MindYoga: Scaffolding the Metacognitive Reflection Process within Learning Ecosystems

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ABSTRACT

To learn how to self-direct research, students must learn to reflect and improve upon a diverse set of metacognitive skills. Models like Agile Research Studios (ARS) provide ecosystems of tools and processes designed to help students hone their reflection skills as they practice research. However, students still struggle to enact their reflection processes across the supports available to them, as mentors coach them to do. MindYoga integrates a process framework that helps students monitor and enact their metacognitive reflection process across an ARS ecosystem. Findings show students using MindYoga were (1) able to monitor which metacognitive risks may affect their upcoming project work, (2) able to develop action plans based on mentor feedback to address these risks, and (3) actively reminded of their action items during relevant practice sessions. Moving forward, process frameworks like MindYoga can help learners develop and improve their work processes as they practice within learning ecosystems.

CCS CONCEPTS

• **Human-centered computing → Collaborative and social computing systems and tools**; **Interactive systems and tools**.

KEYWORDS

Metacognition; Reflection; Learning Ecosystems; Agile Research Studios

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1 INTRODUCTION

For novice student-researchers, learning to reflect on their ways of working is fundamental to improving how they learn, practice, and approach new problems [1–3, 13]. Researchers agree that reflection is an essential skill that drives metacognitive development in expert learners [10–12]. Literature suggests that expert learners enact a metacognitive reflection process, where they monitor, evaluate, and focus their ways of working as they practice. For example, an expert learner may identify that they often forget upcoming deadlines, which means they are frequently rushing to complete their deliverables. They may address this by introducing the use of a planner, sprint log, or to-do list to their work processes. Agile Research Studio (ARS) introduces a learning ecosystem for student-researchers that is designed to develop these metacognitive reflection skills as they learn to self-direct research work [18]. ARS scaffolds the reflection process through a series of tools, venues, social structures, and processes (i.e. a metacognitive goal setting process at the start of term, a weekly meeting for planning feedback, a mid-term and end-of-term self-assessment tool, an end-of-term metacognitive reflection feedback session). Together, these components weave together as a subsystem, designed to scaffold students in metacognitive reflection as they practice research in the ecosystem.

While learning ecosystems like ARS may provide a rich set of supports to help students practice metacognitive reflection, we have observed that students still struggle to monitor and improve their metacognitive process across all of the supports available to them. This occurs because students often lack awareness of the risks in their metacognitive practice and how to practically address these risks as they work. Prior work has produced systems that are designed to improve students' metacognitive skills, such as template-based systems and cognitive tutors. While template-based systems can provide structure that guides a student in a metacognitive process, they lack awareness of the state of a specific user's metacognitive skills and provide the same type of scaffolding to all users, irrespective of their unique practice needs at the time. Cognitive tutors can give real-time, tailored feedback to a student, but are often limited to discreet, detectable metacognitive behaviors.

To help students better monitor and improve their metacognitive reflection process across the available supports, we introduce ***MindYoga***, a three-part process framework that guides students to monitor their metacognitive processes, evaluate strategies they can use to improve these processes, and implement these improvements in practice. MindYoga integrates into the existing learning ecosystem as three scaffolds: (1) an *on-action dashboard* to help students and mentors review the students' metacognitive strategies across weeks, (2) the *4-box model* to develop a plan to address risks based on mentor feedback, and (3) *in-action cues* to point students towards practice opportunities. Based on a 2-week pilot study with four student teams and three mentors, we found that MindYoga was able to guide students through the metacognitive reflection process as they practiced research. Students were able to (1) monitor which metacognitive risks may affect their upcoming project work, (2) develop action plans based on mentor feedback to address these risks, and (3) be actively reminded of their action items during relevant practice sessions. These findings suggest that process frameworks like MindYoga can guide students to monitor for metacognitive challenges and act on opportunities to improve their practice, as experts coach them to do. By integrating into a learning ecosystem, such process frameworks can scaffold students to fully leverage the many supports available to them as they practice.

2 BACKGROUND

Cognitive psychology defines metacognition as the ways in which a person reflects on and improves their problem solving strategies [4, 5, 11, 12]. Researchers who have studied metacognitive practice across disciplines assert that reflection is the essential skill that drives metacognitive improvements in expert learners [10]. Further, literature on metacognition and deliberate practice suggests that expert learners reflect and set specific practice goals as they work, where they focus their efforts on the most critical gaps in their skills and practices [3, 7–10, 16, 17]. When expert learners practice reflection as they work, they iterate by (1) monitoring for key risks in their ways of working, (2) evaluating specific strategies they can practice in response, and (3) selecting specific strategies to apply to their practice that overcome their most critical risks [3, 7–10, 17]. Often, such expert practices are learned through a combination of observation, coaching, and practice alongside an expert mentor [6]. While effective, this 1:1 training is not scalable when mentoring resources are limited.

Research has explored how technical systems might support students in improving metacognitive practices. Some existing systems take a template-based approach which provides a structured process that learners can use to practice and improve upon a metacognitive skill. For instance, Digital Ideakeeper provides a template that outlines a generalizable synthesis process (i.e. skim, read, summarize) for students learning to conduct online research [14]. However, template-based systems typically provide the same scaffolding for each student, irrespective of the unique metacognitive risks each student faces. To illustrate, a student writing a research paper may need to focus on improving their helpseeking abilities by asking for peer feedback more often. Another student running a study may need to improve their planning skills when allocating time for follow-up interviews. While template-based systems can provide helpful structure to scaffold a student's metacognitive practice, they are limited in the tailored support they can provide to students.

Other systems like cognitive tutors can adapt to the individual metacognitive behaviors of students by monitoring and sending real-time feedback on their metacognitive processes. For instance, HelpTutor is an adaptive cognitive tutor system which improves helpseeking behavior as students work through geometry problem sets [15]. HelpTutor monitors for when students click the "hint" button as they work through a problem, and provides students real-time feedback on their helpseeking strategy (e.g. if students do not attempt the problem first, they are prompted to do so before asking for a hint). While these systems can monitor and respond to a student's metacognitive practice, they tend to only support specific behaviors (i.e. requesting help before attempting a problem) in specific areas of metacognition (i.e. help-seeking). Further, these systems are not designed to detect metacognitive behaviors that are difficult to identify automatically. For example, within helpseeking, it is much more complex to define and quantify *why* a student asks for help or *how* they formulate their help requests, which are important to improving their overall helpseeking process. For novice student-researchers seeking to improve their practice, it's important that scaffolds can flexibly adapt to the variety of complex metacognitive strategies that are requisite for leading research work.

3 NEEDFINDING

Within an Agile Research Studio (ARS), students have access to a number of supports designed to scaffold the metacognitive reflection process (i.e. a weekly planning meeting, a process of setting term-long metacognitive goals for the term, a mid-term and an end-of-term self-assessment tool, and a final reflection feedback meeting). At the beginning of the term, all students set a metacognitive goal that they want to focus on throughout the term and a project goal they want to reach by the end of the term. Mentors coach students on metacognitive practice during weekly planning meetings. During the mid-term check-in, students independently reflect on their progress towards each of these goals using the self-assessment tool, and meet with mentors to get feedback on their plan for the remainder of the term to reach these goals. Finally, the students use the self-assessment tool at the end of term to reflect on if they were successful in reaching these goals, and get feedback from mentors in their final reflection meeting. Together, these supports are designed to scaffold students to monitor and improve their ways of working. Despite these existing supports in an ARS ecosystem, we observed that students still struggled to connect the parts of their metacognitive practice across these supports in the ways their mentors coached them to do. Below, we discuss two practical process breakdowns that we observed in formative rounds of needfinding and prototype testing with students.

3.1 Lack of Awareness of Metacognitive Risks

We observed that novices often have trouble monitoring their ways of working because they lack awareness of how their metacognitive processes impact their project work week-to-week. During weekly planning meetings, students often struggle to identify risks in their metacognitive practices and only cite practical risks that relate directly to their project work. Based on interviews with project teams, we learned that students focused on risks such as: "lack of prototype", "designing a user study to test our prototype", and "our findings section [of our end-of-term paper] is still weak", and often

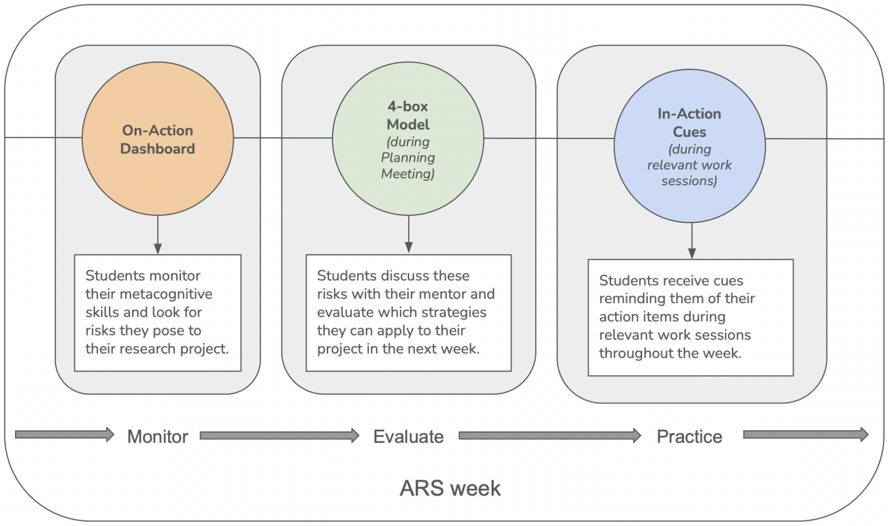


Figure 1: An overview of the MindYoga process framework. Three scaffolds (on-action dashboard, 4-box model, and in-action cues) work together to help students monitor, evaluate, and practice better metacognitive strategies each week.

didn't recognize how their *ways of working* may also be risky. Even when mentors raised a metacognitive risk to the student as feedback, we observed multiple instances of students still focusing on the practical feedback that directly references their project work instead. For example, we interviewed a mentor and their mentees separately after a planning meeting. The mentor paraphrased the feedback they gave in that meeting as coaching the student to believe in themselves as an *"expert designer"*. They told the student, *"You don't have to take baby steps"* because the student already had a lot of the knowledge and expertise they needed. However, the student interpreted the same feedback as: *"[They] gave us feedback on ways to collect data on conversations surrounding various situations [using] prior research...like using what we already know from our experience with user studies so far, talking with friends etc."* Here, we see that the students are focused on the practical risks of how to synthesize what they already know from their previous design work on the project. However, the mentor's feedback is much more focused on the novice's *process*: that they do not have to "take baby steps" in their research process and that they should believe in the knowledge they already have, rather than designing a new study.

: *"I gave them feedback on believing in themselves as expert designers. I told them 'you don't have to take baby steps' and that you already have a lot of the knowledge and expertise you need."*

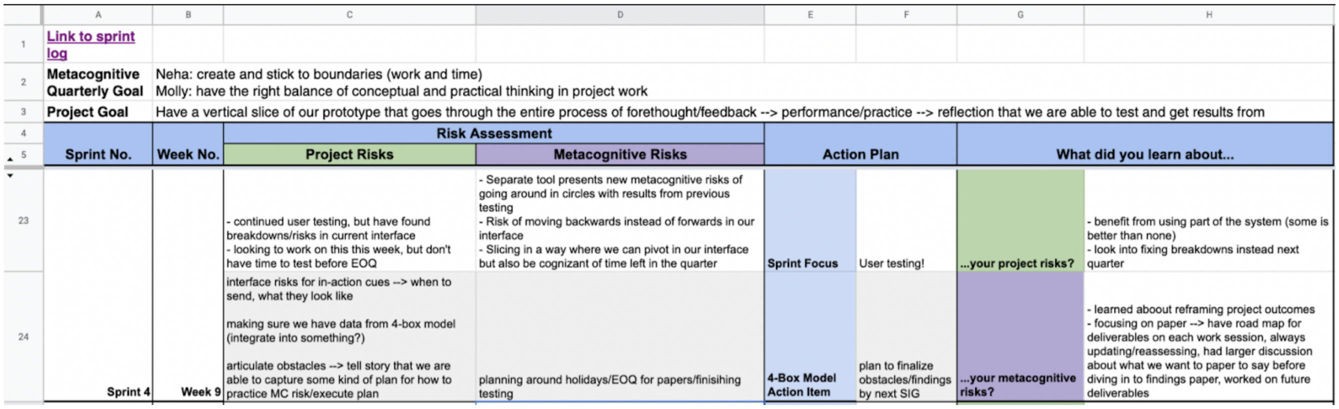
3.2 Failure to Identify Metacognitive Practice Opportunities While Working

We also observed that students in an ARS have trouble evaluating metacognitive strategies and applying these strategies to their ways of working after they have identified a metacognitive risk. Students were often unsure of how to turn a metacognitive risk into a practical task that can improve their ways of working while also making progress on their project. In our early prototyping, we found that students often captured strategies to address their risks that were too broad and not easily actionable (e.g. I should *"helpseek better"*). This makes it difficult for students to implement better metacognitive strategies because it is unclear how they can and should implement these changes in their practice (i.e. what does practicing "better" helpseeking look like in the context of this student's project?). Even if students were able to identify their most critical metacognitive challenge and select an appropriate and specific strategy to overcome it, they commonly reported forgetting to implement this strategy in practice. For instance, students may intend to use the strategy in an upcoming work session, but by the time it arrives, we observed that they often forgot what the strategy was, which prevented them from ever implementing it.

4 THE MINDYOGA FRAMEWORK

We introduce ***MindYoga***, a process framework that scaffolds students to monitor and improve their metacognitive practice as they work. MindYoga integrates into existing ecosystem supports, guiding students to explicitly capture the metacognitive risks and strategies that mentors implicitly raise via existing reflection tools and processes. The MindYoga framework is implemented as three scaffolds for each stage of reflection within the ecosystem: (1) the *on-action dashboard* that scaffolds students in monitoring their metacognitive skills, (2) the *4-box model* that scaffolds students in evaluating their plans to improve their ways of working, and (3) the *in-action cues* that scaffold students in incorporating these plans into their practice (see Figure 1).

The *on-action dashboard* integrates into the existing planning view that is used to discuss project risks during the planning meeting, and gives users a place to monitor their metacognitive skills and identify their risks alongside their project details across weeks (see Figure 2). To overcome challenges of lacking awareness of their



	A	B	C	D	E	F	G	H
1	Link to sprint log							
2	Metacognitive Quarterly Goal	Neha: create and stick to boundaries (work and time) Molly: have the right balance of conceptual and practical thinking in project work						
3	Project Goal	Have a vertical slice of our prototype that goes through the entire process of forethought/feedback --> performance/practice --> reflection that we are able to test and get results from						
4			Risk Assessment					
5	Sprint No.	Week No.	Project Risks	Metacognitive Risks	Action Plan		What did you learn about...	
23			- continued user testing, but have found breakdowns/risks in current interface - looking to work on this this week, but don't have time to test before EOQ	- Separate tool presents new metacognitive risks of going around in circles with results from previous testing - Risk of moving backwards instead of forwards in our interface - Slicing in a way where we can pivot in our interface but also be cognizant of time left in the quarter	Sprint Focus	User testing!	...your project risks?	- benefit from using part of the system (some is better than none) - look into fixing breakdowns instead next quarter
24	Sprint 4	Week 9	interface risks for in-action cues --> when to send, what they look like making sure we have data from 4-box model (integrate into something?) articulate obstacles --> tell story that we are able to capture some kind of plan for how to practice MC risk/execute plan	planning around holidays/EOQ for papers/finisihing testing	4-Box Model Action Item	plan to finalize obstacles/findings by next SIG	...your metacognitive risks?	- learned aboout reframing project outcomes - focusing on paper --> have road map for deliverables on each work session, always updating/reassessing, had larger discussion about what we want to paper to say before diving in to findings paper, worked on future deliverables

Figure 2: An example of the MindYoga dashboard view. The dashboard integrates into a view used in weekly planning meetings. The augmented view highlights to students the alignment between their metacognitive and project risks for the week, their action item that will help them mitigate both, and their takeaway learnings for their project and their process. In each row, students can see their progress week- to-week.

metacognitive risks the dashboard helps students keep track of their metacognitive risks alongside their project risks week-to-week. The dashboard not only shows a history of the student's project and metacognitive risks, but also shows the student's planned strategies to practice, and an area where they can reflect on how they've overcome both risks that week. Using the dashboard, students can zoom out to monitor how their metacognitive and project progress evolves across weeks.

The *4-box model* integrates into the weekly planning meeting to help students evaluate their metacognitive process as they discuss their project plan with their mentors during the last 10 minutes (see Figure 3). At the end of their planning discussion, students first capture their interpretation of the mentor's overall feedback (see top), and are then guided to parse out the project feedback from the metacognitive feedback (see left and right sides). At this point, mentors can validate, correct, or expand upon their feedback, ensuring accurate interpretation. Students are then guided to develop a specific action plan that addresses their metacognitive risks in their project work (see bottom). The action plan section requires students to describe a task that addresses both risks, how this task addresses both risks, and a specific upcoming opportunity where they can practice this task. This structure guides students and mentors to explicitly discuss the metacognitive risks and strategies most relevant to their upcoming project work. Notably, this approach captures the tailored mentor feedback on metacognitive practice that generalizable templates may miss, and automated systems may struggle to detect (e.g. a mentor can observe that while a student is great at requesting help at appropriate times, they are struggling to formulate their help requests and, therefore, are unable to receive the help they need).

The *in-action cues* consist of a Slack notification integrated into team channels to remind them of their action plan during the practice opportunity they indicate in their action plan (see Figure 4). The cues aim to scaffold students to practice improved metacognitive reflection processes at the opportune practice moments they self-identify (e.g. during their next work session). By sending a cue to the student during the opportunity they identified in their 4-box model, they are actively reminded of their action plan when they plan to enact it. Unlike cognitive tutors that are limited to detectable metacognitive practices, this approach carries forward the student-specific practices, validated by mentors, that would be useful for that student to attempt in the moment. The in-action cues take the following structure, with each message using the following input from the 4-box model to remind students of their personal action plan: *"Do you still want to [task] in [practice opportunity] to address [metacognitive risks] and [practical risks]?"*

Here, we walk through an illustrative example of the MindYoga framework from our user testing, as seen in Figures 3 and 4. For context, this project team had just completed a round of user testing that did not go as expected. Prior to their planning meeting, the student team noted in their dashboard that they were concerned about the effectiveness of their system and their study design, and about being able to revise the system and study during a week where they were busy with many other commitments outside of their research (i.e. extracurriculars, interviews, etc.). The 4-box model structured an explicit conversation around this metacognitive risk with their mentor. As a strategy for iterating, despite little available time, their mentor coached them to reduce stress by conducting a simpler user test that focused on the core functionality they wanted to showcase in their paper. In their 4-box model, the students noted this metacognitive strategy as an action plan they would like to be reminded of at their next work session. The in-action cues then used this data to later send students a Slack reminder at the start of their usual Saturday practice session, reminding them to *"Make a realistic goal for what we want to accomplish next week. Don't do any [project work] over the weekend to reduce burnout."* Students can then use the on-action dashboard to see how they progress in their metacognitive and project risks week-to-week.

5 METHODS

To understand how MindYoga might support a student's metacognitive reflection process across supports in an ARS ecosystem, we

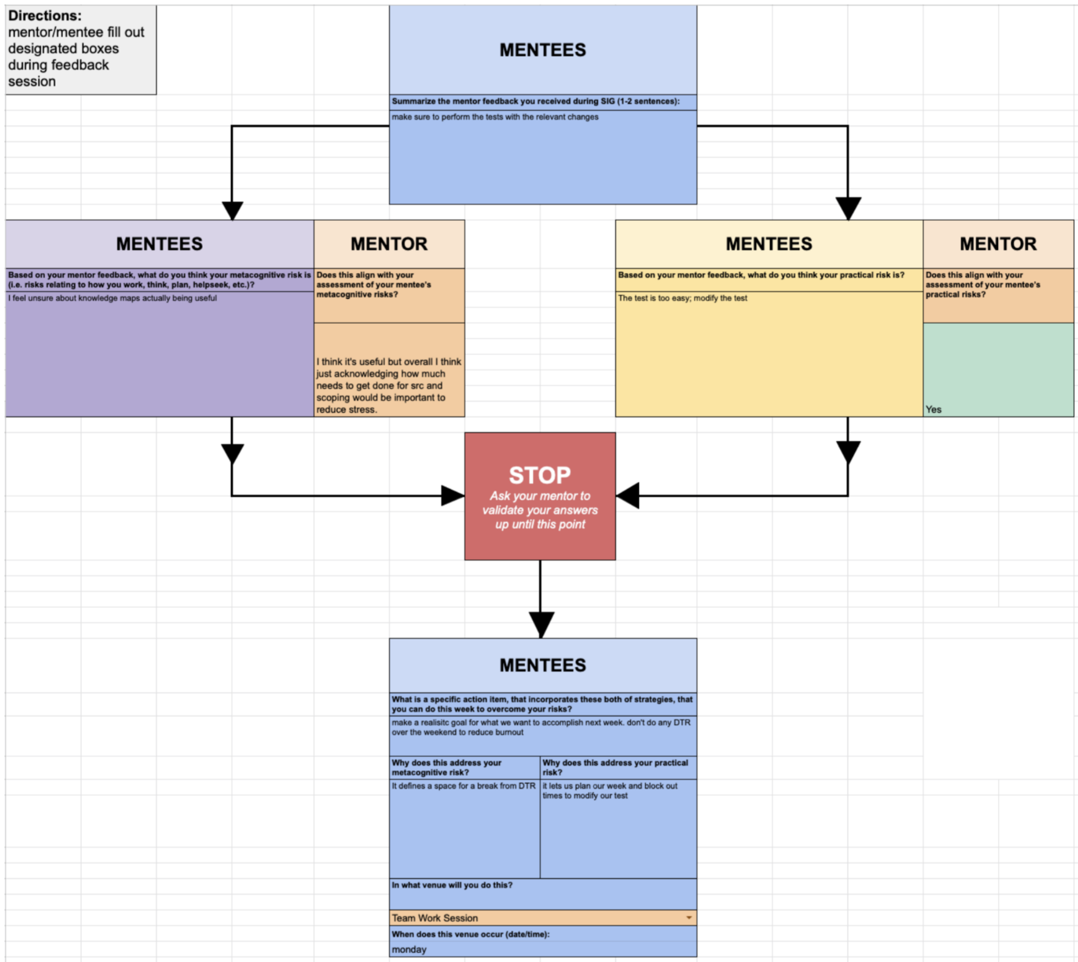


Figure 3: The 4-box model interface is used during weekly planning meetings to guide students and mentors in an explicit conversation about project and metacognitive feedback.

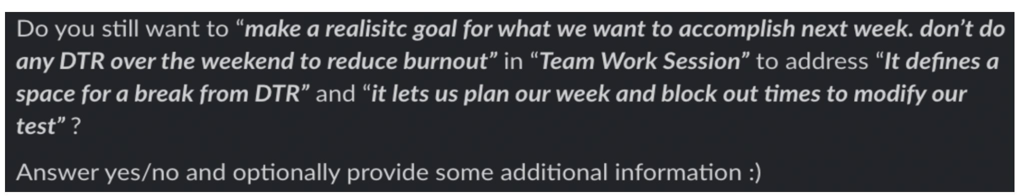


Figure 4: An example in-action MindYoga cue sent to students over Slack. The cue reminds them at the beginning of their work session of the action item they identified in their 4-box model, designed to tackle the project and metacognitive risks they discussed with their mentor in their planning meeting.

recruited three mentors (M1, M2, M3) and seven students (S1, S2, S3, S4, S5, S6, S7) across four project teams (PT1, PT2, PT3, PT4) from an existing ARS to participate in a 2-week study. M1 oversaw PT1 (S1 and S2), M2 oversaw PT2 (S3), and M3 oversaw PT3 (S4 and S5) and PT4 (S6 and S7). We asked all participants to incorporate the complete framework into their existing ARS work processes. To measure adoption of each scaffold, we observed whether students entered data into the 4-box model and the on-action dashboard, or interacted with the Slack cues by replying or reacting. Further, we used the interviews to assess whether they read or changed their behavior in response to the cues. At the end of the 2 weeks, we asked all students to fill out a feedback survey about their experience. This included binary questions about the perceived benefit of the different scaffolds within the MindYoga framework like "Did the 4-box model help you understand mentor metacognitive feedback and create a relevant action item?". The form also asked the students to elaborate on why and how they found the system to be helpful or not. Additionally, we conducted individual follow-up interviews with three students (S1 and S2 of PT1, and S7 of PT4) and the two mentors (M2 and M3). We selectively interviewed individuals from teams that represented most adoption of the scaffolds (PT1) and least adoption (PT4), to understand potential causes for variance in adoption. Similarly, to capture variation in mentoring approaches, we focused our interviews on M2 and M3. Based on the data students entered into the scaffolds, and responses in the feedback surveys and interviews, we evaluated if users were (1) able to reflect on the changes to their metacognitive processes (risks, strategies, and actions) and reassess their risks, (2) able to determine their metacognitive risks and an action plan for addressing them in the 4-box model with alignment from their mentors, and (3) reminded of this action plan during relevant work sessions.

6 FINDINGS

Our results show that our users were able to reach all three outcomes when they engaged with our prototype at the respective stages (see Figure 5). We had two project teams that engaged with the entire reflection process at least once with our prototype. PT1 and PT2 reflected on their risks in the on-action dashboard, used the 4-box model in their planning meeting, and interacted with our in-action cues during relevant work sessions, thereby completing all three stages of metacognitive reflection at least once. PT3 only used the 4-box model scaffold, while PT4 used the 4-box model and the in-action cues. Even in project teams that did not engage with the prototype across all three stages, we still saw improvements in the stages where they did utilize the prototype.

When used, we found that the on-action dashboard encourages students to monitor and explicitly state their recent metacognitive process improvements and metacognitive risks. S3 of PT2 reflected on their metacognitive practice across the 2 weeks: *"I didn't really understand what [my mentor] meant when [they] kept telling me to be agile but I think I really internalized it this week– I spend a lot of time worrying about all the risks when it's best for me to just try to test something."* With this scaffold, PT1 and PT2 were able to monitor their metacognitive processes and identify metacognitive risks for that week. Both teams also reported that this prototype helped "internalize" the metacognitive strategies they used and produced reflections in the on-action dashboard on how these strategies helped their work process. Additionally, these teams were able to explicitly identify metacognitive risks that were impacting their project work for the upcoming week, as evidenced by user input in the on-action dashboard.

The 4-box model support helped these project teams clarify their understanding of the mentor's metacognitive feedback. S1 of PT1 reported: *"...getting [mentor] feedback on what we thought was *[their]* feedback made the actual feedback extra clear. Often we were just wrong about the metacognitive feedback and so doing this made [our mentor] actually say our metacognitive feedback directly, which we wouldn't have gotten otherwise."* We also received feedback that the 4-box model's structured conversation promoted reflection around metacognition in the planning meetings that was beneficial. S3 of PT2 reported: *"just being given the space to reflect was helpful"* and *"the 4 box model does force us to talk ab[ou]t [metacognitive risks], whereas sometimes metacognitive risks get skipped."* From these results, we determined the 4-box model was useful for students in creating a space for reflecting on their metacognitive risks and structuring a conversation with their mentors about how to address them. We can see that the tool promotes discussion and reflection within the mentor-student dynamic in an existing ARS support (i.e. the weekly planning meeting). This gives the students an opportunity to become self-aware and direct their metacognitive process while also giving the mentor visibility into the students' current metacognitive processes. These findings show that the students were able to use the mentor feedback to evaluate their metacognitive processes and develop an action plan to address any relevant risks.

In PT3 and PT4, we saw evidence of increased awareness of their metacognitive risks and the development of action plans after using the 4-box model through observed user behaviors and quotes. S4 of PT3 reported that: *"I sometimes am able to [identify metacognitive risks in the weekly planning meeting], but generally I identify those risks after the [weekly planning] meeting or only think about them when filling out the 4-box model."* This quote reinforces that some students and mentors do not usually talk about the metacognitive risks in the weekly planning meeting and the introduction of the 4-box model improves that process. Similarly, S6 from PT4 reported the 4-box model helped them to create their action plan, saying: *"[The 4-box model] helped me reflect on the feedback and solidify an action item in my head."* The members on PT4 had been struggling with burnout and staying on top of busy schedules. During our user study, we observed that this team did not discuss their concerns of scheduling and burnout until they engaged with the 4-box model. After filling it out, this team identified their action plan to be: *"Make a realistic goal for what we want to accomplish next week. Don't do any [project work] over the weekend to reduce burnout."* This evidence shows that both PT3 and PT4 demonstrated improved ability to determine their risky metacognitive processes from mentor feedback and develop an action plan to address these risks after using the 4-box model. Further, we gathered initial evidence that the 4-box model and on-action dashboard could also benefit mentors. M3 stated that these tools *"can be useful to see what [my mentees] think and if they need to be corrected."* These findings suggest that these process scaffolds can also give mentors increased visibility into their mentees' work processes, and how they interpret mentor feedback.

Both project teams interacted with the in-action cues during the time of their work session indicated in the action plan. S3 from PT2 stated that *"I would have never done [my action plan] if not for Slack [reminders]"*. This shows that users are reminded of their action plan during relevant work sessions. Additionally, we saw improvement in project team 4 in the practice phase. S6 from PT4 reported that the in-action cues were helpful and occurred at an optimal frequency: *"Seeing my action item visually a few days later was helpful but any more reminders would have been too much."* The team also demonstrated behavior change to address their risks around burnout. We observed PT4 ask to have an upcoming project presentation postponed to make their workload more manageable. This improvement in time management of project deliverables seems to stem from the conversation surfaced by the 4-box model, and, when coupled with the self-reported user feedback, demonstrates

	(1) On-action dashboard		(2) 4-box model		(3) Slack in-action cues	
Project Team #	# Times Used	# Times Reflection of Metacognitive Process Changes Complete	# Times Used	# Times Metacognitive Risks and Action Plan Identified	# Times Used	# Times Reminded of Action Plan During Work Session
PT1 (S1, S2)	2	2	2	2	1	1
PT2 (S3)	1	1	1	1	1	1
PT3 (S4, S5)	0	0	2	2	0	0
PT4 (S6, S7)	0	0	1	1	1	1

Figure 5: Scaffolds used and outcomes reached for each project team in user study.

that some students who were reminded of their action plans were even able to enact them, revising their process as they practiced.

7 DISCUSSION

From our findings we determined that students using MindYoga were able to engage in the metacognitive reflection process. Specifically, students who used the MindYoga process framework were (1) able to monitor their metacognitive processes and identify metacognitive risks in the on-action dashboard, (2) use mentor feedback to evaluate their metacognitive risks and to address them in the context of their project with the 4-box model, and (3) more actively think about their plan to practice improved metacognitive strategies with our in-action cues.

When used, the MindYoga framework is able to scaffold the metacognitive reflection process across a learning ecosystem, allowing students to more actively improve their overall ways of working, as they learn to lead research work. Unlike prior work that provides generalizable templates to guide metacognitive practice for all students in an environment, or uses cognitive tutors to surface very specific and limited metacognitive breakdowns and strategies, MindYoga is able to provide individualized support for a wide range of metacognitive process risks that are specific to each student's metacognitive practice, relevant to project goals, and difficult to detect automatically. By explicitly structuring and capturing mentor and student discussions on metacognitive practice, MindYoga leverages the implicit metacognitive coaching that already occurs to provide contextualized support to each user at opportune moments, depending on their personal and project needs. Further, by scaffolding across the metacognitive reflection process itself (i.e. monitoring, evaluating, and practicing) our approach can flexibly generalize to the metacognitive processes that mentors find most critical for each student.

One key limitation of the MindYoga framework was that, despite integrating into existing ecosystem designs, users still reported points of friction that would deter them from interacting with the full framework. For instance, M3 reported in a follow-up interview that while the 4-box model *"can be useful to see what [students] are thinking and if they need to be corrected"* there was still *"a lot of overhead"* required to use the scaffold. These results suggest that when designing a process framework that guides practice across an existing ecosystem, it's critical that the scaffolding integrates in a way that maximally reduces any friction that may inhibit users from interacting with core framework components. Such friction can limit the benefits students garner from engaging in the full reflection process.

It is also possible that some of the interactional friction was the result of learnability barriers from modifying an existing process in ARS during a brief 2-week exposure to the intervention. A longer-term study may help overcome learnability concerns, allowing one to focus on any friction related to integration in an ecosystem. A longer-term study with more mentors may also account for any variation due to different coaching styles. For instance, we observed that novice mentors were less likely to focus on metacognitive feedback than senior mentors. In such cases, novice mentors may have experienced more friction as they learn to coach metacognitively. While we did gather some qualitative evidence that MindYoga could generally be valuable for mentors, further research is required to understand the value of such metacognitive scaffolding for mentoring outcomes.

MindYoga's approach to scaffolding each stage of the metacognitive reflection process also has potential implications for other learning ecosystems outside of ARS, particularly in settings where mentoring resources are limited and learners practice metacognitive reflection as they work. The use of process frameworks could be introduced in environments such as startup mentorship programs or student-teaching programs, where learners are actively practicing new domain skills, trying to improve their work processes, and receive regular feedback from limited mentoring resources. By providing integrated, individualized scaffolds throughout the reflection process, process frameworks like MindYoga can increase the support a learner has throughout the reflection process without increasing the burden on existing mentoring resources in such learning ecosystems.

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