceive scholars in the humanities (e.g., history) or social sciences (e.g., sociology) (Fiore, 2020). This relegation of disciplines rings true on college campuses, where business majors have been belittled as "weed outs" from engineering. Alternatively, those studying communications may be seen as students who could not perform well in the accounting or finance courses in the business school.

These disciplinary rankings are further articulated in the common expression 'soft' (e.g., humanities and social sciences) versus 'hard' (e.g., technical fields such as computer science, physical sciences, and engineering) sciences, where 'soft' sciences are seen as lesser and lacking a cohesive paradigm compared to 'hard' sciences (Biglin and Pratt, 1973). 'Soft' sciences also have a connotation of being "easy, not demanding of great effort," where 'hard' sciences are perceived as "difficult or laborious" (Storer, 1967, p. 76). This terminology matters, causing humanities (e.g., history, philosophy, languages) and social sciences (e.g., psychology, sociology, political science) to be regarded with "skepticism, doubt, and derision… [that causes] negative implications on policy decisions and research funding" (Landis and Cortina, 2014, p. 1).

For these reasons, rather than represent the expertise of their discipline with pride, cross-disciplinary team members representing the 'soft' sciences may suppress their devalued social identities to avoid negative stereotyping or prejudice (Roberts et al., 2008). Cross-disciplinary researchers belonging to the 'soft' sciences may also employ impression management, a process of interpersonal sensemaking that aims to create and sustain positive identities (Ellemers, 1993). For example, psychologists may be hesitant to ask questions of their engineer teammates, as doing so may exacerbate the perception that their disciplinary background is less sophisticated. Further, if team members feel that their disciplinary expertise is not valued in the team setting, they may be hesitant to share their perspective, which undermines the purpose of cross-disciplinary teams and is counterintuitive to the goal of integrating diverse academic perspectives.

Methodology

Mixed-method data collection

The data presented in this paper are part of a larger research project examining what knowledge should be shared and what knowledge should remain unique to individual members for cross-disciplinary teams to be effective (Mohammed et al., 2023). To achieve methodological fit (Edmondson and McManus, 2007), we adopted a mixed-methods approach featuring archival and interview methods in the current study. Mixed methods have been shown to have higher article impact than monomethod studies (Molina-Azorin, 2012) because they leverage important benefits such as elaboration (deeper and expanded insights) and triangulation (documenting convergent findings using different methods) (Gibson, 2017). Therefore, merging both quantitative and qualitative results permitted a superior understanding of post-award PI/co-PI cross-disciplinary collaboration than either methodology alone (Gibson, 2017).

Archival data was used to answer the first overall research question regarding how cross-disciplinary authorship compared to disciplinary authorship after winning an NSF award. Archival data and interviews assessed the second broad research question addressing the factors that facilitated and hindered cross-disciplinary collaboration and authorship. An integrated design was used to answer the third overall research question concerning the effects of cross-disciplinary integration on collaboration and research productivity. In an integrated design, coded interviews are transformed into quantitative data (Srnka and Koeszegi, 2007), which were then linked to the archival data.

Research population

We studied recipients of NSF EAGER (EArly-concept Grants for Exploratory Research) grants because they provided an ideal population to answer our research questions. First, EAGER grants support research projects that are considered high-risk but have the potential for high rewards. As such, we sampled cross-disciplinary researchers exploring innovative and potentially transformative phenomena. Specifically, EAGER grants foster diversity in knowledge by necessitating collaboration across NSF's directorates, which encompass biological sciences; computer and information science and engineering; engineering; geosciences; mathematical and physical sciences; social, behavioral, and economic sciences; and education and human resources.

Second, our population made it convenient to access publicly available data because nsf.gov discloses the names of PIs and co-PIs who have received funding. With these names, we established an archival database by gathering additional publicly accessible information, such as vitas on university websites and publications from Google Scholar. Consequently, our population was restricted to EAGER PIs and co-PIs, excluding postdoctoral researchers, graduate students, undergraduate research assistants, and other potential team members. Third, compared to longer-term grants, the two-year timeframe of EAGER grants facilitated our ability to collect post-award research outcomes, including conference presentations and publications, within a more manageable timeframe.

We collected data from EAGER awardees in the Secure and Trustworthy CyberSpace (SaTC) program. Therefore, funded research emphasized cybersecurity topics such as security practices, cybercrime, password security, cyberbullying, and privacy. Our population extended between 2013 (the first year of EAGER grants in this program) and 2019. The breakdown of EAGER grants awarded by year was 13 in 2013, 12 in 2014, 14 in 2015, 0 in 2016, 7 in 2017, 0 in 2018, and 12 in 2019.

The individual population included 149 PIs and co-PIs, 66% of which were males. The population had a median of 17 years since earning their Ph.D. (Mean = 19.83 years, range of 2–54 years). Investigators from more than 50 different disciplines were represented, with the largest percentage from computer science (34%), followed by psychology (6%), communication (4%), and electrical and computer engineering (4%).

The team population was 58 EAGER-funded team projects comprising 76 awards (collaborative proposals include multiple universities with their own sub-budgets that are subsumed within the same overall project). The mean award amount was $219,153.57

(median = \$224,675, SD = \$75,610.71), with a range of \$31,579 to \$316,000.

PI/co-PI dyads comprised 59% of the population, followed by 28% three-person PI/co-PI teams, 10% four-person teams, and 3% five-person teams. The mean team size was 2.81 (median = 3.00, SD = 0.91). Almost half were mixed-gender teams (46%), 40% were male-only teams, and 14% were female-only teams. Sixty-seven percent of the teams included members from the same university.

Archival methodology

Our research team collected the research output of PIs/co-PIs during and after their EAGER award using publicly accessible sources such as grants.gov, PI/co-PI vitas on university websites, and LinkedIn. Team research productivity was operationalized as the cumulative sum of publicly available conference papers, publications, and grants PIs and co-PIs produced with each other during and after their EAGER grant between 2013 and 2021. This count included instances in which all PIs/co-PIs were authors, as well as cases in which only a partial subset were authors. For instance, a four-person PI/co-PI team (representing the disciplines of information science, computer science, math, and psychology) wrote a conference proceeding authored by three investigators (information science, math, and computer science) as well as a journal article authored by two investigators (information science and psychology).

Due to the common practice of grant recipients seeking one or more no-cost extensions, it proved challenging to determine from publicly available data whether research productivity extended beyond the conclusion of their EAGER grants. Therefore, the research productivity attributed to post-EAGER award encompassed both during and after the grant period.

We further catalogued whether PIs and Co-PIs engaged in disciplinary (single discipline) or cross-disciplinary (multiple disciplines) authorship after their NSF award. Cross-disciplinary authorship consisted of multidivisional (Ph.D. disciplines across NSF *divisions*) and/or multidirectorate (Ph.D. disciplines across NSF *directorates*) authorship. Examples of multidivisional pairings include political science and cognitive psychology or computer science and management information systems. Examples of multidirectorate pairings include communication and computer science or psychology and engineering. Of the 58 EAGER original PI/co-PI teams, 57 were multidirectorate and one was multidivisional in composition.

Interview methodology

Interview recruitment and sample

In 2020, 149 EAGER PIs and co-PIs were asked via email to participate in a study on cross-disciplinary team collaboration. The response rate was 22%, with 33 interviews conducted in 2020. To assess the variations in means between the 33 individuals who were interviewed and the remaining 116 participants, independent samples t-tests were run on team size, years since receiving the grant, award amount, number of universities represented in the grant, and years with a Ph.D. Only significant mean disparities in team size emerged ($t = 4.77$, $p < 0.001$). Specifically, individuals from smaller teams ($M = 2.33$, SD = 0.54) were more inclined to participate in the interviews compared to individuals from larger teams ($M = 2.95$, SD = 0.95).

In alignment with the broader sample, 76% of those interviewed were male, 21% were female, and 3% had unreported gender information. The mean number of years since interviewees obtained their Ph.D. (as of 2023) was 21.67 (Median = 18, SD = 11.87), ranging from 6 to 54 years. Interviewees spanned 19 universities, with two respondents from private industry.

The interview sample represented 26 distinct EAGER projects, accounting for 45% of the larger sample of 58 EAGER grants. Seven interviewees (21%) were part of the same EAGER grant. The average duration since EAGER grants were awarded was 4.00 years (SD = 2.21), with a range of 1 to 7 years. The awards averaged \$225,272 (Median = \$227,709, SD = \$84,594), with a range of \$31,579 to \$316,000.

Interviewees represented an average PI/co-PI team size of 2.33 members (SD = 0.54), ranging from 2 to 4. Teams were predominantly male-only (48.48%) and mixed gender (42.42%), with only 9.1% consisting solely of female team members. Two-thirds of PI/co-PI teams were affiliated with the same university.

Interview protocol

PIs and co-PIs participated in Zoom interviews lasting 30 min to 1 h from February to November 2020. All interviewees provided consent to record interviews. As part of a larger research project, the comprehensive interview protocol covered six main categories: cross-disciplinary training and experiences, the history, workload distribution, and ongoing practices related to writing and communication in PI/co-PI collaboration, factors facilitating and hindering interdisciplinary collaboration, and the convergence and divergence of knowledge.

To answer the research question of what factors facilitated and hindered cross-disciplinary collaboration and authorship, we asked the following interview questions: "What factors made collaborating with [PI/co-PI] easier?" and "What factors made collaborating with [PI/co-PI] challenging?" We also asked interviewees to reflect on the research experience by asking the question, "What do you see as your biggest successes of the EAGER grant cross-disciplinary collaboration?"

Coding process

Verbatim transcripts of the interviews were obtained from an external service and imported into NVivo (Release 1.5.2) software (QSR International, 2021) for data analysis. Following a thematic analysis approach integral to qualitative analysis, we performed these steps: (1) become familiar with the interview data, (2) generate initial codes, (3) identify patterns in the data, and (4) define and label fundamental themes organized hierarchically to establish relationships within and between them (Braun and Clarke, 2006). Initial or first-order codes were formulated using participants' language (Charmaz, 2006) and subsequently organized into higher or second-order codes that helped reveal patterns in the first-order data (Van Maanen, 1979). The generated second-order codes were refined, divided into subcategories, or merged until no new categories were necessary (reaching deep saturation; Morse, 2015). Second-order codes were then reassessed to ensure they met the four requirements of qualitative content analysis: unidimensionality, mutual exclusiveness, exhaustiveness, and saturation (Schreier, 2012).

Throughout this process, we developed a manual that detailed the labeling and definition of second-order codes, along with inclusion and exclusion criteria to establish decision rules and norms. Finally, we aggregated second-order codes into broader themes that encapsulated "some level of patterned response or meaning within the data set" (Braun and Clarke, 2006, p. 82). These themes were semantic in nature, reflecting only what the interviewees communicated (Braun and Clarke, 2006).

To demonstrate the reliability of our coding (Lincoln and Guba, 1985), three research assistants independently coded the same two interview transcripts (6% of the data set). Coders met to jointly discuss their results, calibrate their coding metrics, and update and refine the coding manual. Interviews were then coded independently (Schreier, 2012), but approximately 2 weeks later, one interview was coded by all three coders to check and ensure consistency. Following this initial round of systematically assigning codes to text units, the percentage of agreement across the three raters was 99.99% for factors facilitating cross-disciplinary collaboration (Kappa = 0.9997) and 99.99% for hinderances (Kappa = 0.9996). An additional coded interview yielded a 96% agreement for facilitators to collaboration (Kappa = 0.62) and 96% for hindrances to collaboration (Kappa =0.90). The question regarding the biggest successes of cross-disciplinary research reached 100% agreement (Kappa = 0.9994) for the first interview and 96.86% (Kappa = 0.4901) for the second.

Results

How did cross-disciplinary authorship compare to disciplinary authorship after winning an NSF award?

We divided our first broad research question into several sub-questions. First, what percentage of PI/co-PI teams produced research outcomes after receiving their NSF award? Relatedly, of the PI/co-PI teams who produced research outcomes after receiving their NSF award, what percentage of conference presentations, publications and/or grants were authored by cross-disciplinary versus disciplinary team parings? In addition, what was the quantity of research outcomes (conferences, publications, and grants) authored by multidisciplinary versus disciplinary PI/co-PI teams after their NSF award? We addressed each of these questions archivally.

Archival results

What percentage of PI/co-PI teams produced research outcomes after receiving their NSF award?

As shown in Figure 1, of the 58 original EAGER PI and Co-PI teams, 74% (43/58) authored conference presentations, publications, and/or grants after receiving their EAGER award. Of the 74% who collaborated post-EAGER award, 53% only authored outcomes with their full team, 21% authored outcomes with their full team and a partial subset, and 26% only authored outcomes with a partial subset.

Of the PI/co-PI teams with research outcomes after receiving their NSF award, what percentage of authorships were cross-disciplinary versus disciplinary?

Summing the combinations of full and partial subsets of the teams who authored conferences, publications, and/or grants during or after the EAGER grant resulted in 61 post-EAGER authorship pairings. Shown in Figure 2, of the 61 post-EAGER authorship pairings, 13% were authored by disciplinary teams, and 87% were authored by cross-disciplinary teams (78% conference posters/presentations, 73% publications, and 33% grants). Of the cross-disciplinary authorship pairings, 8% were multidivisional (e.g., computer science and technology management) and 79% were multidirectorate (e.g., sociology and computer science). Of the 79% multidirectorate authorship pairings, 75% were conference posters/presentations, 46% were publications, and 25% were grants.

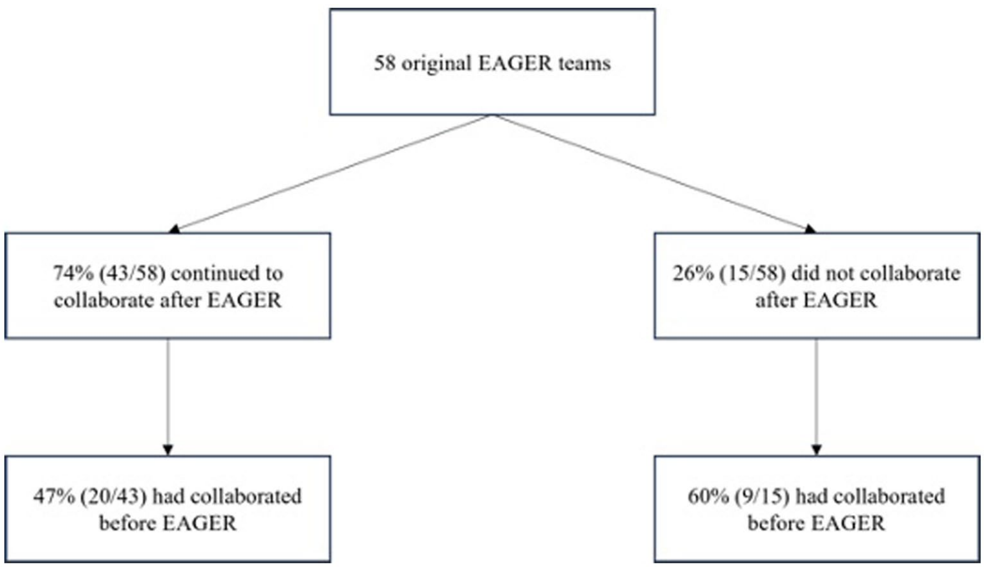

FIGURE 1
Pre EAGER collaboration and Post-EAGER collaboration.

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What was the quantity of post-EAGER award research productivity for cross-disciplinary versus disciplinary PI/co-PI teams?

Outputs produced by post-EAGER award authorship pairings included an average of 3.4 conferences (0–16 range), 4.1 publications (0–13 range), and 2.4 grants (0–7 range). Shown in Figure 3, of the 327 collaboration outputs (conferences, journals, grants) produced after EAGER awards were granted in our population, 19% were produced by disciplinary PIs/co-PIs and 82% were produced by cross-disciplinary PIs/co-PIs (15% were multidivisional and 67% were multidirectorate). Multidirectorate authorship produced more conference outputs (52%) than multidivisional (36%) or disciplinary (39%) authorship. Similarly, multidirectorate collaboration resulted in more grants (9%) than multidivisional (1%) or unidisciplinary (1%) collaboration. However, multidivisional (56%) and disciplinary (51%) authorship was higher for publications than multidirectorate (35%) authorship.

What factors facilitated and hindered cross-disciplinary collaboration and authorship?

Why did some PI/co-PI teams collaborate post-EAGER award and others did not? Why did some teams collaborate across disciplines while others primarily collaborated within disciplines? To address these questions, we first analyzed pre-EAGER award authorships from the archival data.

Archival results: pre-EAGER award authorship

Pre-EAGER award authorship quantity: team analyses

Of the 58 original EAGER PI and Co-PI teams, 43% collaborated on conference presentations, publications, and/or grants before receiving their EAGER award (all PIs and co-PIs in a team or any partial subset). Of the 43% who collaborated pre-EAGER award, 77% were cross-disciplinary and 23% were disciplinary. Of the cross-disciplinary teams, 3% were multidivisional and 73% were multidirectorate. Comparing pre- and post- EAGER award results, more PIs and co-PIs collaborated with multidisciplinary members after (87%) than before (77%) their EAGER award, but authorships with multidirectorate members were similar (79% after versus 73% before the EAGER award).

Pre-EAGER award authorship quantity: output analyses

Outputs produced by pre-EAGER award collaboration teams included a range of 0–62 conferences, 0–35 publications, and 0–7 grants. Of the 263 collaboration outputs (conferences, journals, grants) produced before EAGER awards were granted in our population, 26% were disciplinary and 74% had cross-disciplinary authorship (40% were multidivisional and 34% were multidirectorate). Comparing pre- and post-EAGER award output quantity results, more cross-disciplinary conference, publication, and grant authorships were post-EAGER (85%) than pre-EAGER (75%) award. A similar pattern was found for multidirectorate authorship (63% post-EAGER versus 33% pre-EAGER award). No further investigation was done of the researchers who did not continue cross-disciplinary collaboration, as this was outside the scope of our study.

Comparison of pre-EAGER and post-EAGER award authorship

Of the 43% pre-EAGER award teams, 8% authored research output only pre-EAGER, and 92% continued to collaborate on conferences, publications, and grants after their EAGER award. Of the 74% of teams that continued to collaborate on research output after their EAGER award, 47% authored research output together pre-EAGER. Of the 26% that did not author research output after their EAGER award, 60% had pre-EAGER authorships.

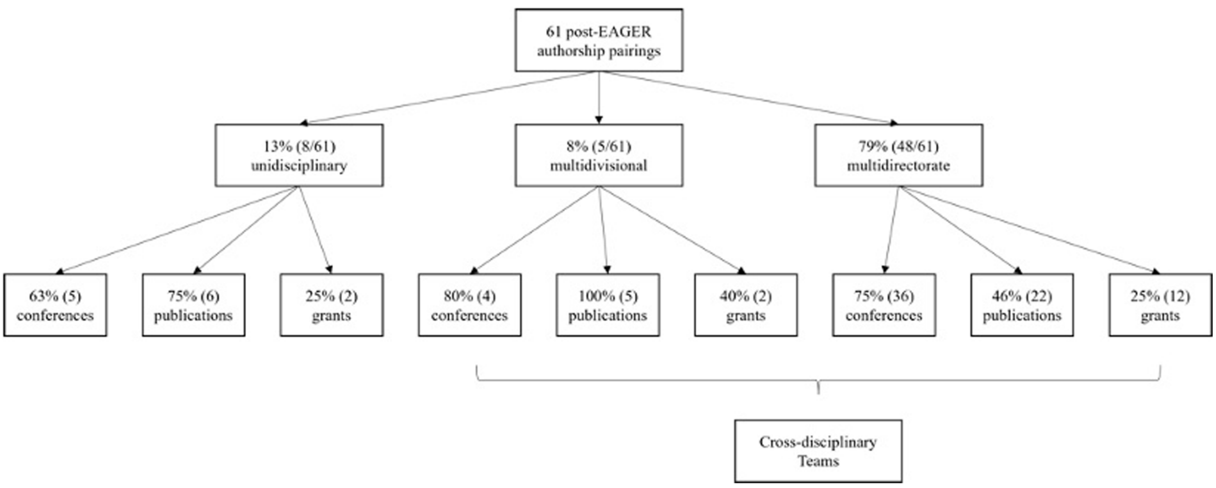

FIGURE 2
Post-EAGER authorship team analyses of conference, publications, and grants.

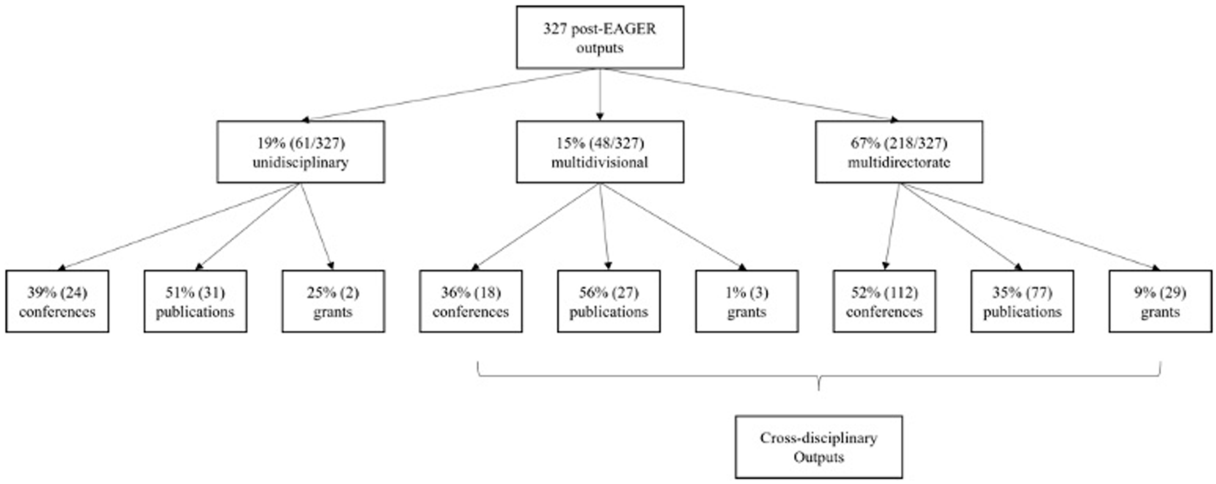

FIGURE 3
Post-EAGER research productivity of conferences, publications, and grants.

To further explore the factors facilitating and hindering post EAGER award authorship, we complemented our archival research by obtaining rich, detailed, and in-depth information from interviews with PI/co-PIs.

Interview results

Coding themes

Three broad themes emerged as facilitators to collaboration, including (1) cross-disciplinary attitudes and experience, (2) interpersonal relationships, and (3) situational factors. As shown in Table 1, these three themes capture qualities of the individual, the interpersonal exchange among researchers, and the context within which the research team operated.

To begin, the cross-disciplinary attitudes and experience theme captured (1) an intrinsic interest in the research question and curiosity in cross-disciplinary research, (2) an openness and willingness to learn and engage with techniques outside of one's own discipline, (3) an appreciation and respect for the contributions of disciplines outside of one's own, and (4) previous exposure to cross-disciplinary collaboration or background knowledge in disciplines outside of one's home field.

The interpersonal relationship theme outlined elements that defined the exchange among cross-disciplinary researchers, including (1) a liking for collaborators, where spending time together is enjoyable, and researchers generally get along, (2) agreement around the team's purpose and the role of individual members is interpersonally beneficial, and (3) the importance of relationship-building interactions, like regular meetings and discussions, in continued cross-disciplinary collaboration.

The situational factors theme revealed characteristics of the environment that the cross-disciplinary team operated within. These situational factors included (1) access to resources, such as sufficient funds, ample time to work on the project, and departmental support, as well as (2) physical proximity to other collaborations, like the ability to drop by a researcher's office on campus or see one another physically at conferences.

In addition to summarizing the themes and sub-themes of collaboration facilitators, Table 1 also includes the number of interviewees mentioning each category along with illustrative quotes. The most popular facilitators to continued cross-disciplinary collaboration described the interpersonal relationship among researchers, which was mentioned by almost half (47.96%) of interviewees. Within the interpersonal relationship theme, the three subcategories of (1) liking for collaborators, (2) having a shared end goal, and (3) meeting and collaborating regularly were mentioned with similar frequency (14.29–17.35%).

The second most popular theme, mentioned by 38 % (37.78%) of respondents, highlighted the influence of cross-disciplinary attitudes as facilitators to continued collaboration. The two most frequently subcategories in this theme included an intrinsic interest in research and cross-disciplinary collaboration (13.27%) and an openness to new experiences (11.22%). The two subcategories of this individual level theme, respect for other disciplines and previous cross-disciplinary knowledge and experience, were referenced evenly by interviewees (6.12–7.14%).

Finally, situational factors were the least popular theme of factors facilitating interdisciplinary research (14.29%). The subthemes of physical proximity and access to resources were mentioned with roughly equal frequency (6.12–8.16%) as elements that facilitated continued collaboration.

Mirroring the three themes of facilitators to collaboration, the same overall themes also emerged as hindrances to continued collaboration: (1) cross-disciplinary attitudes and experience, (2) interpersonal relationships, and (3) situational factors. Again, these themes represented characteristics of the individual, the interpersonal interactions among collaborators, and the contextual factors within which the research team functioned. However, as shown in Table 2, different sub-themes emerged across facilitating and hindering factors.

The cross-disciplinary attitudes and experiences theme captured individual-level elements that negatively impacted collaboration. These factors included (1) a researcher's lack of intrinsic interest in the research question or cross-disciplinary work generally and (2) a low

TABLE 1 Facilitators to cross-disciplinary collaboration.

What factors facilitated cross-disciplinary collaboration?		
Second-order codes	**Number of interviewees mentioning category and percentage**	**Illustrative quotes**
Theme 1: cross-disciplinary attitudes and experience	37 (37.78%)	
Intrinsic interest in research and cross-disciplinary collaboration: Intellectually curious, engaged in the general research question, wanting to understand collaborators' backgrounds, excitement about the project	13 (13.27%)	"Their general interest in understanding cognition and my background interest in computer science help us gel together." (int 12) "To make a multidisciplinary collaboration work well, both PI's have… a common interest, desire. I want to pull you in." (int 27)
Openness to new experiences: A willingness to learn new techniques outside of one's own discipline; asking, for example, "How do you do that?"	11 (11.22%)	"A willingness to try a new thing and the willingness to step out of discipline." (int 28) He is not like, "Oh, I know all this." He said, "How do you do that?"" (int 10)
Respect for other disciplines: Appreciation for what other researchers contribute to the project's end goals, seeing value in cross-disciplinary partnerships, understanding how the weaknesses of one discipline are the strengths of another discipline	7 (7.14%)	"I felt very affirmed, and valued in a way that I was surprised to be working in a partnership with an engineer...I felt like she really took seriously my contributions." (int 26) "Finding that kind of skill set or complimentary kind of expertise that is quite remote from what you do in your work...in general...helps expand your boundaries, or your horizons." (int 7)
Disciplinary and cross-disciplinary knowledge and experience: Exposure working with researchers in other fields, background knowledge outside one's own discipline, experience in own position or discipline over time	6 (6.12%)	"I think it helps to get some understanding of each other's area." (int 13) "I was already familiar with the work. I knew what kinds of things [co-Pi] cared about." (int 23)
Theme 2: interpersonal relationship	47 (47.96%)	
Liking for collaborators: Enjoy hanging out with collaborators, could be or are friends outside of research, see each other as 'cool' people	17 (17.35%)	"We were good friends…we hit it off as friends even if we did not do any research together." (int 15) "They're so easy to get along with...It is really sort of symbiotic and [has] no conflict." (int 20)
Shared end goal: Awareness and agreement of the purpose of the team and what the team is working towards, understanding that shared efforts are needed to achieve the goal, shared awareness of member roles (e.g., who will be the project manager? Who will 'own' the proposal?)	16 (16.33%)	"When writing an interdisciplinary proposal, you need clear goals... you need, like some kind of process method." (int 13) "Trying to go "Okay, what are they looking for?"...to really get going, what is the problem of the world that we are trying to solve here?" (int 32)
Meeting/collaborating regularly: Talking about the project frequently, collaborative discussions that help align researchers and facilitate thinking together as a team	14 (14.29%)	"…the strong collaboration helps, like to talk more frequently ….to collaborate in person…frequent collaboration discussions…" (int 13) "Weekly meetings and this kind of proactive communication...I think this is important to make sure that our collaboration is kind of effective and efficient..." (int 31)
Theme 3: situational factors	14 (14.29%)	
Resources: Financial resources, temporal resources (e.g., ample time to write the proposal), departmental support (e.g., structures that foster cross-disciplinary interaction), university tradition of cross-disciplinary respect	8 (8.16%)	"...both [Co-PI] and I, at that point we are pretty available... we had the time needed to invest in this and [Co-PI] was really able to put in the time" (int 11) "...others in our department have encouraged me to give more... bring more ideas to the table and propose more, write more papers...then take my ideas and put them in their grants." (int 32)
Physical proximity: Able to drop-in easily, walkable distance to other's offices, can see each other at research conferences or meet on campus	6 (6.12%)	"...physical proximity... definitely made things a lot easier, that we went to the same conferences." (int 23) "We were all in the same office... It helped a lot to be on the same floor...being able to just walk to someone's office or just happening to see them in the coffee room, and just say, "Hey, you know, blah, blah, blah." (int 32)

investment in achieving project outputs or seeing the project through to its completion.

Interpersonal elements that hindered cross-disciplinary collaboration included differences among researchers stemming from disparate educational backgrounds, such as difficulty understanding vocabulary terms or researchers understanding the same word to have different conceptual meanings (e.g., “model” meaning a simulation in computer science vs. “model” meaning proposed relationships between variables in psychology). Disciplinary differences among researchers also originated from a lack of exposure to software or techniques used by those outside of their home field, for example. In addition, interviewees reported that different output priorities among researchers had negative impacts on cross-disciplinary collaboration. For example, based on the value systems native to individual disciplines, computer science scholars prioritized presenting at conferences, whereas psychologists valued publishing in journal articles (König et al., 2020), whereas English scholars prioritize publishing books.

Finally, unfavorable situational factors included a lack of resources (e.g., too little funding to sustain the project, difficulty finding time to meet with all members of the team, or a lack of university support for the research). In addition, a lack of physical proximity to other researchers contributed to an awkwardness that made it hard to get to know collaborators. This was exacerbated by time zone differences among researchers or difficulties joining video conferences that ultimately inhibited collaboration.

Table 2 also details the number of interviewees mentioning each category and respective illustrative quotes. The two most popular overall themes of hindrances to collaboration were interpersonal relationships among researchers (45.65%) and situational factors (43.48%). Similar to facilitating factors, almost half of respondents mentioned the critical theme of getting along with members of the

TABLE 2 Hindrances to cross-disciplinary collaboration.

What factors hindered cross-disciplinary collaboration?		
Second-order codes	Number of interviewees mentioning category and percentage	Illustrative quotes
Theme 1: cross-disciplinary attitudes and experience	5 (10.87%)	
Lack of interest in research and cross-disciplinary work: Low motivation for the project itself, not wanting to work with other disciplines, low investment in achieving project outputs (e.g., published articles, conference presentations)	5 (10.87%)	“I think that one of the challenges in interdisciplinary project is to keep the interest and motivation alive.” (int 13) “I did not feel like a lot of multi-disciplinary and coming together. It was just like one more collaborator.... Neither he cared about publication, nor I cared...both of us did not.” (int 19)
Theme 2: interpersonal relationship	21 (45.65%)	
Cross-disciplinary differences: Difficulty understanding vocabulary terms of other disciplines (e.g., feeling that you are talking about two different things), lack of experience in fields outside of one’s own, lack of exposure to another field’s relevant software or techniques (e.g., being introduced to machine learning or making apps during the project)	11 (23.91%)	“…we are...using different languages and we are coming from relatively different areas in our background...there [are] a lot of techniques, not just content that we need to learn, but also ways of doing research that were new...” (int 16) “...each of us...were pulled in different directions...They had their own faculty meetings and things going on in their department, so the disciplines tend to pull you away from interdisciplinary work.” (int 21)
Different output priorities: Disciplines value different contributions (e.g., preference for conference proceedings versus journals), certain outputs are not valued in tenure decisions, struggling to find ‘fit’ among members about what outputs to move towards	10 (21.74%)	“...we do not count conference papers...it does not help me in my promotion.... I have to... produce general papers.” (int 12) “He wanted to publish in conference proceedings, whereas I wanted to try to publish...a journal paper.” (int 11)
Theme 3: situational factors	20 (43.48%)	
Lack of resources: Lack of funding needed to sustain the project, difficulty scheduling around busy schedules or involvement in other labs or projects, lack of departmental/university support for research (e.g., teaching buyouts)	11 (23.91%)	“Her school provides funding and buyouts for classes....so she....has more time to devote to research than I do. Because I’m teaching either four or five classes a year” (int 26) “By Friday afternoon, I’d done most of the other stuff I was actually being paid to do and could free up some time... The relatively low dollar amounts were the biggest barrier.” (int 24)
Lack of physical proximity: Awkwardness of joining groups virtually, time zone differences make it harder to ‘get to know’ team members	9 (19.57%)	“It’s always challenging when people aren’t in the same building, right?... Walking through the rain in the snow, it was so hard to get over there.” (int 9) “I think the main thing that’s difficult is we have a time zone shift... three-hour difference between East Coast and West Coast has sometimes been a challenge.” (int 4)

TABLE 3 Successes of cross-disciplinary research.

Successes of cross-disciplinary research		
Second order codes	**Number of interviewees mentioning category and percentage**	**Illustrative quotes**
Productivity: Outcomes of research productivity such as journal publications, conference presentations, prototypes	11 (43.48%)	"We've also produced some intellectual content in terms of publications...So I think the success is...potential broader impact, but also intellectual contributions." (int 31) "We did get a project completed, and we are eventually able to get the results published. So, I think... that's the biggest success." (int 9)
Learning/Growth: Own learning/growth as well as student and faculty learning, professional development opportunities	8 (30.43%)	"Students will get involved, they get a lot of...rigorous training in a field that helps them become better scholars. So, in that respect it also has those benefits in overall scholarship..." (int 7) "For me, the contacts with [co-PI] and [co-PI] were by far the most valuable part... I now have somebody I can call at [university] in cyber security area of things, and I did not before." (int 24)
Contributions to solving big picture challenges: Creating novel approaches, pioneering new ideas that progress understanding in important ways	4 (17.39%)	"We were making a lot of progress...and coming up with really interesting ideas, and really pioneering logical stuff." (int 23) "The multi-disciplinary science...kind of novel advancement in knowledge that we actually are creating new knowledge." (int 7)

research team. Within this theme, subcategories of cross-disciplinary differences and different output priorities were mentioned with similar frequency, 23.91 and 21.74%, respectively. Regarding situational factors, a lack of resources (23.91%) and physical proximity (19.57%) were mentioned with similar frequency. Finally, the least popular hindrance to continued collaboration involved the cross-disciplinary attitudes and experience of the researchers (10.87%). This theme included one subcategory, which referenced a lack of interest in the research question or in cross-disciplinary disciplinary work generally.

In addition to the factors that facilitated and hindered collaboration, interviewees were asked to name their greatest successes of cross-disciplinary research (Table 3). Interviewee responses revealed that cross-disciplinary successes stemmed largely from output productivity, such as journal publications, conference presentations, or prototypes, which was listed by 43 % of (43.48%) respondents. The next most popular response highlighted researchers' appreciation for learning and growth opportunities, such as professional development opportunities, listed by 30 (30.43%) of interviewees. Seventeen percent (17%) of interviewees commented that contributions to solving big picture challenges was a success of their cross-disciplinary research.

What are the effects of cross-disciplinary integration on collaboration and research productivity?

Cross-disciplinary scholars agree that substantial integration is needed to harness the richness of diverse expertise (Bammer et al., 2020; O'Rourke et al., 2016). According to Balakrishnan et al. (2011, p. 524), "integration is the extent to which a research team combines its distinct expertise and work into a unified whole." More than simply the sum of individual parts, high levels of integration require teams to work interdependently to merge expertise (Balakrishnan et al., 2011) in what is known as transdisciplinary research. Transdisciplinary research involves "the [fusion] of different disciplinary approaches" and is considered necessary to solve grand challenges (Wickson et al., 2006, p. 1050). However, how does the level of integration within a team relate to research outputs that amount to more than the sum of individual disciplines?

Tasks such as how research teams prepare their proposals, plan projects, and coordinate and manage their work reveal the extent of their integration (Balakrishnan et al., 2011). Therefore, to understand the degree to which interviewees achieved transdisciplinary collaboration, we asked the following interview questions:

1 Can you describe how you went about writing the EAGER proposal with [co-PI]?
2 There are a variety of ways that multidisciplinary teams collaborate. Which of the following best describes the nature of your multidisciplinary EAGER collaboration?
  a sequentially, each from their own discipline-specific perspective,
  b jointly and some integration occurred, but contributions remained anchored in their own disciplines.
  c work to extend discipline-specific theories so that new approaches were created to address a common problem (transdisciplinary collaboration).
  d or another option?
3 How was the EAGER grant workload divided between you and PI/Co-PI? Do you work independently and then pool your work together?
4 Can you tell me about how you communicated with [co-PI] on EAGER grant work? How frequently did you work together? How were your meetings structured? How did you communicate?
  a Email?
  b In person?
  c Virtually (e.g., Zoom, Teams)?
5 Did you meet socially together outside of the project?

The percentage of agreement across three raters was 100% for the question about the writing the grant proposal (Kappa = 0.9993) and 100%

for the question detailing the nature of multidisciplinary collaboration (Kappa = 1.0). The question about workload division had a 93.46% agreement (Kappa = 0), and the question about the type and frequency of team communication had a 90.74% agreement (Kappa = 0.5432).

An additional two interviews that were coded yielded a 100% agreement codes for the question about writing the grant proposal (Kappa = 1.0) for both interviews. A 95.67% agreement (Kappa = 0.7381) was found for the question about the nature of multidisciplinary collaboration and a 97.55% agreement (Kappa = 0.6143) in the second. Further, the question about the workload division within the team yielded a 94.99% agreement in the first interview (Kappa =0.2721) and a 97.81% agreement in the second interview (Kappa = 0.6204). The question regarding the type and frequency of team communication reached a 100% agreement (Kappa = 0.9995) for the first interview and 100% (Kappa = 1.0) for the second. Rater agreement about meeting socially was also tested, yielding a 96.21% agreement in the first interview (Kappa = 0) and a 99.99% agreement in the second (Kappa = 0.9958).

Interview results

Cross-disciplinary integration continuum

Coding revealed that responses to the questions listed above were categorized from lower, moderate, to high levels of cross-disciplinary integration. For example, for the question about how PI/co-PIs wrote their grant proposal, coded themes represented a continuum from low (e.g., one person led and the co-PI(s) added content from their own discipline) to moderate (e.g., equally divided, with each investigator independently adding in their own content and editing back and forth) to high (e.g., in-depth discussion of viewpoints throughout the writing and review of the proposal). Table 4 depicts each interview question and the coded responses across the cross-disciplinary integration continuum (low, medium, high), and the percentage of interviewee responses representing each category.

As shown in Table 4, most interviewees (42.4%) felt that the process of writing the grant proposal was equally divided among members, with back and review after adding in one's own content. Further, most interviewees (67%) reported that they did not believe their research team achieved true transdisciplinary research, but instead that disciplines remained more separate. To continue, the way the workload was divided among interviewees was mainly by each member collecting data in their own study and then combining the results together (60.6%). Most interviewees communicated by e-mail as needed (66.7%). Only 21.2% of interviewees communicated with their teammates in-person every week. Fewer (18.2%) communicated virtually (e.g., via Zoom) weekly. 24.2% of interviewees met socially (e.g., for a meal or a drink).

As shown at the bottom of Table 4, a total integration score was given to interviewees by combining scores across the seven individual questions. Coded interviewee responses were almost equally divided across low, medium, and high levels of cross-disciplinary responses.

Effect of cross-disciplinary integration on archivally measured research productivity

Because coded interviews were transformed into data on a continuum in an integrated design (Srnka and Koeszegi, 2007), data presented in Table 4 was linked with archival data to speak to the effects of cross-disciplinary integration on research outputs.

First, we examined the relationship between interviewees' overall cross-disciplinary integration score (combining all 7 questions in Table 4) and total research productivity (including articles, book chapters, grants, and conference participation during and after the grant award). This relationship was not significant [r (32) = −0.152, p = 0.21]. A more nuanced approach was then taken, analyzing the relationship between interviewees' total integration score and different types of research outputs, including total conferences [r (32) = −0.067, p = 0.72], grants [r (32) = 0.035, p = 0.85], and articles [r (32) = −0.239, p = 0.19]. Although not reaching statistical significance, the relationship between articles and cross-disciplinary integration was larger than that of conferences and grants. Surprisingly, the higher the cross-disciplinary integration, the lower the journal articles published. To further investigate this counterintuitive finding, we examined the relationship between the total number of articles produced after EAGER grants were awarded and each of the seven integration questions in Table 4 separately.

There were no significant relationships between the number of articles published and writing a grant proposal [r (32) = −0.02, p = 0.92], the nature of cross-disciplinary collaboration [r (32) = 0.19, p = 0.32], workload division among team members [r (32) = 0.11, p = 0.57], the frequency of email [r (32) = −0.21, p = 0.32], or social communication outside of the research process [r (32) = −0.26, p = 0.22]. However, compared to these effects, the correlation between virtual communication and total articles was substantially larger in magnitude [r (32) −0.43, p = 0.17], which accounted for the negative relationship between the overall integration score and article productivity. The higher the level of virtual collaboration among PIs and co-PIs, the lower the number of articles published. In contrast, a higher frequency of in-person communication among collaborators was associated with a greater number of articles published after being awarded an EAGER NSF grant [r (32) = 0.58, p = 0.01]. Thus, PI/co-PIs who had more frequent face-to-face meetings (e.g., weekly or biweekly), published more articles together than investigators who had less frequent face-to-face meetings (e.g., monthly).

What factors Foster higher cross-disciplinary integration?

When asked what would have helped the team reach the deeper levels of cross-disciplinary integration necessary for transdisciplinary research, having similar goals for the research project was listed most frequently by 39% of interviewees. Thirty percent (30.43%) of researchers mentioned that more resources, in the form of time, money, or potential publishing outlets, would have encouraged transdisciplinary research within the team. Seventeen percent (17.39%) of interviewees mentioned the importance of communication and open discussions to reach deeper integration among collaborators, as illustrated by the following interviewee comment:

> "...communication...trying to really understand what the other side has been doing....takes a lot of back-and-forth discussions...and building the necessary background and filling the holes and the gaps on both sides... bringing everything on the same page." (int 1).

The potential benefit of having a greater familiarity with disciplines outside of one's home field was mentioned by 13 % (13.04%) of interviewees, as illustrated by the following quote:

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TABLE 4 Coded interview responses representing a cross-disciplinary integration continuum.

	Integration continuum								
	Lower integration			*Moderate integration*	*Higher Integration*			MISC	Other
Category	1	1.5	2	3	4	4.5	5		
Writing grant proposal	N/A	One lead, other add some content about own discipline	N/A	Equal division, adding in own content, and review with back and forth	N/A	Integration throughout discussion and review*	N/A	N/A	No recorded response
Responses		*13 (39.4%)*		*14 (42.4%)*		*4 (12.1%)*			*2 (6.1%)*
Nature of cross-disciplinary collaborations	Sequentially from own discipline	N/A	Between sequential and some integration*	Some integration but contributions anchored in own discipline	Between some integration and transdisciplinary*	N/A	Transdisciplinary (extend discipline-specific theories and methods)	N/A	No recorded response
Responses	*1 (3.0%)*		*0*	*15 (45.5%)*	*7 (21.2%)*		*7 (21.2%)*		*3 (9.1%)*
Workload division	Separate assignments (e.g., one provides input and feedback, other designs and collects data)	N/A	Divided (e.g., each collects own data in own study, puts results together)	Consecutive (e.g., results of one study inform design of second study)	Interdependent (e.g., both involved in study design and/or data collection)	N/A	N/A	N/A	No recorded response
Responses	*2 (6.1%)*		*20 (60.6%)*	*3 (9.1%)*	*7 (21.2%)*				*1 (0.9%)*
Communication—type and frequency: Email	N/A	Monthly*	N/A	Biweekly*	N/A	Weekly*	N/A	As needed	Not specified
Responses		*0*		*0*		*2 (6.1%)*		*22 (66.7%)*	*9 (27.3%)*
Communication—type and frequency: In-Person	N/A	Monthly*	N/A	Biweekly*	N/A	Weekly*	N/A	As needed	Not specified
Responses		*4 (12.1%)*		*3 (9.1%)*		*7 (21.2%)*		*8 (24.2%)*	*11 (33.3%)*
Communication—type and frequency: virtual	N/A	Monthly*	N/A	Biweekly*	N/A	Weekly*	N/A	As needed	Not specified
Responses		*0*		*2 (6.1%)*		*6 (18.2%)*		*4 (12.1%)*	*21 (63.6%)*
Communication—meeting socially	No	N/A	Some social conversation during meetings	Once or twice (e.g., at an event)	For a meal or drink	N/A	Visits (e.g., to each other's homes)	N/A	No recorded Response
Responses	*3 (9.1)*		*3 (9.1%)*	*7 (21.2%)*	*8 (24.2%)*		*3 (9.1%)*		*9 (27.3%)*
Total	*46 (20.5%)*			*44 (19.6%)*	*51 (22.8%)*			*34 (15.1%)*	*49 (21.9%)*

Numbers indicate the number of interviewees mentioning each category, followed by the percentage in parentheses Asterisk (*) indicates translated code level from original description (e.g., A = 3, B = 1, C = 2). Percentages based on 33 total interviews.

> "I think for us to really be able to jointly work together and kind of transcend both fields, I would have to have a better working knowledge of the literature [co-PI] is pulling from, and I think [co-PI] would maybe have to be more receptive to some of the things that I'm pulling from my literature." (int 6)

Discussion

Summary of key findings

Three key findings emerged from this study. First, even though grants are not contracts, almost 90% of investigators in our population co-authored with a collaborator from a different discipline after receiving their award. Almost 80% worked with a researcher from a field very dissimilar to their own. Therefore, most grantees moved from the cross-disciplinary team *composition* required for the grant proposal to be competitive for funding to cross-disciplinary post-award *collaboration*, although it was not enforced by NSF. Given their intention that EAGER grants be a catalyst for continued cross-disciplinary collaboration and research output, NSF resumed funding for EAGER grants in cybersecurity in part due to these promising findings.

Second, the major categories of facilitators and hindrances to cross-disciplinary collaboration were consistent: cross-disciplinary attitudes and experience, interpersonal relationships, and situational factors. For hindrances, the interpersonal (e.g., lack of exposure to other disciplines, disagreements about where to publish research) and situational (e.g., lack of funding and inability to meet face to face) categories were dominant. For facilitators, interpersonal relationship (e.g., liking collaborators, having a shared end goal, and regular meetings) and attitudes towards cross-disciplinary work (e.g., intrinsic interest in the research and an openness to new experiences) were the top categories. Archival research also identified that prior collaboration was an important predictor of continued collaboration. Cross-disciplinary researchers defined success as research outputs and opportunities for learning and development.

Third, investigators recognized the importance of integration to synthesize diverse perspectives. Their reflections on the specific qualities that would facilitate deeper integration largely paralleled the factors that facilitated more general cross-disciplinary collaboration. Specifically, researchers recommended that team members have similar goals for the outcomes of the research project to achieve deeper integration. Access to more resources (e.g., time, money, publishing outlets) was also mentioned as a boost to transdisciplinary research. Although our sample size was small and these results need to be replicated, we found that cross-disciplinary teams with higher amounts of in-person communication experienced greater researcher productivity in the form of article output. In contrast, higher levels of virtual collaboration were associated with lower article output.

Elaboration of study findings

How did cross-disciplinary authorship compare to disciplinary authorship after winning an NSF award?

Because NSF and other granting agencies increasingly require cross-disciplinary team composition, it is urgent that we discover the benefits, limitations, and objective outcomes of promoting collaboration across NSF's directorates. Given the prevalence and importance of interdisciplinary teams across a variety of contexts (e.g., government, business, education, science, health care), understanding why members choose to remain or leave these collaborations is key to improving their effectiveness.

Although cross-disciplinary collaboration holds much promise, especially at the outset of team interaction, it can quickly devolve into miscommunication, conflict, and coordination breakdowns due to different vocabularies, disciplinary perspectives, and expectations (Lovelace et al., 2001). Therefore, PIs/co-PIs may include members from other disciplines in their grant proposals to meet the requirement for cross-disciplinary team composition, but then decide to publish only with investigators from their own discipline because NSF does not enforce post-award collaboration. However, our data did not find support for this potential loophole. Instead, of the 74% of PI and co-PI teams who collaborated after their EAGER award, almost 9 out of 10 co-authored with an investigator from a different discipline, and almost 8 out of 10 worked with a researcher from an extremely diverse discipline from their own (e.g., computer science and psychology).

Research on interdisciplinary teams largely emphasizes the challenges and problems researchers face (e.g., distinct disciplinary languages, strong subgroup identities, unstructured problems, high status differentiation, e.g., Salazar et al., 2012), but the current research demonstrated that 90% of the population chose to continue working together across disciplines after EAGER awards. Therefore, future research should dedicate more attention to the intangible benefits members receive in interdisciplinary teams. We begin to do so by addressing our second research question.

What factors facilitated and hindered cross-disciplinary collaboration and authorship?

According to our archival results, pre-EAGER award authorship facilitated post-EAGER award authorship. Of the teams who collaborated on conference submissions, publications, and grants prior to their EAGER award, 92% collaborated before EAGER. Among post-EAGER award collaboration teams, 47% authored together pre-EAGER. More PI and co-PI teams collaborated with cross-disciplinary members after their EAGER award than before, with more multidirectorate authorship post- than pre-EAGER award.

Beyond a history of working together, interviews revealed that individual attitudes toward cross-disciplinary research, PI/co-PI interpersonal relationships, and the environmental context both facilitated and hindered cross-disciplinary collaboration. However, the frequency with which each theme was mentioned differed across facilitators and hindrances, as did sub-themes. For example, situational factors were more substantially represented as barriers to, rather than promoters of, cooperation across research fields. The predominant drawbacks to cross-disciplinary collaboration were interpersonal relationships among researchers and situational factors. In contrast, positive PI/co-PI interpersonal relationships emerged as the most advantageous theme for cross-disciplinary collaboration, followed by supportive attitudes and experience.

Interpersonal relationship facilitators included meeting and collaborating regularly, team members having a shared end goal, and a liking for other researchers. Interviewees reported that regular communication and getting on the same page about research project aims helped ease cooperating across disciplinary boundaries. In contrast, the experience of 'speaking different languages' emerged from difficulty understanding vocabulary across fields and a lack of familiarity with other disciplines' theories, methods, and analyses. Disagreeing on where to publish or disseminate final products were constraints to cross-disciplinary collaboration.

The importance of frequent and open communication among collaborators to overcome cross-disciplinary differences is demonstrated in the following quote:

> "…People are looking for grant funding, and so they pitch the proposal, and then they all go their separate ways…we have not …really been truly collaborative. I think the message needs to be sent that this is not just 'go get the money'…. You've got to kind of get your researchers to articulate how you are going to work together." (Int 3).

Regarding cross-disciplinary attitudes and experience, interviewees agreed that having an intrinsic interest in the research question, an openness to new experiences, a respect for other disciplines, and previous relevant research experience were instrumental in establishing a more positive cross-disciplinary experience. In teams with these characteristics, researchers may have been more comfortable asking clarifying questions or for extra explanation when working with those from diverse disciplines. This freedom to ask questions without fear of judgment may have reduced cross-disciplinary disconnect that may stem from confusion or miscommunication. In this way, valuing diverse perspectives promoted continued collaboration within a team.

In contrast, interviewees often listed the absence or inverse of facilitators as hindrances to continued cross-disciplinary collaboration. A lack of respect for other academic disciplines, as well as little interest in the research project or in achieving integration across disciplines, was mentioned as a hindrance to continued collaboration.

The presence and absence of resources and physical proximity were facilitating and hindering situational factors, respectively. Adequate time, money, departmental support, and university support were needed to navigate challenging cross-disciplinary work. For researchers who were spread too thin with other commitments within their discipline, cross-disciplinary work was pushed to a peripheral priority and collaboration suffered as a result. Physical proximity also influenced the collaboration experience. Researchers who could easily visit their collaborators' offices or interact with teammates at conferences found this helpful in continuing cross-disciplinary work. Alternatively, time zone differences and virtual communication challenges served as roadblocks that made cross-disciplinary collaboration more difficult.

Interestingly, the interview themes correspond with the characteristics of a diversity climate, which captures "efforts to improve the integration of members of minority groups... into all levels of employing organizations" (Kossek and Zonia, 1993, p. 62). A diversity climate is defined by four characteristics, including (1) acceptance of others, (2) institutional commitment to diversity, (3) fairness, and (4) a generalized atmosphere of respect (Garcia and Hoelscher, 2010). The diversity climate quality of accepting others mirrors interviewee comments outlining the importance of team members being open to new perspectives. Situational factors that facilitate cross-disciplinary research, like adequate time and money, relate to the institutional commitment necessary for a healthy diversity climate.

Because one way to gauge an organization's institutional commitment to diversity may be through the resources made available to their personnel, a lack of resources may be a calling card of a weak diversity climate. The feeling of fairness present in a strong diversity climate relates to having a shared end goal in a cross-disciplinary team. For example, interviewees mentioned the importance of making equitable decisions about how to break up project workload. Finally, interviewees mentioned the importance of having respect for other disciplines, which maps onto the general atmosphere of respect found in a strong diversity climate.

As the aim of a cross-disciplinary team is to harness a diverse range of perspectives, a strong diversity climate within a team may encourage members to voice diverse perspectives without fearing that their contributions will be devalued by others. Because the ability to use workforce diversity as a resource for better performance is a component of a diversity climate (Hubbard, 2012), cross-disciplinary teams without a healthy diversity climate may face challenges effectively collaborating across fields.

To continue, interviewees were also asked to describe the greatest successes of their cross-disciplinary research. While productivity and output were important to interviewees (43.48%), growth and learning opportunities (30.43%) were highly valued as well. The importance of productivity is mentioned in the following quote:

> "[T]he biggest success of this grant was…we have one paper and… it got quite a lot of international attention. Blogs from 30 countries talked about it. Wow." (int 15).

Developmental opportunities that were afforded through cross-disciplinary collaboration were demonstrated in comments such as:

> "…I have identified a problem that is interesting…at this junction of my career where you need to diversify yourself from what you have done before… working with [co-PI] can allow me to [do that]." (int 22).

These responses hearken back to interviewees recognizing the importance of both intangible and tangible elements in the research process, as represented through comments about the need for healthy communication juxtaposed with a need for practical resources.

Our research reveals the importance of having an intrinsic interest in working in functionally diverse settings and how that experience, despite what outcomes result from it, can be rewarding if researchers value gaining exposure outside of their discipline. While productivity is an important outcome for cross-disciplinary researchers, developing professionally by being exposed to new methods and techniques is valued as well. This is demonstrated in the following quotes:

> "We go to the next larger NSF grant… but from a wider perspective, different methods and approaches." (int 11).

> "I do not want to be surrounded by me [or] by people whose methods and focus is exactly the same as me....If you frame questions around a problem, and you said, "Well, what kind of people do we need to make headway on this problem?," you are never going to have a single discipline… [it] is going to require lots of different people and a willingness to listen to different ideas…" (int 18).

What are the effects of cross-disciplinary integration on collaboration and research productivity?

While educational and disciplinary diversity can benefit a team's access to information, this information may not be combined effectively. Integration is needed to effectively leverage cross-disciplinary expertise (e.g., Balakrishnan et al., 2011). As one interviewee shared,

> "It requires two different kinds of disciplines coming together and saying, "Okay, here's what we know," and then the harder questions are, "Okay, well, we know it, but how do we...build it?"" (int 3).

However, most interviewees in our sample felt their work was segregated by discipline, demonstrated in the following quote:

> "It was not like we [were] applying some techniques of one discipline into another, which...overlap substantially. So, his area was there, ours is there." (Int 13).

Research calls for an understanding of the team processes necessary for integration to be effective (Jansen and Searle, 2021). When highlighting characteristics that would promote transdisciplinary research, interviewees reiterated themes mentioned previously as facilitators to effective collaboration. Interviewees highlighted a familiarity with disciplines outside of their own as beneficial to deeper collaboration, harkening back to the subtheme that cross-disciplinary knowledge and experience facilitates continued collaboration. The importance of communication was further underscored, where the crucial nature of 'back and forth discussion' was mentioned as a means of crossing disciplinary boundaries. To continue, interviewees stated that having similar goals for the research project as their teammates was instrumental to deeper integration, again mirroring earlier responses to facilitators of cross-disciplinary collaboration. Finally, interview responses highlight the importance of resources once more. Access to sufficient time, money, or more publishing outlets would have encouraged transdisciplinary research within the team.

Interviewee responses revealed that these characteristics are not only influential on perceptions of the quality of collaboration, but on archivally measured research productivity. Greater in-person communication among PI/co-PIs was associated with higher overall article output. Therefore, encouraging more in-person communication appears to be a key lever to offset cross-disciplinary disconnect.

Contributions

Whereas previous studies have examined why individuals join cross-disciplinary teams (e.g., Lungeanu et al., 2014; Salazar et al., 2011), we examine the subsequent choice of whether PIs/co-PIs continue to collaborate with members of different disciplines after being awarded a research grant. Given that grants are not contracts, investigators may disengage with those outside their field without losing the money awarded to fund their work. However, our research revealed that the promise of cross-disciplinary composition largely translated into authorship with members of diverse disciplines.

Although existing research has primarily emphasized the challenges of cross-disciplinarity (e.g., Lovelace et al., 2001; Salazar et al., 2012), our findings showed that intrinsic factors are significant motivators for why PIs/co-PIs collaborate with others from diverse fields. As such, this study builds on Mathieu and Gilson's (2012) emphasis on team effectiveness including intangible outputs by demonstrating the importance of team members' interpersonal experience and attitudes towards new perspectives in influencing continued cross-disciplinary collaboration. Further, this study considers the kinds of intangible benefits made available to cross-disciplinary researchers by isolating learning and growth experiences as successes of their research experiences. Therefore, this paper speaks to how the intrinsic rewards researchers receive from cross-disciplinary research may counteract the challenges they face (e.g., Salazar et al., 2012) and propel them to continue this work. By doing so, our findings broaden our understanding of the importance of motivation in predicting continued collaboration in teams with high amounts of deep-level diversity.

This study also expanded our understanding of the implications of virtual work in cross-disciplinary interactions. According to Perry et al. (2016) "team virtuality [can be viewed] on a continuum from low virtuality (e.g., all in person communication between members) to high virtuality (e.g., no in-person communication between members) (p. 452). Virtuality has been referenced as key determining factor in teams (Foster et al., 2015), which is supported in the current study, as physical proximity acts as a facilitator to deeper and continued collaboration. As communication depends on a previously established common ground to build understanding (Srikanth et al., 2016), this study furthers this conclusion by emphasizing the importance of in-person interactions in cross-disciplinary teams.

In addition to these empirical contributions, the current study also makes a methodological contribution. Whereas studies on cross-disciplinary teams have relied primarily on archival measures (Wagner et al., 2011), we answer the call for more mixed-method studies (Laursen et al., 2022) by incorporating both archival and interview approaches. The combination of qualitative and quantitative methods permitted a superior understanding of post-award investigator collaboration than was possible with only one approach.

Limitations and future directions

Several limitations must be acknowledged across and within the archival and interview methodologies of our study. Our population was limited to PI/co-PIs awarded NSF EAGER grants investigating cybersecurity. Therefore, future research should expand to other cross-disciplinary contexts. In addition, a significant limitation of our quantitative approach is that we were not able to gather data from investigators who applied but did not receive grant funding because this data was not publicly available. Therefore, we could not compare whether grant recipients engaged in more cross-disciplinary authorship on conference presentations, publications, and grants than non-grantees. Our data also do not permit us to make causal inferences of the effect of funding on cross-disciplinary authorship.

Because we concluded archival analyses at the end of 2021, later rather than earlier grant awardees were penalized in our archival analyses. For example, 2019 EAGER grant awardees only had 2 years of productivity included in their output score compared to 8 years of productivity for 2013 awardees.

The research productivity of respondents may have been adversely affected by the COVID-19 pandemic in 2020 and 2021. Furthermore, since interviews were conducted in 2020, interviewees were mostly reporting on pre-pandemic collaboration. Therefore, this context needs to be considered in interpreting the negative effects of virtual collaboration and the positive effects of in-person collaboration with journal article publications.

Because interviewees were asked about their team collaboration between two and eight years after their EAGER grant had been awarded, responses may have been influenced by retrospective bias (Evans and Leighton, 1995). However, given the time needed for research peer review, this time lag also had the beneficial effect of allowing for a more precise estimate of the number of conference presentations, publications, and grants.

Although our archival research was limited to examining the quantity of post-grant award research productivity, quality is also a key, but challenging, metric to evaluate across disciplines. Whereas some disciplines (e.g., psychology) value journal articles over conference presentations, others (e.g., computer science) value conference presentations over journal articles (König et al., 2020). In addition, several weaknesses have been identified with commonly used quality metrics such as journal impact factors (the average number of citations received by published articles over a particular period) and the *h*-index (reflects quantity and quality by comparing publications to citations). For example, journal impact factors have been criticized for their susceptibility to inflation by self-citations and publishing qualitative and quantitative reviews (Archambault and Larivière, 2009). Whereas the *h*-index is less sensitive to journals that have articles with citation outliers, it disadvantages journals that publish fewer articles (Hirsch, 2005). These metrics can also be misleading because they do not evaluate the innovativeness of a single research article but rather reflect the average citations of all articles within a journal. Cross-disciplinary research teams tend to produce more innovative products, publications, and diverse publication venues than teams representing one discipline (Hall et al., 2018).

Future research should investigate facilitators and hindrances to cross-disciplinary research using more investigators beyond the small sample size of 33 interviews in the present research. In addition, we mainly interviewed only one person per team and only the PI or co-PI given the limitations of the publicly available data to which we had access archivally. Nevertheless, a more comprehensive assessment would gather data from multiple team members, including post docs, graduate students, undergraduates, and research staff.

Due to the low power to detect effects, our correlational results needed to be higher to reach statistical significance. Therefore, the findings linking cross-disciplinary integration with archival research productivity should be interpreted with caution and tested with larger samples of cross-disciplinary researchers. Because our archival analysis relied on publicly available data, which did not include gender, race, nor culture, we were unable to investigate these characteristics, nor did we ask explicitly about demographic diversity in our interviews. However, future research should consider how surface-level diversity interacts with cross-disciplinary diversity to impact collaboration. König et al. (2020) specifically reference the gender imbalance across academic disciplines (e.g., male dominance in computer science versus more equal representation between males and females in industrial-organizational psychology) and its likelihood to play a role in cross-disciplinary team dynamics. For example, consider two female, Latina postdocs who represent "soft" sciences in a team with two white, male, tenured professors who represent "hard" sciences. This hypothetical dividing line splitting the team into two sub-groups creates what is known as a faultline (Thatcher and Patel, 2012). Faultlines have generally been shown to have a detrimental effect on team performance and other outcomes (Thatcher and Patel, 2012), but demographic faultlines have dominated research. Therefore, deep level diversity, like cross-disciplinary differences, represents a promising area for future faultline research to explore. Because of the parallels we discovered between interview themes and the characteristics of diversity climate, scholars should investigate the extent to which the drawbacks of cross-disciplinary collaboration can be mitigated by having a strong acceptance of diversity in teams.

Due to the hierarchical nature of many academic teams (e.g., full professors, associate professors, assistant professors, postdocs, graduate students, undergraduates), studies should also examine how power and status differences interact with cross-disciplinary differences to affect team outcomes. Our study also implies asymmetric influence patterns among team members, such that in diverse groups, high-status individuals may have a greater influence. In the case of a cross-disciplinary team, high-status members (e.g., the PI belonging to the 'hard' sciences) may influence the team more than low-status members (e.g., a graduate student belonging to the 'soft' sciences) (e.g., Ridgeway and Correll, 2006). Because an asymmetric influence pattern is harmful for collective decision-making and stifles the sharing of task-relevant information (Shim et al., 2021), future research should explicitly test the impact of asymmetric influences in cross-disciplinary teams.

Moreover, the performance expectations of members in cross-disciplinary teams should be investigated. Performance expectations are established through status characteristics (Berger and Conner, 1969) that reveal how likely an individual is going to be helpful in accomplishing team goals (e.g., Bunderson, 2003). Due to disciplinary arrogance or pride, members of the 'hard' sciences may have low performance expectations of those from the 'soft' sciences, or vice versa.

Tackling "grand challenges" demands broad representation across multiple disciplines, but teams must also build substantial integration to best use diverse expertise. One way interdisciplinary teams may overcome communication challenges caused by distinct disciplinary languages is to include a cross-disciplinary translator role. A cross-disciplinary translator is knowledgeable about the background, values, and context of two or more disciplines to help team members understand the language and jargon of other disciplines (Knoedler, 2019). To bridge the gap between team members' expertise, cross-disciplinary translators facilitate understanding and communication by converting specialized jargon, technical language, and cultural references from one discipline into language that is comprehensible and meaningful to team members from other disciplines (Ashby, 2022). Specifically, a translator "absorbs and adapts the original idea, the context in which it was presented, the tone of the meeting and reactions to the behavioral idea, different perspectives discussed around the idea, and additional behavioral cues from the participants and integrates all of this information and observations into a new perspective on the idea and how best it may be delivered for the remainder of the meeting" (Knoedler, 2019). Although this promising idea has been explored conceptually (Ashby, 2022; Knoedler, 2019), empirical research is lacking. Therefore, future qualitative and quantitative studies should explore the extent to which a cross-disciplinary translator can help researchers from diverse disciplines navigate the communication challenges to achieve deep knowledge integration.

Practical implications

This study makes several contributions to practice. The findings from this study may motivate team leaders to be more intentional when forming cross-disciplinary teams. For example, team leaders should seek members who enjoy stepping outside of their comfort zone, care about the perspectives of others, and have an intrinsic interest in considering diverse perspectives. Team leaders should also encourage cross-disciplinary members to meet in person regularly and devote time to strengthening interpersonal relationships.

In addition, our research may encourage team members to reflect on their approach to working in cross-disciplinary contexts to consider ways they can affirm the value of perspectives dissimilar to their own. Further, the learning and growth opportunities enabled by cross-disciplinary research were identified as one of the greatest benefits by interviewees. Therefore, team leaders and practitioners should not ignore the intangible benefits of participating in cross-disciplinary research as an incentive to endure the rigorous demands required to collaborate with members from diverse disciplines. In addition, when recruiting researchers to join these teams, granting agencies and universities are advised to highlight the non-tangible and tangible outcomes of cross-disciplinary work.

Researchers should also carefully attend to their institution's commitment to support cross-disciplinary teams. Commitment is communicated via resources, such as adequate pilot funding, ample time to collaborate, and departmental and university climates that respect research spanning multiple disciplines. Granting agencies should ensure that grant reviewers have adequate cross-disciplinary expertise to evaluate proposals representing multiple disciplines. Granting agencies should also consider increasing support for cross-disciplinary teams, including providing funds to facilitate in-person meetings, social gatherings, and team training. Extending the grant time to allow scholars to achieve the deep level of interpersonal and knowledge integration required for transdisciplinary research is also recommended.

Conclusion

This study examined the extent to which cross-disciplinary composition translated into cross-disciplinary authorship in grant-funded teams and explored the facilitators and hindrances motivating cross- disciplinary authorship. Although not enforced by NSF, most PIs/co-PIs moved from the cross-disciplinary team *composition* required for the grant proposal to be competitive for funding to cross-disciplinary post-award *collaboration*. Due, in part, to these encouraging results, NSF resumed funding for EAGER grants in cybersecurity. Interviews highlighted both facilitators and barriers to ongoing collaboration. Key facilitators included strong personal relationships, shared objectives, and receptivity to new ideas. Barriers involved funding limitations and reduced face-to-face interactions. Success in cross-disciplinary collaboration was marked not only by research outcomes but also by learning experiences, underscoring the intangible value of cross-disciplinary work.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Pennsylvania State University Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

CB: Writing – original draft, Writing – review & editing. SM: Writing – original draft, Writing – review & editing. BT: Conceptualization, Data curation, Investigation, Software, Writing – original draft. JM: Conceptualization, Data curation, Investigation, Software, Writing – original draft. KH: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. TZ: Data curation, Methodology, Writing – original draft. CD: Data curation, Methodology, Writing – original draft. HH: Data curation, Writing – original draft. XL: Data curation, Writing – original draft. GM: Data curation, Writing – original draft.

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Conflict of interest

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

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