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The Critic as Designer: How Metacognition Makes Transdisciplinarity Possible

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Abstract

For students to learn how to address complex problems spanning domains, they need practice in transdisciplinary teamwork. However, practice alone is not sufficient preparation. In order to learn and retain ways of continuously gaining knowledge across disciplines, students must also practice processes of self-regulating their own ways of learning. In the context of a transdisciplinary design education course, we used in-class critique as a type of metacognition instruction. Through thematic coding of student reflective writings, this qualitative study reveals patterns of metacognition that emerged as student teams identified problem spaces, conducted problem framing research, and proposed solutions. Results indicated that while some students were prompted by the critiques to advance in cycles of metacognitive *Knowledge* and *Regulation*, the metacognitive action of planning was largely overlooked.

Introduction

Mono-disciplinary solutions are falling short as we face complex issues (e.g. climate change, housing shortages, medical crises) in a globalized world where individuals with diverse experiences and training work beyond disciplinary categories, often leading to expanded perspectives on daunting problems with socio-technical concerns [1]. As undergraduate students prepare for careers that will involve solving complex problems requiring input from heterogeneous domains, they need practice working in interdisciplinary teams. However, students and instructors face challenges in these settings. Within undergraduate curricula, such learning objectives are often measured as individual outcomes in courses but accomplished through teamwork. In these scenarios, students face challenges in navigating performance of individual skills in groups, and instructors face challenges of assessing student skills performed collaboratively.

Since interdisciplinary structures are not the norm in academia or most formal education, metacognitive skills can be particularly helpful for identifying and improving both *Knowledge* and *Regulation* of learning strategies needed for working in heterogeneous groups. Simply put, metacognition is the process of a learner self-monitoring their own thoughts and viewpoints; metacognition of learning (setting goals, self-monitoring, controlling, and evaluating) helps students understand the ways in which they learn and how they can become better at learning in different situations [2]. In interdisciplinary settings, metacognition may add value in knowledge of self and others, as well as in regulating learning strategies as a functioning team. However, students struggle to accurately report their own learning, and assessment of students' collaborative work is challenging. To address this issue, Cunningham et al. have created a metacognition model that presents a fluid and cyclic process of identifying and acting on indicators of knowing and regulating [3]. These indicators are designed for use by educators and students and can be applied in a variety of learning settings.

One learning setting that takes place across disciplines is the design critique, which is often a central element but is enacted in different ways. Most critique methods provide public appraisal and feedback on an individual's or a team's work, usually with peers present as audience members, and often at points throughout the design process as well as for the end product. Many critiques are structured so that an expert or team of experts evaluates the work, while some critique methods also include peer input. The presenter prepares for the critique with a display of their work and often a narrative or "pitch"; in some critique methods the experts or peers also prepare, based on materials provided beforehand. We believe that these characteristics of critiques can provide opportunities for both presenters and critique-providers to engage in metacognitive behaviors around learning, such as gaining knowledge of self, persons, and strategies, as well as self-regulating their learning in response to feedback. In particular, engagement in critiques can provide insight for students who present and provide feedback as teams.

Building on this logic, we have centrally embedded a critique element for a design course in which students focus on problem framing and ideation in interdisciplinary teams. We are interested in learning how engaging in continuous collaboration and critique with peers and experts from multiple disciplines can promote students' metacognition. We employ two types of critique methods in the course: during the ideation process we introduce and enact Lerman's formative Critical Response Process [4]; at the end of the semester, we use more traditional summative evaluative methods. The Critical Response Process was developed to enable artists and makers to take more agency in generating feedback and thus focus on issues that are important to them at critical points in project development. In many other critique approaches, the feedback often comes from the evaluators' not the creators' perspective and focuses on criteria for the expected end product rather than the design process.

The purpose of this study is to explore how Lerman's Critical Response Process, paired with guided self-reflection, might facilitate the elements of metacognition and transdisciplinary teaming in a design course based in an engineering department and open to students from all majors at the university. The following research question guided this investigation: *How can critique as a pedagogical strategy promote metacognition of learning and transdisciplinarity?*

Literature review

Research that explores transdisciplinarity draws attention to the value of metacognition for advancing students' abilities to both contribute to and learn from working in heterogeneous teams. In addition, there are indications that both metacognition and transdisciplinarity can be taught using formative peer critique processes.

Transdisciplinarity. Collaboration in teams that include members from multiple disciplines entails awareness of differences and synergies between one's own area of expertise and others, both in terms of content and epistemic practices that occur in "seeing one another at work" [5]. This includes not only awareness but also valuing of alternative perspectives, and instruction in transdisciplinary contexts can provide valuable experiences that prepare undergraduates for cross-functional workplaces [6]. Awareness of one's own expectations about concepts, methods, and principles affords transdisciplinary integration for the purpose of reaching a shared goal [7]. This kind of integration includes both bringing together the knowledge and principles of team members from different fields as well as recognizing and engaging in skills and actions that transcend disciplines [1], [7]. Our goal with this course is to reach a level of transdisciplinary collaboration where students are aware of their own and others' mindsets and are able to use and build on this knowledge through metacognitive self-regulation. In other words, a primary learning outcome in the course is for students to be able to learn about ways of learning - in themselves and in others - and to take actions that improve and build upon their abilities in a process of learning to adapt to novel environments as lifelong learners [8]. In terms of metacognition, this entails the metacognitive model proposed by Cunningham et al. as a cycle of *Knowledge* and *Regulation* - 1) increasing one's *knowledge* of learning tasks and strategies, and of other people's ways of learning, and 2) using this knowledge in *self-regulating* actions like planning, monitoring, controlling, and evaluating [3], [9].

Metacognition. Metacognition is the awareness and regulation of one's own learning. Metacognition's origin was in the context of learning in the early 1970's [10]. In this paper, we are focused on the knowledge and awareness of cognitive activities, though other fields have suggested metacognition could reasonably encompass all aspects of psychology [11]. Metacognition of learning develops naturally as children mature and can also be advanced through active instruction and practice, which has been advocated by scholars for decades [11], [12]. In undergraduate contexts, students are likely to have "scripts" for learning that are resistant to change [2]. To address this challenge, Cunningham, Matusovich, Hunter, & McCord created the Metacognition Model (Fig. 1) to characterize the indicators of knowledge of cognition and regulation of cognition that can be observed in students, particularly in STEM classroom settings [3]. Instead of relying on students to report their own practices of monitoring their learning, the metacognition model can be used by students and instructors to classify their descriptions based on the cycle of awareness and regulation as they interact in teams with students from other majors.

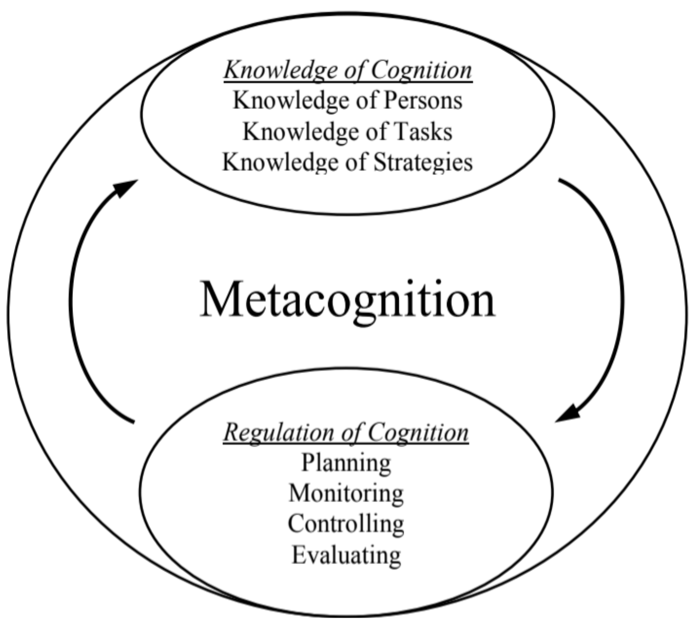

Figure 1: Conceptual Framework of Metacognition
(Cunningham, Matusovich, Hunter, & McCord, 2015)

Participating in transdisciplinary team projects provides valuable experience for undergraduate students, and, according to Tan, Nesbit, Ellis, and Ostafichuk, "Metacognition also plays a significant role in transdisciplinary interactions by enabling individuals to monitor, reflect on, and adapt learning processes in a multidimensional context" [1]. However, many instructors do not intentionally teach metacognitive skills. As noted above, metacognition is the process of a learner self-monitoring their own thoughts and viewpoints, but a deeper look reveals productive metacognitive cycles in which learners use existing knowledge of their own and others' strategies to improve their own performance, leading to further advances in knowledge and improvements in regulating learning behaviors [3].

Critique methods. Improving metacognition is relevant to students in transdisciplinary teams as they learn problem-framing and human-centered approaches, and critique with peers, instructors, and experts from other disciplines may be an effective mode of metacognition instruction. The practice of critique is central to design processes across disciplines, though it is enacted in very different ways. The Critical Response Process (CRP), created by Liz Lerman, provides feedback in formative modes of inquiry and feedback centered on process rather than final products. Lerman constructed multiple roles in the feedback process with the goal of improving students' problem solving abilities and reflection on their own work and on the work of others [13]. In her approach, students have an active role in the critique of their work and experience the connection with the audience that is the goal of artists and designers. The CRP consists of several steps performed by participants in different roles: first, the Artist/Designer presents a work-in-progress and states questions or issues of focus for Responders, who then communicate their understanding of the Artist/Designer's perspective and work through positive statements of meaning and posing neutral questions. The Artist/Designer participates in this process either by answering or posing more questions. Finally, the Responders give their opinion on the project with the Artist/Designer's full permission; the Artist/Designer is fully empowered to decline discussion of a topic at this point in order to maintain their current focus in the creative process. Our study explores how Lerman's Critical Response Process paired with guided self-reflection facilitates the elements of metacognition (planning, self-monitoring, controlling, and evaluating).

Lerman, a dancer and university faculty instructor, originally designed the CRP for art education and it is still not often used in STEM courses. We used the sparse examples of studies of the Critical Response Process to guide our work. For example, Carey and Coutts had music instructors implement the practice one-on-one with students, then performed focus group interviews [13]. The outcomes they observed were a leveling of the hierarchy between instructor and student, with student-led language and greater student autonomy in learning. Tosterud et al. performed a mixed-methods, quasi-experimental study comparing the Critical Response Process and the Steinwachs structure when debriefing a medical simulation with Nursing undergraduate students [14]. Quantitatively, the instructor spoke less when the Critical Response Process was used. The role of the instructor also was less central as all participants focused on the learning outcome. The Responders addressed the Artist directly, instead of filtering through the Facilitator. The focus was learning-oriented instead of goal-oriented.

Overlap. Metacognition has been linked to other team critique methods. The Comprehensive Assessment of Team Members' Effectiveness (CATME) system is an online peer evaluation tool that has been used with engineering teams at multiple universities [15]. The relationships between metacognition, critique, and interdisciplinary teams have been explored in different ways. For example, a study measured the improvements in interdisciplinary engineering teamwork with the CATME when metacognitive exercises are implemented and found that team scores and metacognitive awareness rose for all students that were part of the group projects, regardless of the presence of exercise interventions [16].

Current research is investigating Frame-of-Reference (FOR) training for metacognitive development, as demonstrated by improvements in team and self-evaluation skills [17]. FOR training defines dimensions of performance and gives examples for each, so that team members' expectations are aligned as they begin the project. One study that Loignon et al. are undertaking is the connection between repeatedly taking part in team evaluations and more accurate monitoring of one's self, which is a demonstration of metacognitive learning. They are measuring students' improvement of knowledge of behaviors by having students categorize and rate behaviors, with the correct answers established by the creators of CATME [17].

If students take control of their own learning, as in Carey and Coutts' study [13], an improvement in metacognitive skills might be anticipated. If the students are focused on improving their learning instead of primarily focusing on outcomes, we might expect them to monitor their learning and calibrate methods based on their metacognitive observations. In transdisciplinary settings, these instructional strategies could be effective as students learn to understand and value other perspectives as they practice contributing their own disciplinary and transdisciplinary skills in diverse teams.

Methods

In this study, we performed a qualitative analysis of student reflective writing assignments. Our goal was to understand students' thought processes and metacognition, and we attempted to gain an understanding of that through their self-reported reflections. While the writings were individual assignments, the prompts for reflections asked students to consider aspects of their experiences in their interdisciplinary project team. Therefore, our analysis was expected to reveal both individual and team-level patterns that would help us address the following research question: *How can critique as a pedagogical strategy promote metacognition of learning and transdisciplinarity?*

Setting. This study was performed at a mid-Atlantic research university in an interdisciplinary project-based course that encourages creative thinking and productive critiques. The class met online during Fall semester 2020, using Zoom and other apps to meet and collaborate with peers and invited guests from the community and businesses.

The course description in the syllabus states:

> This course is designed to lead students through the process of creative inquiry, design, and collaboration to explore the nexus of the arts, science, and design. Through activities and discussions students will build an understanding of the ties between multiple disciplines. To identify these ties, students will engage in activities that build participation and questioning strategies for workshops and lectures, problem finding, analogical and metaphorical thinking, and collaboration in multiple formats. The collaboration of students, faculty, and visiting artists will encourage students to explore their own interests as they are situated within the boundaries of disciplines and provide strategies to create and innovate within and among disciplines.

As a central element of the course, students engage in Lerman's Critical Response Process feedback with peers to promote transdisciplinary learning.

Participants. Thirty out of 38 students enrolled agreed to take part in the study, signing consent forms approved by the IRB. They represent each undergraduate year and a variety of majors, including six in the College of Science, thirteen in the College of Engineering, four in the College of Business, three in cross-college programs, and one each in the School of Architecture & Urban Studies, the College of Agricultural & Life Sciences, the College of Natural Resources and Environment, and the College of Liberal Arts & Human Sciences.

Data collection. Data selected for analysis included four individual reflective writing assignments that students completed across the span of one semester (Table 1). The student assignments we analyzed included two Free Writes in which the students took five minutes to respond to suggested prompts; and two longer Reflections on their performance as a group, one at mid-semester during the time when the Critical Response Critiques were occurring, and one at the end of the semester. Although students worked in teams throughout the semester, the writing assignments we analyzed were completed individually.

After the close of the semester, the researchers downloaded all of the assignments, replaced names with anonymous student identifiers (including author and team members), and uploaded the files to a shared Dedoose coding software account.

Table 1

Data Sources: Course Writing Assignments

Assignment	Due Date	Prompts
Mid-Semester Evaluation	10/23/20	1. Your problem, like most problems, is transdisciplinary in nature. What are some of the skills your teammates have brought to helping address this problem? What are some of the skills that you have brought? 2. Overall, how effectively has your team worked so far on this project? 3. What is something specific that you learned from your team that you probably wouldn't have learned alone? 4. Provide at least one change that the team could make to improve its performance moving forward.
Free Write 6	10/29/20	Please submit a 5-minute free write entry in your journal. Set up a 5-minute timer on your phone/computer and write freely for the allotted time. Use the time to reflect on what you're learning (and/or frustrated by) in this class, or other classes. Suggested Prompt: How do you feel that the Lerman Technique is working out for us?
Free Write 7	11/12/20	How has participating in the in-class peer critique process changed how you think about your own project? Did you see

		any changes in the way you considered other teams' projects before and after the critique?
End of Semester Evaluation	12/9/20	1. Discuss the Lerman technique and compare it with the final presentation critique. How did Lerman prepare you for the final presentation style? 2. In hindsight, how do you think the Lerman process helped the class as we come to the end of the semester? Do you think the Lerman technique will have an influence on how you will solve problems in your other classes or in your career? 3. What was the most uncertain point your project team went through? How did your team get through it? 4. Your problem, like most problems, is transdisciplinary in nature. What are some of the skills and knowledge your teammates brought from their discipline to help address this problem? What are some of the skills that you brought? 5. What is something specific that your team learned from you on this project that they probably wouldn't have learned alone?

Data analysis. In the first step of the analysis the researchers used a combination of *a priori* codes drawn from the elements categorized in terms of knowledge and regulation in Cunningham et al. and thematic coding informed by the learning outcome goals for the course [3]. The three authors engaged weekly during the semester to discuss the course in progress and, after the semester, in four cycles in which they each coded the data separately and met to discuss patterns and resolve divergences, identifying and documenting themes. Once the authors reached near consensus, the codes and descriptions were finalized in Dedoose for consistency and ease of reference during coding. The final codebook is presented in Table 2, including the description as it was used in Dedoose during the coding rounds and an example for each code.

In the second step of analysis, the researchers used individual reflections at multiple phases of the semester to construct narratives from the point of view of each of the five teams' progress through their design projects, focusing on metacognitive activities used as they navigated interdisciplinary teaming and participating in critiques. We then analyzed the team narratives and selected three teams to describe distinct patterns. This version of narrative analysis diverges from recent methods suggested by engineering education researchers in that the "story" being recounted and analyzed is that of a group of people, not an individual. The "authorial distance" is low and the use of thematic analysis results in an "authoritarian" view [18]. To mitigate this potential threat to trustworthiness, we have included first-person direct quotes from participants and provided contextual information about the course setting.

Table 2
Final codebook, including adapted *a priori* codes [3] and emergent codes.

Code	**Description**	**Examples**
Metacognition: Knowledge of Cognition		
● Persons (Others or Self)	Knowing about how people process information in general and how you process information in particular.	"We get so zoned in on one path that we can fail to consider many other aspects."
● Tasks	Knowing the cognitive demands of different cognitive tasks.	"I tend to spend a long time on written assignments, presentations because there's always something I could phrase better or do better"
● Strategies	Knowing various ways of thinking about or engaging with different tasks.	"I learned that to get a better result you need to plan it over time and in small increments instead of all at once."
Metacognition: Regulation of Cognition		
● Planning	Taking stock of a cognitive task, to set goals and select initial strategies in balance with knowing how you process information.	"As we move forward, I plan to bring my take to the team and hope that they can see my viewpoint and take it into consideration when we devise our possible solutions."
● Monitoring	Keeping track of progress or issues with performing a task.	"My team was very uncertain early on in the process. We weren't sure what part of the field of [our project] we wanted to get into, and everyone had their own ideas."
● Controlling	Taking action in response to monitoring assessments.	"So we had a meeting and decided that we should completely start over on our project and make our new focus on [our problem space]. And this topic related to all of us very well."
● Evaluating	Assessing how a cognitive task went after completing the task, building your cognitive knowledge.	"Participating in the class peer critique process has developed how I do critique and give feedback. The Lerman technique was very helpful in identifying some of the things I

		was doing wrong in giving feedback. I had some things right with being brutally honest, but I have to remember to praise the good things that people do.”
Transdisciplinarity subcodes emerged that were distinguished by viewing team member contributions in terms of (1) disciplinary knowledge aligned with their majors (e.g., a business major will be good at marketing), (2) domain general knowledge (e.g., organization), or (3) exploring an area outside of their major (e.g., creating graphics for a presentation).		

Results

We report our findings by describing three of the five groups that we identified as exemplifying patterns of metacognition related to interdisciplinary teaming and Lerman’s Critical Response Process. Each of the three teams is described with a brief overview of group membership and activity across the semester, followed by descriptions of patterns related to metacognition, interdisciplinarity, and the critiques.

Team 1

Overview. Team 1 was composed of 5 students with majors in the Science, Engineering, and Business colleges, at levels spanning freshman to junior. In the first assignment we analyzed (mid-semester evaluation), the team acknowledged issues they were having with coordination. They were having difficulties meeting as a group and finishing assignments ahead of time but they did not have a solid plan to address these issues. As they considered their project space, they began to recognize personal and societal connections between mental health and education. They also identified the differences in mindsets and strategies within their transdisciplinary team. When writing Free Write 6, this group had participated in Lerman CRP critiques as Responders but not yet as Artists/Designers. Their comments were positive about the process, and they mentioned that in performing the critique they had learned from other groups different ways to approach competing interests in their project. In the Free Write 7 reflections, after the team had participated as Artists/Designers, the team members wrote that the feedback they received from classmates gave them a new perspective on the viability of their solution, particularly from the point of view of potential responses of their imagined clients. The critique step had helped them to better understand the strategies other groups used to work with the constraints of their problem space, some of which overlapped with their own project. In the end of the semester reflection, the students commented on how the critique had made them more motivated to give and receive the neutral feedback, since it was not discouraging. When working on their final project, they identified a range of stakeholders and changed their design based on how their solution would be perceived from these diverse perspectives, aided by the input from their classmates as Responders. As a group, they noted that they had learned from their early struggles and controlled for deadline issues at the end of the semester by creating a buffer for their assignment deadlines, and they found this strategy effective.

Metacognition. All of the members of this group demonstrated metacognitive knowledge of strategies and progress throughout their project. At the team level, they monitored issues with planning: “Moving forward, we could stand to plan a little better, since we do a lot of work, albeit productively, last minute” (Student 4, Mid Semester). At the individual level, the students also monitored challenges of learning in an online class, “It is so hard for me to pay attention and do work when I have to do most of the educating myself” (Student 15, Free Write 6). At the end of the semester, their discussions showed evidence of controlling their process and evaluating a solution of creating more space in their timeline as an effective strategy. One student explained: “Our uncertainty point was mid semester when all of us were busy with midterms and could not get a chance to interview stakeholders. To mitigate this, we split the work up more efficiently, and had buffer space in our timeline to account for this scenario” (Student 4, End Semester).

Feedback from the Lerman CRP led them to gain a new perspective on their solution and monitor potential issues. They described this progression by saying “At first, I thought our idea of implementing a robot for people with mental health issues in rural areas was a great idea, especially if they are really far or unable to get to one. But some people from other groups criticized our idea saying they wouldn’t be comfortable expressing their thoughts and emotions to an object or rather something not alive. That made me actually rethink our idea and realize it may not work out for everyone, but it still could be a good solution or temporary solution to say the least" (Student 15, Free Write 7). This reflection on “rethinking” shows that their knowledge of other persons’ perspectives (both peer learners and potential users) had an impact on their final product. At the end of the semester, this kind of monitoring led to the identification that this was their largest issue, leading to actively controlling their response “How we got through the problem was that one day, we met through zoom and listed out ideas to each other. What we thought of while listing ideas was what we would want if we were in the situation of a person who needed to talk to a therapist but was too far physically to get there. It really helped when we put ourselves in the shoes of the people we are creating the solution for” (Student 15, End Semester). Another student described the entire process as consisting of monitoring, controlling, and evaluating: “The most uncertain point for my team was when some of us came to the conclusion that our product had not developed up to our expectations and seemed very simple and similar to our original idea, this happened in the very late stages, but led to us adding the hotline aspect to set it apart from other products and even toys” (Student 24, End Semester). The critique process seemed to promote metacognitive knowledge that led to regulation of their cognitive approaches as they learned about product development.

Transdisciplinarity. This group showed a combination of transdisciplinary behaviors. For example, Student 24 used disciplinary experiences to control issues they identified: “I liked the idea we came up with but didn’t like how we were trying to market it, so using business skills developed in other classes I helped to reinvent the way we would present and market the product” (Student 24, End Semester). Student 15 also invoked the team members’ varying disciplinary knowledge: “I think each one of my team members brought in a different thing from their unique discipline. I think Student 4 brought in his technological and science background into coming up with how [our project] works... Student 24 brought his science background to help with the idea of [our project] . What I brought in was my psychology background by recognizing how people would react to each idea we added on to our solution and if people would buy into it or not” (Student 15, End Semester). This knowledge of other ways of knowing and awareness of disciplinary differences allowed them to select strategies that suited their skills.

Since the group members did not have prior experience in their specific problem space, they also identified transdisciplinary differences that were not specific to domain knowledge as situated in disciplines or majors. For example, one student noted that in terms of discipline-specific knowledge, "The interdisciplinary component in all honesty was not very helpful from our knowledge standpoints, but from our mindsets" (Student 4, End Semester). Student 15 identified their own collaboration style in terms of what they contributed to the team: “I think something specific that my team learned from me in this project is that even though I may not be the most talkative in the group, I can still help give ideas after I hear everyone else's thoughts on a problem. Just because someone isn’t the active speaker doesn't mean they don't have ideas to contribute” (Student 15, Mid Semester). Student 4 highlighted a nexus point in their own background: “As a neuroscience major, I see things very scientifically and methodically, but also as a business owner, I see a customer or patient’s need as the number one priority” (Student 4, Mid Semester). With experiences in multiple domains and a knowledge of self, they were able to contribute a transdisciplinary approach to the team’s process.

Critique. By taking on roles of both Artist and Responder, the students learned to withhold judgement and think through their solution: “Due to the organized structure of the technique, it helped me think in a more step by step way instead of trying to immediately come up with a solution. I learned that to get a better result you need to plan it over time and in small increments instead of all at once” (Student 15, End Semester). They observed changes in their own mindsets and demonstrated a knowledge of self: “As for other teams, the critique allowed me to think with a more neutral stance, preventing my biases from entering” (Student 4, Free Write 7). They also noted that all feedback was more appreciated because of the Lerman approach: “Having a facilitator made the whole process run smoothly and removed the stigma of giving unwanted advice in an attempt to be helpful” (Student 24, End Semester).

When acting as the Responders, the group described monitoring practices of observing other groups’ approaches to improve their knowledge of strategies, specifically “In this vein, I liked learning about other teams’ progress and how they went about compiling data for their project. Especially with the [topic] team, I liked the breadth with which they conducted their interviews, looking on both a national and local scale. I think we could benefit from this as well, and frame our questions to our “clients” in this manner” (Student 4, Free Write 6). They observed the issues that other groups were monitoring and used this to improve their knowledge of tasks as related to their own topic: “Participating in the peer critique process has primarily served the purpose of helping me understand others’ thought processes. In particular, it is interesting to see what parameters and constraints other people are working with. These challenges are not unique to these groups either – they are simply forms of bigger challenges such as monopolies and regulation. Especially in the field of medicine, both loom large over smaller, newer healthcare solutions. Thus, I have found a new name and entity to the problems we might face in the future with [our project]” (Student 4, Free Write 7). By the end of the semester, they acted on their new understanding gained through monitoring their own progress in relation to their peers’ and potential users’ perspectives by changing their presentation approach: “The Lerman technique helped to even get to this functional stage, and now that we understand how the audience sees our solution, we could adapt our presenting style accordingly for the final presentation” (Student 4, End Semester).

Summary of Team 1. These reflections reveal a metacognition cycle between *Knowledge* and *Regulation* of cognition. Team members became aware of design processes through their own work and seeing their peers' strategies in the critiques - not just through passive observation but through engaged roles as both Artist/Designers and as Responders. Monitoring, controlling, and evaluating were clear ways that the team acted on the knowledge gained through the critiques. The critiques provided a pedagogical vehicle in which the teams learned not only by observing but also from actively monitoring and evaluating their own approaches and their peers. The team members also reached awareness of not only interdisciplinary teaming in which they each contributed through skills gained in their disciplines, but also at a transdisciplinary level in which the contributions were not as much domain-specific but rather "mindset." As our own team of researchers analyzed this cycle of student metacognition, however, we noted the absence of one of the sub-components of Regulation of Cognition - planning.

Team 2

Overview. The second team consisted of two students majoring in business and three in engineering. They immediately recognized the differences in mindsets but seemed unsure about what that would mean for their project. At the beginning of the semester, the group members showed low levels of metacognitive observation. When they were able to identify issues, they struggled to control their responses. They also gave unspecific evaluations of their team and work styles. They had positive impressions of their group and the CRP critiques but did not specify actual benefits. However, when it was their turn to give feedback as Responders, they became aware of the multiple stakeholders and approaches of the other teams, and they used this experience to change their own data collection plan. They formed a system for using each team member's relevant skills in the brainstorming and feasibility aspects of the project. After this turning point sparked by their participation in the CRP as Responders, they gained the skills to better monitor problems during their project, control for them, and thoroughly evaluate their process and team members.

Metacognition. In the mid-semester team evaluations, before the critiques, the group members had positive but vague evaluations of their team. One said "I feel that we don't need to change anything for my team because I feel that we already have a good dynamic in working together and are able to do the best we can to achieve/finish projects...There isn't really one specific thing that I learned from my team that I remember" (Student 17, Mid Semester). At the end of the semester, the same student still had positive impressions of their team but was able to specifically identify what skills had made their work successful and even described intentions to use these skills in the future: "Overall I feel that the most important thing I learned was, communication is the key to success. This is because most of my other classes do not involve group projects; it is an individual assignment. So this class gave me better experience on expressing when I can be available, what I can do for my group, everything that I need to learn on how to collaborate and communicate efficiently" (Student 17, End Semester).

Early on, another student monitored a potential issue in their team's brainstorming process but did not have a specific plan to control for it besides spending longer in discussion: "For improvements in the future, I would like us all to take more time to create concise ideas and not fall into repetition in our solution formulation" (Student 23, Mid Semester). Similarly, another student identified an issue that they were personally having with deadlines but wanted the instructor to solve the problem, instead of seeking a solution to control for it by adopting a new monitoring practice of checking the course site regularly: "I believe, however, that some assignments (like these free writes) sneak up on us without warning and could be missed without constantly checking the Canvas site. It would be nice for us to have a reminder either in class or via announcement when some of these assignments that are not talked about in class are due" (Student 28, Free Write 6). Later in the semester, the students showed evidence that they had improved their ability to respond to issues they had knowledge of by taking action to address them. For example, one student described an instance of the team responding to new knowledge of tasks and then evaluating their team's actions: "Our solution focused on addressing the problem statement. The concerns that many of the panelists were bringing up were asking about the logistics of how we would implement our solution which caught us off guard. However, I think our team handled it well. In a team meeting, we addressed these concerns and added our response to our Portfolio Part II presentation" (Student 28, End Semester). This example shows how, even though the students were monitoring their work (by "addressing the problem statement"), they were missing an important component. With this knowledge gained through the CRP they were then able to evaluate their process and make changes. Another student described their response to feedback in a way that further highlights a cycle of monitoring and controlling challenges resolved by applying knowledge gained from the CRPs to evaluate and iteratively improve: "We had some issues with narrowing our scope to a definite area/problem space. To find our answer, we used the responses from our classmates and teachers to refine our ideas and took each other's input to find our example area" (Student 23, End Semester).

Transdisciplinarity. Team 2 primarily made disciplinary observations about their group by comparing their business backgrounds and engineering backgrounds. From the beginning of the semester, one student observed the interdisciplinary contributions of perspectives when it came to addressing their problem space, along with the transdisciplinary skills that related to teamwork: "As an engineering student, I think that I bring an analytical mindset to break the problem down into its core components to further analyze their importance overall. [Student 28] and [Student 17] also bring those viewpoints to the table as they are also engineers, whilst (another student) and [Student 19] bring a more personal or business perspective. Everyone has used many social and analytical skills to address our problem with cooperation being a key focus" (Student 23, Mid Semester). At the end of the semester, the same student again pointed to the process of creating their project and how team members used their specific disciplinary strengths: "My team used its business and engineering backgrounds to address the problem in a systematic yet reasonable way. The engineers of the group (including myself) used our more scientific backgrounds to devise a plan at our problem space that will solve the overall problem in several different ways. Then our business group members took our idea and made sure whichever option we chose was financially feasible for an array of applications" (Student 23, End Semester). Interestingly, while the engineering and business students were bringing certain approaches to a problem space, they were also working in a transdisciplinary mode that stems from focusing on the problem space and entertaining multiple ways to frame and address it.

This team had students from each year of university. One student grew in awareness throughout the semester of their own unique perspective as a freshman. Initially, they wrote generally about each student's perspective by saying "since we all come from different majors and in different years, we learn from each others' experiences and knowledge. This enables us to approach our problem in different ways and have a variety of perspectives" (Student 17, Mid Semester). At the end of the semester, the same student identified their own role and knowledge of strategies more specifically: "Because I was the only freshman in my group and living on campus I was able to give my group insight on how Virginia Tech on campus is addressing COVID-19" (Student 17, End Semester). An older student in the group also cited this experience as a strength "I believe that [Student 17] brought a unique set of skills to the team as a freshman in general engineering by getting a 'freshman in college' experience to our COVID-19 problem" (Student 28, End Semester). Though some upperclassmen may not see the advantages of working with a first year student, this group was aware of the perspectives group members were bringing and leveraged them into strengths.

Critique. This group was one of the first to present their initial progress and receive CRP feedback, doing so between writing the Mid-Semester Team evaluation and Free Write 6. Their initial impressions were positive from the Artist/Designer's perspective, but did not include information about how their project would be affected: "I believe that there are some good ideas with using the Lerman technique, such as forcing the presenters to ask questions to receive feedback. I also like the idea of the reviewers being tasked with giving feedback with the permission of the presenter. At first it seemed awkward, but I understand now that presenters should have the option of receiving pointers/comments about their project" (Student 28, Free Write 6). The CRP critique process led this group to engage in rare instances of planning. One student decided that the team should broaden their approach and planned to explain their insights to the team: "Considering the feedback and how we can apply our solution to a widespread problem, I think that being more general in our approach can prove to be more effective in the long run. As we move forward, I plan to bring my take to the team and hope that they can see my viewpoint and take it into consideration when we devise our possible solutions" (Student 23, Free Write 7). The students' knowledge of strategies and planning improved when they offered feedback as Responders as well. One student stated that "Participating in the design review has allowed me to better understand other projects as well as my team's project. One main way that the way I've considered other team's projects has changed is when each team explained their data collection plan. I thought that understanding how other teams collect their data really helps me understand their stakeholders as well as their problem statement" (Student 28, Free Write 7). The critique process enabled this group to better take stock of the project and change their strategies before beginning their final project.

At the end of the semester when they were reflecting on their process, the students were able to identify the impact of CRP on their own monitoring abilities and knowledge of tasks. One student used feedback to evaluate and improve their team's plan for collecting data: "Understanding and experiencing the Lerman Critique Technique has absolutely changed the way I think about our case study. Upon reading the critique I came over a question for inquiry regarding the process we will use in order to collect data from our first stakeholder, the people of Blacksburg. My first thought was immediately google form, however, I then came to realize there needed to be an efficient way to reach out to members of Blacksburg regarding this form" (Student 19, Free Write 7). At the end of the semester, a student reflected that gaining knowledge from Responders about their strategies changed the way the team approached the final presentation: "Using this technique during the Portfolio Part 1 and Mid-Semester presentation allowed our group to understand the problem statement from the perspective of our peers.

Specifically, I remember our peers gave us the great idea of investigating how a solution we come up with at Virginia Tech can be scaled to other businesses. This helped us brainstorm solutions for our problem statement as well as prepare for the feedback from the panel of judges during the final presentation" (Student 28, End Semester).

Summary of Team 2. The metacognition cycle that is most apparent in these students' reflections is one of comparing *Knowledge* practices between their own and other teams, and then applying that knowledge through *Regulating* activities. Like Team 1, the students in Team 2 benefitted from the CRP in roles both as Artist/Designer and of Responder. Both roles engaged students in metacognitive activities of recognizing knowledge of persons, tasks, and strategies and evaluating their own and others' learning processes. Through the critiques the students became aware of other approaches to learning about design; specifically, the critiques demonstrated for the students the importance of considering multiple viewpoints when framing a problem space and identifying and evaluating potential solutions. Although there was not much evidence of continuous monitoring in this team in terms of keeping track of learning during the project, at the end of the semester the students evaluated their own processes against those of other teams. Noticing differences, they engaged in the controlling activity of revising their presentation approach. In a similar way, one student even used their knowledge in an intention to plan.

Team 3

Overview. Team 3 was a group of four engineering and one business students. Their project area aligned closely with their disciplinary backgrounds and they viewed themselves as having similar outlooks on the project. This led them to struggle to engage in transdisciplinary thinking. Even before the CRP, the group showed monitoring and controlling abilities. They found an issue with their data collection and drew on disciplinary knowledge to find a solution. When the CRP took place, this group initially acted as Responders. They had difficulties adapting to giving neutral feedback. After their group presented, they found some of their feedback to be helpful but did not make any big adjustments based on the process. By the end of the semester, several of the group members were dissatisfied with the critique method and found that there were other aspects of the project that had taught them more and that input from their stakeholders was more impactful than their peers.

Metacognition. This group demonstrated metacognitive monitoring and controlling before performing the CRP critique. For instance, at the beginning of the semester, they recognized an issue in their data collection process and then as a team collaborated to automate this task. One student stated: "One specific thing I have learned from my teammates is not to work hard but to work efficiently," and described an example of a controlling activity of putting it into practice and knowing that they could apply this new method when planning similar projects: "I was able to do the first 100 on the spreadsheet, but it was very time consuming and tedious. Student 8 then showed me that you can code in excel that would produce the data we needed automatically, which saved us a lot of time and was very cool to see the process to get that certain code. Now I know for the future what I can do if I need a lot of data and do not want to spend large amounts of time to type all the data in manually" (Student 3, Mid Semester). Student 8 described how much they learned from making this improvement: "This has led to my teaching myself how to build improved concurrent web scrapers that can use proxy servers. I've played around with web scrapers before but never bothered to make them handle multiple requests at the same time, but the site we're getting data from is intentionally slow to load so concurrency is important to pull data" (Student 8, Mid Semester). This example demonstrates metacognitive *Knowledge* and *Regulation* that led to adaptive lifelong learning.

When evaluating their team, however, there were mismatches in the perception of the quality of their communication and cooperation. One student described their experience early in the semester: "I don't think we have effectively worked together much. For the beginning of this project I felt as though I was speaking to an empty room because I was not getting responses or people to meet in a Zoom call to deal with assignments" (Student 16, Mid Semester). In the same assignment, another student recognized a similar issue but came to the opposite conclusion: "We have worked really effectively when we have time to get together. It has been difficult sometimes to bring the team together as a whole, but when we do the assignments are completed very quickly" (Student 8, Mid Semester). Another student demonstrated planning when it came to future approaches to this problem, but did not explain whether they had followed through: "Currently we just message ... and we usually receive these messages very late. I would like if there was some alternative poll around an hour before the meeting that checked in with everyone to see if they could make the meeting" (Student 25, Mid Semester). Although this knowledge of persons and strategies was clear at mid-semester, in their evaluations at the end of the semester the students who had struggled with the team's communication did not explain whether anything had changed.

Transdisciplinarity. This group did not have an opportunity to grow in their transdisciplinary thinking in the same way as many of the other students did. Four of the five students on this team came from similar engineering disciplines and their topic was in the same field. Instead of learning about an unfamiliar problem space, they primarily split up the work based on existing skills aligned with disciplines, which seemed to limit their growth in transdisciplinary thinking: "One of the data analytics majors was able to very quickly gather all of the data we needed and used his skills to analyze [the data]. The electrical engineering major was able to understand how the radios worked and explain it to the team overall and figured out how complicated it would be to setup such a system in more remote areas. The computer science major was able to find information on stakeholders and understood how the networking side of the network was setup" (Student 21, End Semester). Two of the students thought that their disciplinary similarities extended to their mindsets: "I think most of group members were of similar majors so our thought process for taking on the issue had a consistent approach from all of our group members" (Student 25, End Semester), and "Our team had very similar disciplines...because of this we had very similar approaches on how to work through the problem" (Student 21, End Semester).

The non-engineering student had a business background. The engineering students found this disciplinary difference helpful in bringing in presentation and other non-technical skills. One student described this contrast as: "Many of the team members are from a technical background [...] but we have one team member who is in business and he has been able to bring different ideas and viewpoints on who to contact. He also has had better ideas about making the submissions look good" (Student 8, Mid Semester). The business major student described how their own strengths in marketing fill a gap in the team, and their lack of technical knowledge compared to their peers: "The skills I bring to the project is, though not knowing as much as my teammates, being a business major and having the skills of public speaking and interacting with people, I am able to make our assignments looks presentable and enjoyable for the viewer to listen and understand our material to the best of their ability" (Student 3, Mid Semester).

Perhaps due to the amount of work required, the engineering students did work with the business major on the presentation. One student identified that even though the engineering group members were all familiar with the topic, to bring together the project some would have to take on non-technical roles. They characterized their part in making the final deliverable as an exploration: "The biggest thing is that because everyone in our group has similar strengths in our group it forces a lot of us to explore and try and learn and do more things to help contribute to the group. I have no history with music editing but decided to take on the responsibility of cutting and editing our podcast to make individuals sound better as well as add an intro" (Student 25, Mid Semester). Similar to projects in the workplace, they realized that almost no one works in a technical problem-solving space all of the time.

Critique. Initially, some of the students in this team were hopeful that the CRP feedback process would be effective. The Responders' questions led the team to rethink the scope of their solution: "By participating in my in-class peer-critique this week, the questions asked by my peers have really changed how I look at the solution for my project. When viewing others as well as hearing the questions and advice from my peers, I saw that doing [this project] even for just the state is too large of a scale and impossible to truly develop a solution" (Student 3, Free Write 7). However at the end of the semester, the same student did not find the feedback to be as effective as they had anticipated: "In hindsight, I believe the Lerman technique did not help us as much as we hoped by the end of the semester due to the questions being answered, the comments and opinion from the other classmates would not truly be applied to the project since it was the final presentation which means from that point on, most students will not try to change their project due to the fact that someone had an idea on their critique" (Student 3, End Semester).

Even when the students saw benefits in the CRP critiques, it was not differentiable from typical feedback that might be provided by grades or instructor feedback: "The way the Lerman technique prepared in such a way that we knew what the problems were in our previous proposals. The portfolio critiques really helped guide us in the direction to properly complete our final presentation" (Student 25, End Semester). Another student found one area of feedback helpful but did not think the process changed their metacognitive perspective: "I don't believe my view of other projects or my own directly changed from seeing all the projects. However, the feedback that we received has allowed my group to understand that we might need to focus more on collecting data that has already been gathered and understand the reasons a company may not be in an area" (Student 16, Free Write 7). The feedback showed them issues in their project and they made the necessary improvements, which is standard for project critiques.

The students had differing opinions on the neutral feedback element. One student thought that the technique would be useful in future critiques: "I do believe however this technique will affect decisions I make in my other classes now or even in the future, since it truly is a helpful tool. This technique will allow me to not judge people's work if I am peer reviewing but ask questions that have no opinion whatsoever and provide them so it can help whoever provides a more clear and pressure project/idea" (Student 3, End Semester). Another student saw the general benefits of neutral feedback but did not have a high opinion on it for themself: “The Lerman technique seems to allow for a certain amount of failure when proposing solutions to problems due to the main use being that of receiving feedback in a neutral manner. I personally don’t appreciate neutral feedback as it always feels as if it had to be worded different as to not offend or provoke emotion” (Student 16, End Semester). A third student did not see issues with their mindset coming in and had no plans to change in the future: “I don’t necessarily think it will affect how I solve problems in other classes. I think I still have a very logic-oriented approach to taking critique and giving advice” (Student 25, End Semester). Overall, this group had mixed opinions on the CRP critique. Their main improvements came from ideas they learned outside of class: “From our first interview, the one I set up, I learned about the Virginia Wireless Telecommunications Act which became a large hurdle for solutions from companies and municipalities. If not for this interview I don’t believe that any of us would know about this act and all solutions that we would have formed would have failed from the word go” (Student 16, End Semester).

Summary of Team 3. In some ways, this group demonstrated metacognitive activities of monitoring, controlling, and planning before engaging in the CRP. They quickly identified their problem area through a disciplinary lens that was common to four of the five team members, and this commonality enabled them to assign tasks and share knowledge rapidly and effectively. However, a clear cycle in which they used knowledge to inform metacognitive activities was not discerned. According to their self-reports, they did not engage in the CRP in ways that are likely to change their learning and design processes in future projects. Notably absent in their reflections were comments about learning from their roles as Responders. In fact, when summarizing their engagement in the CRP, they focused on receiving feedback from their peers rather than the experience of analyzing other group processes and providing feedback. While one student did note the need to explore beyond their own comfort zone in helping the business student with the presentation, it may be possible that this nearly mono-disciplinary team did not push each other to think in different ways.

Discussion

The students in this study who participated in critiques and course reflection assignments demonstrated that the CRP approach offers opportunities for increasing metacognitive practices of *Knowledge* and *Regulation* of learning as individuals and as transdisciplinary team members. Analysis of their self-reports provides evidence that acting in roles of both Artist/Designer and Responder affected their strategies for completing collaborative projects in the course. However, this investigation considered the concept of “transdisciplinarity” at a rudimentary level. Going forward, more ambitious goals will be set for the pedagogical impacts of metacognition within a framework more aligned to conceptualizations of transdisciplinarity as a critical response to individualization and singular disciplinarity within the university. In Klein’s framework, for example, transdisciplinarity is composed of three “discourses” that instantiate practices of *transcendence, transgression,* and *problem-solving* [19]. Transdisciplinarity as transcendence is a way to bring unity across increasingly fragmenting disciplines; as transgression it resists existing systems of knowledge production that are reductionist and positivist; lastly, as a discourse of problem-solving transdisciplinarity fluctuates between cultivating individual competencies and the need to apply the university’s strengths to address grand societal challenges through large-scale projects and innovation.

As future research examines metacognition and interdisciplinary teams, the power dynamics between majors should also be considered. For example, there was evidence from the nearly mono-disciplinary Team 3 that engineering was perceived as the most valuable major for team members to have, even by the single non-engineer on the team. These power differences often exist at the faculty level as well [20], so the classroom culture regarding disciplines should not be overlooked as the role of students in other majors continues to be investigated. Since there are indications that CRP reduces the power differential between instructors and students, future research could examine whether it has a similar impact on disciplinary differences.

Any discussion of power dynamics should also include examining the roles that race, ethnicity, gender expression, persons with disabilities, and other visible and invisible identities play in transdisciplinary collaboration. Students are more than their disciplines, and future studies will explore how this intersection of identity features into transdisciplinary student teams and pedagogical practices. In addition, research cannot be divorced from the identities of the researchers [21]. In this study, the research team consisted of four white academics, including a full professor, a professor of practice, a postdoctoral associate, and a graduate student. While each has an interest in increasing collaboration across academic silos, particularly in classrooms with engineering students, their differences in experience and rank hold levels of privilege that play a role in how they are positioned to view the impact of educational interventions. Their full positionality statements can be found on their professional websites.

Finally, the dimension of critique that often first comes to mind - *criticism* - is also tacitly present in the current investigation. Lerman's approach to critique was adopted explicitly because it holds promise as a productive and constructive way for students to learn to critique themselves (through practices of metacognition) as well as their peers from a place of care. Future study will include comparative perspectives.

Conclusions

In this initial study of potential relationships between formative critique as instruction with the potential to help students gain metacognition skills and transdisciplinary teaming skills, we investigated the research question, *How can critique as a pedagogical strategy promote metacognition of learning and transdisciplinarity?* Student reflections in all three teams indicated that receiving peer feedback as Artist/Designer in the critiques contributed to students reflecting on their own knowledge of tasks and strategies as well as about others' ways of learning. Since the critiques were conducted as teams, students reflected both on their individual contributions and on the progress of their teams. All three teams showed evidence of using knowledge gained from peer feedback in critiques to take self-regulating action in their own work or the practices their team followed. However, only two teams indicated robust engagement as Responders and indicated learning from that activity. One of these team members described planning activities, a self-regulation element that was sparse in the data. The third team did not describe their roles as Responders in detail, and members of this team stated that they would not be likely to change their approaches in the future as a result of the critiques or the course experiences. This team had the least disciplinary diversity, with four engineering students and one business student.

We found that critique as a pedagogical strategy in and of itself was relatively effective at promoting certain aspects of metacognition - namely knowledge of self and knowledge of others. The practice of participating in critique not only as a presenter but also as a critiquer provides students with a platform to examine other students' work on a problem under which they themselves have worked, essentially providing a parallel path to solution. Students can then examine how they themselves accomplished a task in a parallel but different manner than a peer. Without proper scaffolding, however, elements that are at different points of the metacognition cycle, such as controlling and planning, are not addressed through the critical response process. Our implementation of the CRP process focused on the teams' work at a mid-semester production point and not on the process to arrive at the final work. That is, our presentations were structured to present an overview of the created work and aspects of the consumers of the work. Students were not tasked with presenting elements of planning or controlling in their assignments. The lack of course-directed focus on the importance of these aspects could be a part of the reason why students did not seem to advance in the planning aspects of their learning. Simply put, students were not presented with the opportunity to examine the parallel paths of the design process and project completion using the Critical Response Process technique.

Building on these early findings, we plan to incorporate more Critical Response Process critiques in future offerings of the course. During our analysis of the data, we noted that the writing assignments paired well with the critique activities in that they were instances of reflection that supported metacognitive activities of *Knowledge* of learning strategies and tasks, both of their own individual and team practices and in the regulating activity of evaluating and observing other teams. The pairing also supported *Regulation* activities. In order to encourage students in the self-regulation activities of planning and controlling, we plan to capitalize on the strengths observed in diverse teams engaging fully in both roles of the Critical Response Process with aligned reflective writing prompts.

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