Metacognition in Graduate Engineering Courses

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Abstract

A metacognitive approach to engineering education, including inquiry-based collaboration, can impact and prepare STEM graduates for a modern workforce that requires high levels of critical thinking, problem-solving, and decision-making skills. This exploratory study examined graduate STEM students' perceived metacognition as they worked together to develop and implement applied research in both online and in-person learning environments. It developed and implemented online learning modules for four graduate engineering courses for research question development, literature reviews, and conducting research. Students self-evaluated using a survey at the end of each course. For all course sections and delivery methods, more than 80% reported perceptions of metacognition and satisfaction with the learning modules. Similar results were seen for subsets of the respondents: for individual vs group perceptions, for field of study, and for online vs in-person instruction.

Introduction

Since 2009, when the "Educate to Innovate" [1] campaign was launched, there have been active discussions among educational leaders on how to transform Science, Technology, Engineering, and Math (STEM) education. Researchers and practitioners across different disciplines have been examining the wide range of innovative approaches to maximize transformation of teaching and learning strategies in STEM disciplines. One of the promising and effective instructional approaches to help transform STEM education can be implementation of an inquiry-based collaborative approach. The inquiry-based collaborative approach can impact and prepare STEM graduates for the future workforce following the required high level of critical thinking, problem-solving, and decision-making skills. This innovative approach also can help STEM graduates develop required collaborative and communicative skills while working as part of any team.

The inquiry-based collaborative approach has recently received recognition when the metacognitive approach has been implemented into the design of online, hybrid and face-to-face learning to support the dynamics of reflective thinking and a collaborative inquiry process [2]. Metacognition is a required cognitive ability to achieve deep and meaningful learning that can be viewed both from individual and social perspectives. Understanding how metacognition manifests in a collaborative learning environment, when students work together (e.g., peer review activities), can also help select effective course design and strategies to guide deep learning outcomes [3].

However, there is still limited research done in the field to understand how to design collaborative activities to help students individually and collaboratively regulate their own learning, i.e., metacognition [4]. It is still not clear enough how metacognition should be structured in a collaborative learning environment both face-to-face and online. Therefore, this exploratory study is an attempt to fill this gap by providing examination of STEM students' perceived metacognition when they worked together to develop and implement applied research. The following research questions were asked: (1) what are STEM graduate students' perceptions of metacognition in an inquiry-based collaborative learning environment? and (2) are there differences in metacognition across course modalities, i.e., in-person versus online?

Literature Review

STEM Education. Recent reports on graduate STEM education have placed additional emphasis on the need to use student-focused teaching to provide curricular support for graduate research experiences, while also emphasizing a need to diversify the process and purposes of these research experiences [5], [6], [7]. It is not enough that graduate programs teach traditional academic research skills, they must also provide opportunities for students to collaboratively engage in research to address authentic STEM problems. Despite the fact that many universities are actively pursuing various ideas in their attempt to transform graduate education, federal science agency programs continuously report that even the best research-based Master's and PhD programs that exist in the U.S. today are not fully prepared to provide the kind of support that the STEM workforce needs [8], [9], [10], [11], [12], [13]. It becomes even more relevant when it comes to the Big Data and Data Analytics (BDA) field, which incorporates professionals from across the STEM fields [14].

Though there is a large body of research that provides evidence that it is beneficial for students to participate in course-based research experiences [15], [16], [17], [18], to our knowledge an idea of integrating research experiences in a sequence of courses throughout the curriculum in a master's program so far has not been extensively studied in literature, especially in the BDA field. Moreover, according to the thorough review conducted by PIs, a question on the effectiveness of the innovative learning environment, including inquiry-based and active learning, for this kind of student learning experiences has not yet been thoroughly studied. Our project fills this gap.

Research learning experiences in higher education are often viewed as "high impact practices" that benefit students from different backgrounds [19]. However, developing and effectively incorporating such practices into graduate courses is a challenging task for many instructors who have limited time and resources [20]. Moreover, graduate students are often assigned to perform projects, presentations or papers that require them to provide persuasive answers supported by evidence to a given inquiry. In addition, the instructors often provide domain specific guidance, assuming the students know how to perform the required research in the topic, or direct them to online resources, without having available a step-by-step learning module to guide them in the research process.

Our team developed and investigated the effectiveness of a novel approach that is intended to address the challenges raised by a rapidly evolving workplace by creating a collaborative multidisciplinary research environment for graduate students that utilizes inquiry-based and active learning methods in four courses that are used in two master programs. We developed and evaluated three generic learning modules and their adaptation and implementation in four domain specific courses that will introduce a graduate student to research activities gradually, consistently, and systematically, with the goal of developing collaboration, innovation, and creativity skills. While transforming our current graduate courses into research and innovation-oriented courses, we also documented our experiences and developed guiding materials to facilitate the application of the learning modules in similar domains and how to adapt them in new domains.

We focused our research around the following three goals: (G1) developing a collaborative multi-disciplinary research environment for graduate students that utilizes inquiry-based and active learning methods, (G2) creating a gradual, systematic, and consistent scaffolded research experience across four courses, and (G3) requiring a collaborative advanced research experience to solve real-world problems in the fields of Data Sciences and Information Technology.

Metacognition in STEM. Previous studies examined how group activities can impact students' individual metacognition to self-regulate critical thinking [21], [4]. DiDonato found that group interactions can contribute to individual metacognition when students were given a complex semi-structured task [21]. However, Greenhow, Graham and Koehler found that students did not have effective regulation strategies to deal with the complexity of group ownership [4], [22]. Researchers suggested that group activities should be thoughtfully designed to help students individually and collaboratively regulate their learning.

Within inquiry-based learning, STEM students usually begin by understanding the task from their individual perspectives. Following Garrison [3], this phase can be defined as individual self-regulation because it is based on students' self-awareness (monitoring) and self-regulation (managing) of their own cognitive processes. Only after each student individually understands the task, they can get a deeper understanding and connections with the shared collaborative knowledge (social perspectives or others). This group metacognition phase can be defined as monitoring and managing a complex shared learning dynamic or co-regulated learning [3]. During this group phase, STEM students share their understanding with others, offer new perspectives, help each other, and provide constructive peer feedback.

The group phase depends on peer-peer interaction, and it can't solely exist or be designed without interaction in mind. That's why studies have examined the value of peer-peer interactions in inquiry-based environments because it is an ill-structured environment where students are required to find their own solution. According to social learning theory, students usually learn through interactions with their peers, learning experiences and observations within a learning context. Interaction between students has been examined as a hallmark for knowledge construction and development of critical thinking skills [23] and the key element for effective and meaningful learning [24]. Interaction between students has been also examined as the factor that might influence students' academic achievements, motivation, engagement, self-efficacy, and satisfaction [25]. Studies found that perceived value for participation, competence and autonomy, interest in completing educational requirements, opportunity for interactions, and personal relationships are the major factors to achieve high students' interaction in inquiry-based learning [26].

Studies noted that further research is needed to determine how students can regulate their own learning in inquiry-based environments and move towards group metacognition [4], [27]. Similarly, Garrison [3] noted that the role of metacognition in shared environments has not been sufficiently examined yet. It is not clear enough when and how students can move from individual metacognition (self-awareness and self-regulation) to group metacognition (others and co-regulation) when students participate in group activities, such as discussions and peer reviews. Thus, this study aimed at investigating STEM graduate students' perceptions of their individual self-regulation and group co-regulation metacognition when they participated in discussions and peer reviews applied research activities.

Methods

Research Design. This exploratory quantitative research study examined STEM graduate students' perceptions of metacognition when they participated and completed the applied research course learning modules. Specifically, this study examined how the inquiry-based collaborative approach impacted STEM students' perceived individual (self-regulation) and group (co-regulation) metacognition when they completed the applied research modules as part of their course requirements.

Participants. Participants in this study were graduate students (n=155) enrolled in the Applied Information Technology (AIT) courses at one of the public universities in the Mid-Atlantic area in fall 2022. The students in this study were enrolled in different programs offered by two departments in the College of Engineering and Computing: Accelerated Master of Applied Information Technology (AIT) program, Master of AIT program, Master of Data Analytics Engineering (DAEN), and Ph.D. in Information Technology (IT).

Context. The 16-week AIT courses were designed similarly by following the principles of inquiry-based learning to address the challenges of the workplace by creating a collaborative multidisciplinary research environment for STEM graduate students. Students can take the courses in various order. However, the type of research they are doing is different in each course. The goal of instruction was to introduce students to systematically designed research activities to help them develop collaborative and communicative workforce skills. Students were involved in a scaffolded advanced research experience to solve the real-world problems in the field of data science in STEM. The design of the course modules included the following learning tasks: (1) identify research questions; (2) conduct literature reviews; and (3) conduct research. Each module was divided into sections to scaffold each learning task. Students completed quizzes, online discussions, and peer review activities. By the end of the course, students submitted self-reflections where they shared their research experience, what they learned, what challenges they faced, and what suggestions for collaborative assignment improvement they would offer.

Data Collection and Analysis

The data were collected at the end of the fall semester of 2022 from the 32-item survey in four AIT courses to explore students' perceptions of metacognition during applied research learning module activities. The survey consisted of eight demographic items that we added to collect information about students' characteristics and 24 metacognition items constructed by Garrison and Akyol [28] at the five-point Likert scale anchored by “Strongly Disagree” and “Strongly Agree.” 109 students out of 155 completed the survey with 70.32% response rate. The data were analyzed with descriptive statistics.

In addition, we ran correlation analysis for the survey items. Correlations greater than or equal to 0.85 indicate a high correlation between the question pairs. The correlation was high (0.89) between co-regulation group metacognition questions Q15 (I listen to the comments of others) and Q16 (I consider the feedback of others) explaining that students who carefully listened to their peers’ comments valued their feedback during peer review. Similarly, another pair of co-regulation group metacognition survey items (Q18 and Q19) received a high correlation (0.85). This high correlation between Q18 (I serve the strategies of others) and Q19 (I observe how others are doing) shows that it is very important to provide students with an opportunity to learn from others by observing others’ strategies and how others are doing the tasks. They show that these question pairs are similar, and they can be better designed to allow the inclusion of diverse content.

Results

The first five survey questions asked students about their section, the class format, the program of study, residency, and Bachelor of Science (BS) field of study. The results from Figure 1 revealed that the numbers of students who participated in this study were mostly equal in both online class (50.5%) and in-person (49.5%) formats. Almost two-thirds of the student respondents were international students (61.5%). As for the program of study, 58.7% of students who completed this survey were from MS DAEN, followed by 27.5% from MS AIT, 7.34% from PhD in IT, 2.75% from Accelerated MS AIT, and 3.67% from other programs such as Graduate Licensure Program in DEHD, Graduate Certificate, Exchange Master’s program, and MS Information Systems. The BS field of study of most students were from STEM majors (90.83%).

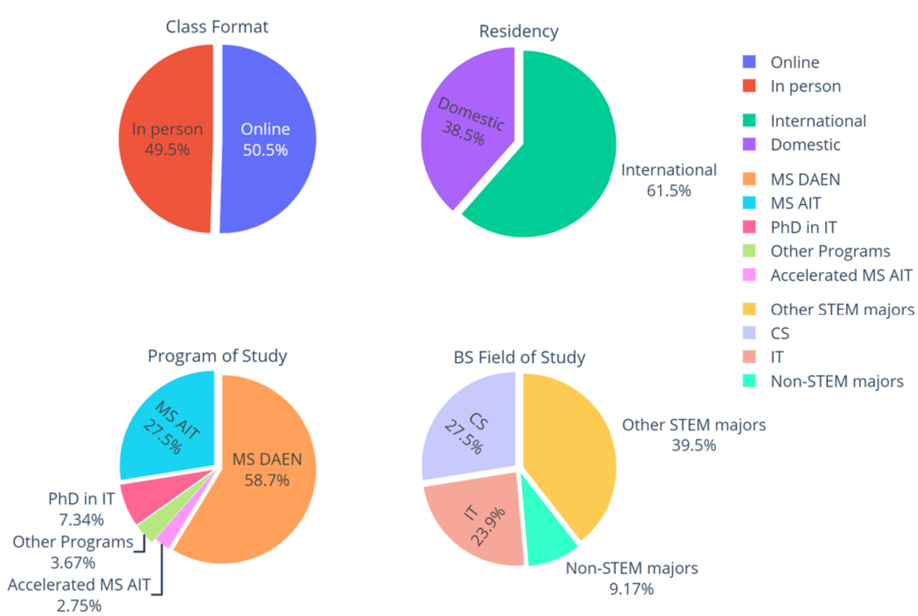

Figure 1. The Score Distributions for all Questions Responded by Students (n=109)

When we examined the distributions of students' response by their average scores for all questions, the results from Figure 2 below show that MS DAEN (M=4.60, SD=0.17) rated highest out of all programs of study, followed by MS AIT (M=4.14, SD=0.24) and PhD in IT (M=3.80, SD=0.27). Both MS DAEN and MS AIT had larger student samples as shown in Figure 1 above, whereas PhD in IT had a smaller sample size (n=8). However, the median for PhD in IT is 3.88, which is close to 4 and means that on a scale from 1 to 5 with 5 being "Strongly Agree", the students almost agreed on perceiving metacognition.

Program of Study	Average	Median	SD
Accelerated MS AIT	3.81	4.00	0.46
MS AIT	4.14	4.17	0.24
MS DAEN	4.60	4.61	0.17
Other Programs	4.19	4.25	0.42
PhD in IT	3.80	3.88	0.27

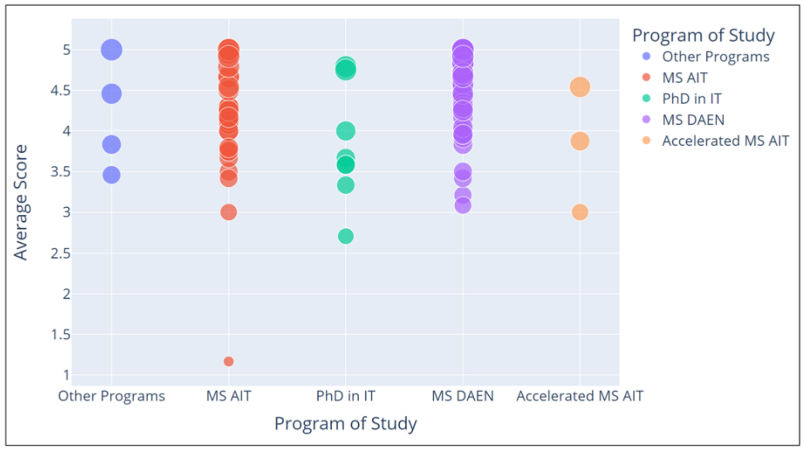

Figure 2. The Distribution, Average, Median, and Standard Deviation of Responded Students' Average Scores of All Questions by Program of Study (n=109)

Research Question #1: What are STEM graduate students' perceptions of metacognition in an inquiry-based collaborative learning environment?

To answer the first research question on students' perceived metacognition, the results revealed that the overall metacognition perception was high (M=4.38; SD=0.89). There were differences between perceived individual self-regulation metacognition (M=4.47; SD=0.78) and group co-regulation metacognition (M=4.27; SD=0.99) showing that students rated their individual learning higher than their learning in groups.

Furthermore, we analyzed students' responses to the 24 survey items on their perceptions of metacognition based on individual metacognition (self-regulation) questions and group metacognition (co-regulation) questions. For all course sections, it clearly indicates that 61% of students reported that they very strongly agreed (score of 5) on perceiving individual self-regulation metacognition while 54.5% of students reported a score of 5 on perceiving group co-regulation metacognition which means learning from others. For a score of 4 to the questions, the numbers of students who perceived both individual self-regulation (27.9%) and group co-regulation (26.7%) metacognition were very close. Above all, the students who gave a 4 or above in the individual self-regulation and group co-regulation metacognition are 89% and 82%, respectively. This demonstrated their overall satisfaction with applying research concepts and methods through both an individual and a group fashions (Figure 3). In addition, these results proved the effectiveness of the inquiry-based learning modules design on applied research.

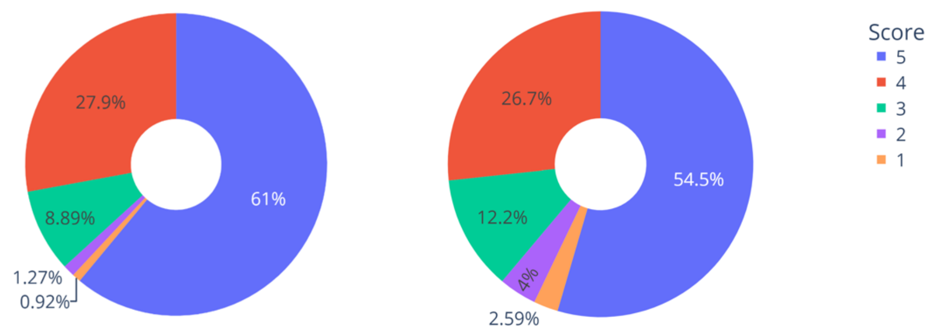

Figure 3. Score Distribution for Individual (left) and Group (right) Metacognition Questions Responded by Students (n=109)

To compare each question related to individual self-regulation and group co-regulation metacognition, we analyzed the average scores of each of them as shown in Figure 4. Q1 had the highest rate (M=4.75, SD=0.56), followed by Q2 (M=4.58, SD=0.74) and Q3 (M=4.58, SD=0.71). The average scores of Questions Q4 to Q20 and Q23 did not vary much, as the values were around 4.40. The means of all students' responses to individual self-regulation questions were above 4.0. This indicates that all students perceived individual self-regulation metacognition better than group co-regulation metacognition, which could be due to the difficulty of online learning since we had more online courses than in-person classes during the worldwide pandemic. This also means that students still learn how to self-regulate themselves first in an inquiry-based environment in order to be able to contribute to the group co-regulation or learn from others. Moreover, three of the average group co-regulation question scores were below 4.0. That is, students did not request much information from others (Q3), monitor others' learning (Q24), or challenge others' perspectives (Q22). This further indicates students collaborated well.

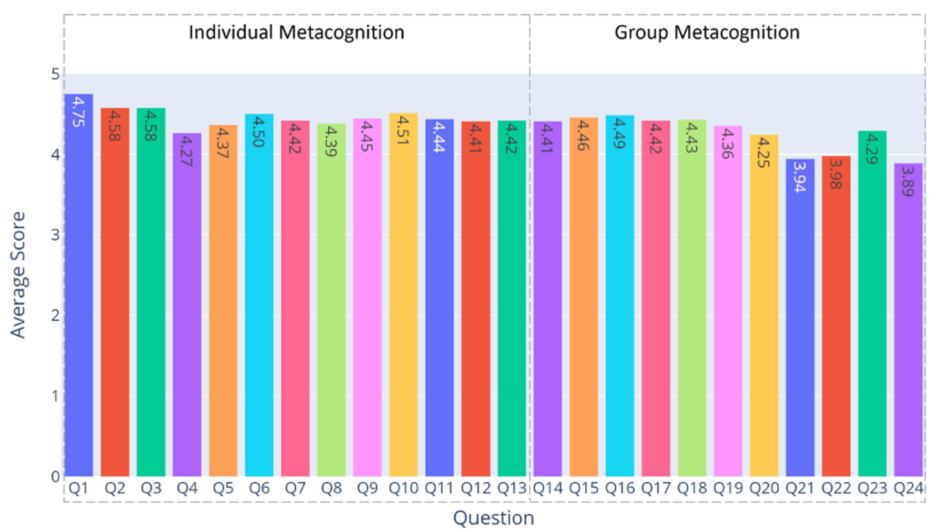

Figure 4. The Responded Students' Overall Average Score of Each Question

Among group co-regulation metacognition, the learning from group feedback (Q16) (M=4.46; SD=0.84) rated as the highest while learning from monitoring others (Q24) received the lowest rate (M= 3.89; SD=1.22). These results showed that it is effective to provide students with an opportunity to help each other in inquiry-based learning. Students need collaborative feedback from their peers, and they need an opportunity to observe the group. When students have these opportunities, they feel more comfortable in ill-structured learning, and they learn for themselves (self-regulation). Their level of anxiety could be decreased when they observe others to make sure that others also make similar mistakes or have similar issues. Among individual self-regulation metacognition, awareness of their own efforts (Q1) received the highest rate (M=4.75; SD=0.56) while questioning themselves (Q4) received the lower score (M=4.27; SD=0.95). These results proved that inquiry-based environment supports students' self-awareness of their own efforts. They learned how to rely on their own efforts and control their own learning to build new knowledge. However, these learning modules may be updated by adding self-reflection at each stage. For example, instructors can ask students to question themselves about whether they learned or not or where they needed to improve. Having these types of learning tasks can help students control their own learning and understand what they need to do in order to be more successful.

When we examined students' responses in comparison with two different metacognitions based on the BS Field of Study, the results revealed that all BS Field of Study individual self-regulation metacognition items ranked higher than corresponding group co-regulation metacognition items in Figure 5, which emphasizes the preference of individual self-regulation metacognition over group co-regulation metacognition. Moreover, we can see that the overall average scores of non-STEM majors are lower than STEM majors. It clearly indicates that non-STEM major students did have difficulties contributing to the group metacognition to build collaborative knowledge with STEM majors. STEM majors rated learning from group collaborative knowledge almost similar to their individual self-regulation preferences. This shows that STEM students did have more competencies to contribute and were more comfortable during group interactions than non-STEM students. To further help non-STEM students, instructors may consider forming groups only for non-STEM majors to minimize difficulties of contributions. However, during the peer review process, instructors may consider mixing groups and assign two non-STEM students to review one STEM student's work. Working together will provide non-STEM students more comfort and opportunities to support each other.

Type	BS Field of Study	Average	SD
Individual	CS	4.59	0.11
Individual	IT	4.40	0.15
Individual	Non-STEM majors	4.14	0.20
Individual	Other STEM majors	4.50	0.12
Group	CS	4.48	0.20
Group	IT	4.13	0.29
Group	Non-STEM majors	3.74	0.26
Group	Other STEM majors	4.32	0.20

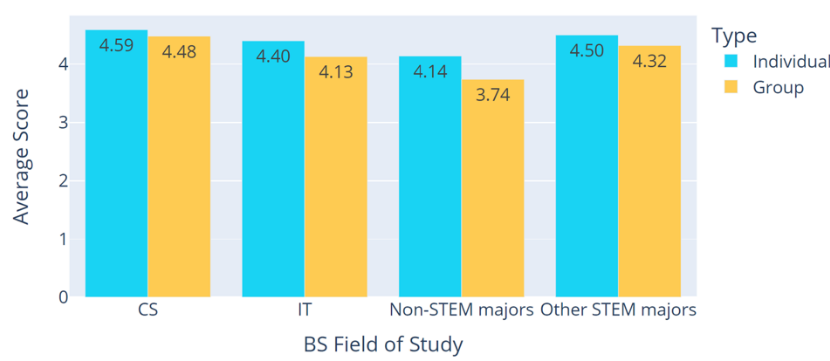

Figure 5. The Average Scores of Individual and Group Metacognitions by BS Field of Study

Likewise, when we examined students' responses based on Program of Study, the results showed that all individual self-regulation metacognition items ranked higher than corresponding group co-regulation metacognition items in Figure 6. Furthermore, MS AIT and MS DAEN had higher ranks for both self-regulation and co-regulation items. Not surprisingly, the average scores of responses from PhD in IT are both lower than 4.0. This is because our current four 500- and 600-level courses in which the surveys were conducted are not designed for PhD students but are rather more generic for all graduate students. These results show that more scaffolding is needed for students in Accelerated MS AIT. For example, similarly to non-STEM majors, instructors may form the groups only for this program. However, during peer review, instructors may mix the groups and assign two students from Accelerated MS AIT to provide feedback for one MS AIT or MS DAEN student. The same scaffolding approach can be applied to students from other programs. More challenging coursework as extra credit can be given to PhD students in the same class.

Type	Program of Study	Average	SD
Individual	Accelerated MS AIT	3.74	0.35
Individual	MS AIT	4.26	0.18
Individual	MS DAEN	4.67	0.10
Individual	Other Programs	4.46	0.19
Individual	PhD in IT	3.91	0.16
Group	Accelerated MS AIT	3.88	0.57
Group	MS AIT	3.99	0.23
Group	MS DAEN	4.51	0.20
Group	Other Programs	3.86	0.40
Group	PhD in IT	3.67	0.33

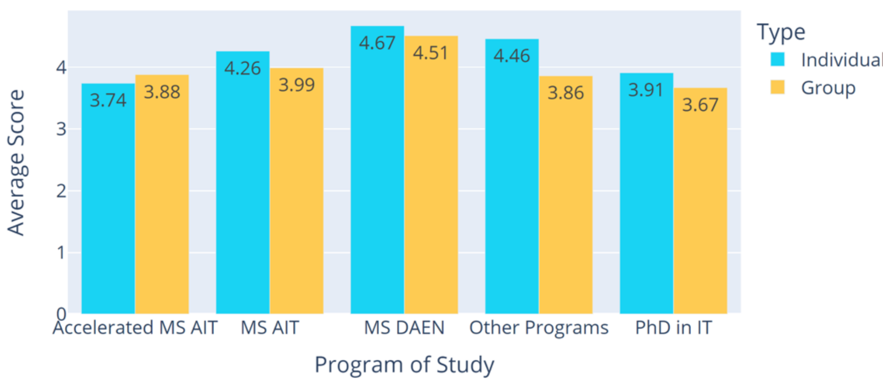

Figure 6. The Average Scores of Individual and Group Metacognitions by Program of Study

When we examined students' responses based on Residency, the results showed that all individual self-regulation metacognition items ranked slightly higher than corresponding group co-regulation metacognition items. Furthermore, domestic students had higher ranks for both self-regulation and co-regulation items. It indicates international students have a better perception of metacognition. However, the sample size of international students is nearly twice the sample size of domestic students (Figure 1). Metacognitive practices can help students become aware of their strengths and weaknesses as learners, group members, etc.

Type	Residency	Average	SD
Individual	Domestic	4.18	0.18
Individual	International	4.65	0.19
Group	Domestic	3.83	0.24
Group	International	4.54	0.20

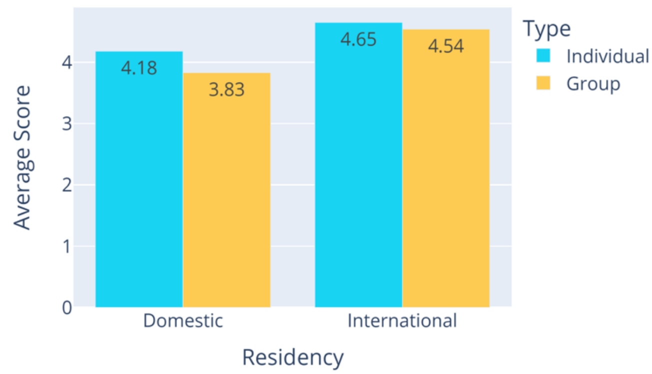

Figure 7. The Average Scores of Individual and Group Metacognitions by Residency

Research Question #2: Are there differences in metacognition across course modalities, i.e., in-person versus online?

To answer the second research question on possible differences between the course delivery modes (in-person versus online), the results revealed that students in in-person courses had higher perceived metacognition (M=4.47; SD=0.2) than online students (M=4.28; SD=0.2). This means that more design considerations of collaborative work should be done to make online delivery more effective (Table 1).

Table 1. The Overall Average, Median, and Standard Deviation (SD) Scores of Students' Responses Based on Class Format

Class Format	Average	Median	SD
In person	4.47	4.52	0.2
Online	4.28	4.31	0.2

When we analyzed the data based on class format (Figure 8), both of the average scores for in-person are higher than the scores for online classes. Additionally, individual self-regulation metacognition scores are higher than group co-regulation metacognition scores, revealing that overall, the in-person class format and individual self-regulation metacognition are preferred by students. Despite that, there are no significant differences between in-person and online (.16 for individual and .11 for group), suggesting that there is no strong preference between the two formats.

Figure 8. The Overall Average Scores of Students' Responses to Individual and Group Metacognitions Based on Class Format

Throughout questions Q1 to Q13 in Table 2, all of the in-person question scores are higher than the online question scores, reinforcing the preference of in-person over online in terms of class formats, which is likely due to the increased interaction between the faculty and students that an in-person class format provides. In particular, questions Q12 and Q13 have the greatest differences between in-person and online. This could be caused by the greater availability of guidance in an in-person class than an online class because online classes tend to feel more isolated, which improves their ability to approach problems and strategize more effectively. But regardless of the class format, the students' awareness of their level of motivation (Q3), their ability to question their thoughts (Q4), and their assessment of their understanding (Q8) are at similar levels. There was no significant difference between online and in person students.

Table 2. The Average Scores and Differences of Students' Responses to Each Question of Individual Metacognition Based on Class Format

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Average	SD
In-Person	4.81	4.69	4.63	4.31	4.43	4.57	4.48	4.43	4.54	4.67	4.52	4.54	4.56	4.55	0.12
Online	4.69	4.47	4.53	4.22	4.31	4.44	4.36	4.35	4.36	4.36	4.36	4.29	4.29	4.39	0.12
Difference	0.12	0.22	0.10	0.09	0.12	0.13	0.12	0.08	0.18	0.31	0.16	0.25	0.27	0.16	0.00

Similarly, all of the in-person format scores are higher than the online format scores in Table 3. In particular, questions Q16 and Q17 have the most significant differences between the in-person and online formats. Since the questions regard the consideration of others' opinions Q16 (I consider the feedback of others) and Q17 (I reflect upon the comments of others), it demonstrates that an in-person class provides a more interactive environment and facilitates direct, face-to-face discussions better than online classes. Interestingly, the differences for questions Q14, Q21, and Q23 are very close to 0. Because these questions are associated with paying attention to others (Q14), requesting information from others (Q21), and helping others learn (Q23), it shows that the material discussed in classes generally do not differ in the in-person and online formats and that those discussions keep students attentive throughout their courses. There was no significant difference between online and in person students.

Table 3. The Average Scores of Students' Responses to Each Question of Group Metacognition Based on Class Format

	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22	Q23	Q24	Average	SD
In-Person	4.43	4.57	4.69	4.61	4.52	4.46	4.33	3.98	4.17	4.33	4.00	4.37	0.23
Online	4.40	4.35	4.29	4.24	4.35	4.25	4.16	3.91	3.80	4.25	3.78	4.16	0.21
Difference	0.03	0.22	0.40	0.37	0.17	0.21	0.17	0.07	0.37	0.08	0.22	0.21	0.02

These results proved the importance of careful design for online formats. Online formats should be enhanced with more support, i.e., office hours or QA sessions. In addition, building community activities can be implemented so that students get to know each other better. Collaborative peer work requires trust and relations. When students know each other, they interact more frequently and are open to learn from each other. For example, the in-class environment itself provides this opportunity, but in online formats, the instructional design should be pre-structured to make it happen. Community building can be added to the syllabus as part of a learning assignment. For example, grouping students for topic search, sharing resources, or any other low-level activities can help build relationships. Forming small groups is always a good idea so that students have the opportunity to contribute equally.

Conclusion

This exploratory study contributed to the field of STEM education and, specifically, to understanding how STEM graduate students learn in shared collaborative learning environments. The findings revealed that inquiry-based online courses with integration of applied research peer review activities need more design considerations, for example, community-building activities to help online students develop relationships and provide frequent timely feedback to help students work together. In addition, to improve the general student performance in online formats, diverse and effective teaching methods as well as interesting course content should be introduced and maintained.

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Appendix - Metacognition Survey Instrument (customized)

Original Version is available at http://dx.doi.org/10.1016/j.iheduc.2014.10.001

24 Metacognition Questions

When I am engaged in the learning process as an INDIVIDUAL while participating in the Research Modules,
Q1: I am aware of my effort.
Q2: I am aware of my thinking.
Q3: I am aware of my level of motivation.
Q4: I question my thoughts.
Q5: I make judgments about the difficulty of a problem.
Q6: I am aware of my existing knowledge.
Q7: I am aware of my level of learning.
Q8: I assess my understanding.
Q9: I change my strategy when I need to.
Q10: I search for new strategies when needed.
Q11: I apply strategies.
Q12: I assess how I approach the problem.
Q13: I assess my strategies.

When I am engaged in the learning process as a member of a GROUP in the Discussion Boards in the Research Modules,
Q14: I pay attention to the ideas of others.
Q15: I listen to the comments of others.
Q16: I consider the feedback of others.
Q17: I reflect upon the comments of others.
Q18: I observe the strategies of others.
Q19: I observe how others are doing.
Q20: I look for confirmation of my understanding from others.
Q21: I request information from others.
Q22: I challenge the perspectives of others.
Q23: I help the learning of others.
Q24: I monitor the learning of others.