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Improving Mathematics Content Mastery and Enhancing Flexible Problem Solving through Team-Based Inquiry Learning

ABSTRACT

This article examines how student learning is affected by the use of team-based inquiry learning, a novel pedagogy in mathematics that uses team-based learning to implement inquiry-based learning. We conducted quasi-experimental and observational studies in intermediate level mathematics courses, finding that team-based inquiry learning led to increased content mastery and that students took a more flexible approach to solving problems. We also found that in the courses using this pedagogy, women (but not men) had a reduction in communication apprehension over the course of a semester. We conclude that team-based inquiry learning effectively enhances student learning and problem solving, preparing students for future academic success and fostering career readiness.

KEYWORDS

team-based learning, inquiry-based learning, flexible problem solving, communication apprehension

INTRODUCTION

A long-standing challenge in education is determining how to help students move beyond surface learning to engage in deep learning (Marton and Säljö 1976). This challenge persists across disciplines. For example, Georgios Papaphotis and Georgios Tsaparlis (2008) found that high school chemistry students in Greece performed well in applying algorithmic procedures but performed poorly on questions requiring conceptual understanding; and John Selden, Annie Selden, and Alice Mason (1994) report that even high-performing university calculus students had great difficulty in solving novel problems for which they had not been shown a solution technique. In mathematics education in particular, this is often framed as a contrast between procedural learning and conceptual learning. One way to distinguish the two is through the notion of flexibility, by which we mean the ability of students to use multiple problem-solving strategies and identify the best strategy for a given problem. In addition to being beneficial prima facie, improved flexibility is associated with using more expert-like problem-solving strategies (Dowker 1992; Maciejewski and Star 2016).

In postsecondary mathematics education, there is a growing movement toward addressing this challenge through inquiry-based learning. Inquiry-based learning is broadly characterized through its "twin pillars" of deep engagement in rich mathematics and opportunities to collaborate (Laursen et al. 2011, 133). In most inquiry-based learning classrooms, students spend the bulk of their time engaged in scaffolded inquiry and discovering new mathematics themselves, rather than watching and listening to an instructor demonstrating the use of various algorithms for problem solving. A large, multi-institution study by Sandra Laursen, Marja-Liisa Hassi, Marina Kogan, Anne-Barrie Hunter, and Tim Weston (2011, 46) found that students in inquiry-based learning courses gained a greater understanding of mathematical concepts and improved thinking and problem-solving skills than did students in courses that did not use this approach.

While the evidence that inquiry-based learning is effective is quite robust, in postsecondary mathematics, implementation has primarily been limited to upper-level courses for majors and preservice mathematics teachers. One driving factor for the lack of wider adoption of inquiry-based learning is class size, as many instructors feel it is difficult to use the approach in classes larger than 30 (Laursen et al. 2011, 42). Recently, however, the inquiry-based learning community has increased its focus on bringing the approach into the first two years of postsecondary mathematics, as evidenced by a special issue of *PRIMUS* focused on the topic. However, Ernst, Hodge, and Hitchman (2017, 641) note in their introduction to the issue, "It is often a challenge to bring an inquiry-based pedagogy into classes with a large number of students, prescribed content expectations, or a heavy computational focus."

In other disciplines, particularly medicine and other health sciences, where large class sizes are the norm, team-based learning is a commonly used active-learning pedagogy designed to promote deeper learning over rote surface learning. Team-based learning is a highly structured framework of collaborative learning that includes individual *preparation* outside of class; a readiness assurance process with an individual readiness assurance test, a team readiness assurance test, appeals, and corrective instruction; and application activities with students working in permanent teams to solve problems, create explanations, or make predictions. The key components of team application activities in team-based learning, known as the 4S's, are (1) activities involve a *significant problem* that is meaningful and relevant to students, (2) all teams work on the *same problem*, (3) students solve the problem by making a *specific choice*, and (4) teams *simultaneously report* their choices. Diverse, permanent teams, accountability for individual and team work, frequent immediate feedback, and carefully crafted assignments that promote both learning and team development are essential to this approach (Michaelsen and Sweet 2008).

In systematic reviews and meta-analyses of studies of the effectiveness of team-based learning across disciplines, authors report trends of improved grades, improved test performance, increased classroom engagement, better performance for teams than individuals, improved communication, and increased self-efficacy (Fatmi et al. 2013; Haidet, Kubitz, and McCormack 2014). While the benefits of team-based learning were observed across achievement levels and demographic profiles, students with lower levels of achievement displayed the greatest benefits. In more recent meta-analyses, Sin-Ning Cindy Liu and A. Alexander Beujean (2017) reported improved student learning gains by approximately 0.5 standard deviations for team-based learning when compared to other methods, and Elizabeth Swanson, Lisa McCulley, David Osman, Nancy Lewis, and Michael Solis (2019) indicated a moderate positive effect of team-based learning on content knowledge across 17 studies, with smaller team sizes yielding higher effects. While there are some studies reporting improved student learning in science and technology fields such as biology (Carmichael 2009), chemistry (Dinan and Frydrychowski 1995), and information systems (Kreie, Headrick, and Steiner 2007), research on the use and effectiveness of team-based learning in mathematics is so far quite limited. Kalman Nanes (2014) and Travis Peters, Elgin Johnston, Heather Bolles, Craig Ogilvie, Alexis Knaub, and Thomas Holme (2020) both report increased student learning in linear algebra and calculus, respectively, using a modified implementation of team-based learning.

Most implementations of team-based learning, including those used by Nanes (2014) and Peters, Johnston, Bolles, Ogilvie, Knaub, and Holme (2020), can be categorized as flipped learning, which Robert Talbert (2017, 20) defines as a pedagogy in which students first encounter new material through structured activities completed individually (outside of class, for example), thus freeing up the group space to be an interactive environment guided by the instructor. However, elsewhere we have recently noted that team-based learning can be an avenue for bringing inquiry into lower-division mathematics courses (Lewis, Clontz, and Estis 2019). We introduced team-based inquiry learning, which implements inquiry-based learning within the team-based learning framework. Rather than using the readiness assurance process to introduce new material, team-based inquiry learning instead uses it to have students review or relearn prior knowledge from prerequisite courses or earlier in the current course that they will need to construct new knowledge in the coming unit. This helps ensure a more even preparation level across students and reduces the cognitive load on students by allowing them to focus on new material rather than struggling to recall prior knowledge, thus making the subsequent inquiry-oriented activities more effective. Additionally, the simultaneous reporting structure from team-based learning provides an explicit avenue for instructors to make students' thinking visible and make use of their thinking, which has more recently been identified as a third pillar of inquiry-based learning (Rasmussen et al. 2017).

However, research lags behind practice. Team-based inquiry learning is new and unstudied, and while, as described above, team-based learning is effective in many disciplines such as the health sciences, research is limited, especially in mathematics and other science, technology, and engineering fields. The purpose of our study was to explore the impact of team-based inquiry learning on student learning in the context of two intermediate-level mathematics courses, Linear Algebra and Differential Equations, and to determine if it is an effective avenue for introducing inquiry-based learning at this level.

In particular, in our study, we addressed the following five research questions:

1. ***Does team-based inquiry learning increase students' content mastery?***
2. ***Does team-based inquiry learning increase students' flexibility in solving problems?***
3. ***How do the individual components of team-based inquiry learning support student learning?***
4. ***How do students respond to team-based inquiry learning?***
5. ***Does team-based inquiry learning have an effect on students' communication apprehension?***

METHODS

Instructional context

This study was conducted across four semesters at the University of South Alabama, a regional public university in the southeastern United States, examining two different mathematics courses: Linear Algebra and Differential Equations. These courses are typically taken in the second year and populated primarily by engineering majors, with some mathematics majors and minors also enrolled. Class sizes in the study ranged from 9 to 34 students, and were disproportionately male, reflecting student enrollment in engineering and mathematics majors. Five different instructors, including the first author, taught the classes involved in this study.

This implementation of team-based learning was associated with a campus-wide quality improvement initiative, linked to our regional accreditation. As a comprehensive, regional-serving university with high percentages of first generation college students and students of color, this initiative is well aligned with our institutional priority of increasing student success and access. With 228 faculty participants over five years, program evaluation showed high mastery of student learning outcomes, improved critical thinking and collaboration skills, increased engagement, better grades, and higher course persistence for courses using team-based learning (Estis 2017).

The study was reviewed and approved by the Institutional Review Board at the University of South Alabama. Students were engaged in the research process in several ways. The rationale for the teaching methodology was discussed in class, and students completed an informed consent process to participate in the research study. Student voices were included through scaled survey questions, open-ended responses, and focus groups. Student feedback was also utilized to improve the quality of the course materials.

Standards-based grading

To assess student mastery of content, all courses in this study used standards-based grading (see Elsinger and Lewis 2019, for details). In this grading scheme, the course content is divided into discrete learning objectives (standards), and students are assessed on whether they have mastered the standard completely or not. Course grades are assigned by counting the number of standards mastered, without regard to when or how (quiz, test, or final exam, for example) the student demonstrated mastery. Additionally, students have the opportunity to voluntarily attempt to demonstrate mastery during the instructor's office hours.

The same list of standards was used across all sections of each course within a given semester, although the list of standards for Linear Algebra underwent some minor revisions between semesters as the team-based inquiry learning materials were refined based on instructor and student feedback. In particular, there were 21 standards in common across all four semesters of Linear Algebra (while the final version of the course had 24 standards). Each instructor reported which standards were mastered by each student over the course of the semester. Measuring content mastery in this way provides a more robust (and in our view more valid) measurement of student learning than any one-time assessment, on which students' performances are influenced by many confounding factors such as test anxiety.

A recent study of standards-based grading (Lewis 2020) found that office hours assessments are frequented by students with high test anxiety but low communication apprehension (defined as fear or anxiety associated with communication or anticipated communication with another person, McCroskey 2015, 41). That is, students with a high level of test anxiety are benefitting from the alternate assessment structure, but only if they have lower levels of communication apprehension. It seems plausible that the highly collaborative nature of team-based inquiry learning might help alleviate students' communication apprehension. For this reason, we asked the fifth research question, about the effect on communication apprehension.

Research design

In the first semester, we used a quasi-experimental design and taught two sections of Linear Algebra via team-based inquiry learning and two via lecture. Students were unaware of the pedagogical setup when registering for the sections. However, the team-based inquiry learning sections were taught in a classroom in a different building, which may have influenced students' choice of which section to select when registering.

In the three subsequent semesters, we used an observational design. All five Linear Algebra instructors (including the first author) independently chose to teach via team-based inquiry learning. Additionally, in the third semester, we included two sections of Differential Equations in our observational study, as the first author also chose to use team-based inquiry learning in that course. The design is summarized in table 1.

Table 1. Research design

Design	Semester	Course	Pedagogy	Sections
Quasi-experiment	1	Linear Algebra	Team-based inquiry learning	2
			Lecture	2
Observational	2	Linear Algebra	Team-based inquiry learning	6
	3	Linear Algebra	Team-based inquiry learning	4
		Differential Equations	Team-based inquiry learning	2
	4	Linear Algebra	Team-based inquiry learning	4

A mixed methods approach was used in the study. As noted above, content mastery was assessed via the use of standards-based grading. To measure flexibility in problem solving, during the first (quasi-experimental) semester, each student's first quiz assessing their ability to compute a determinant was collected and coded as to whether they strictly followed an algorithmic approach (that is, directly computed a cofactor expansion), or whether they took a more flexible approach (such as performing a clever row operation first).

In the first three semesters, students were surveyed at the beginning and end of the course. In addition to demographic questions, students responded via a Likert scale to a number of questions about their perceptions of the course. Additionally, we asked several open-ended qualitative questions; for each of these, we produced concept maps summarizing the responses. To do so, both authors coded the responses pairwise for similarities; that is, each pair of responses was coded as either similar or dissimilar. From this, we produced a concept map of the similarities and applied the cluster analysis technique described by Peter Balan, Eva Balan-Vnuk, Mike Metcalfe, and Noel Lindsay (2015) and Mary Kane and William Trochim (2007). However, the method described therein only allows for a single coder, so we strengthened the method by using a different cluster detection algorithm to account for our use of multiple coders. This process produces a concept map such as that in figure 3, in which similar statements are connected, and thematic clusters are identified. We then assigned names representing the theme of each cluster.

In the third semester, both pre- and post-semester surveys included a personal report of communication apprehension questionnaire for communication apprehension (McCroskey 2015, 40).

Finally, at the end of the second semester, two focus groups were conducted by the second author with a total of 11 Linear Algebra students. Focus group questions were centered around students' learning and their experiences working in teams.

RESULTS

Comparison of lecture and team-based inquiry learning

First, in the quasi-experimental semester, we compared the median mastery between the two lecture sections (n=58) and the two team-based inquiry learning sections (n=62) (see table 2). The lecture sections had a higher median, but the difference in the distributions was not significant (Mann-Whitney U test, $p=0.16$). We then compared mastery between the two lecture sections (n=58) and all 16 Linear Algebra sections (n=366) using team-based inquiry learning, which showed that the students in the team-based inquiry learning sections mastered more standards than did those in the lecture sections (Mann-Whitney U test, $p=0.037$).

Table 2. Content mastery in Linear Algebra by pedagogy

Pedagogy	n	Median mastery	Mean mastery
Lecture	58	19	16.7
Team-based inquiry learning (semester 1 only)	62	17.5	14.7
Team-based inquiry learning (all semesters)	366	19	17.3

To measure students' flexibility in problem solving, we collected the first assessment on which students worked a particular kind of problem (computing a determinant of a matrix), and coded their work as either strictly algorithmic or applying a flexible, hybrid approach. To be more precise, we noted whether they simply applied the Laplace (cofactor) expansion algorithm, or instead took any other approach (for example, by performing a row operation or two before applying a Laplace expansion). While the algorithmic (Laplace expansion) approach will always lead to the answer in the same way, a hybrid approach will often be less computationally intensive, but will involve different steps for different problems. The results are summarized in table 3. (We note that 19 student papers—10 team-based inquiry learning, 9 lecture—were omitted because they did not demonstrate any understanding.)

Table 3. Problem-solving approach

	Hybrid	Algorithmic
Team-based inquiry learning	39	13
Lecture	16	20

Applying Barnard's test showed that the students in the team-based inquiry sections were more likely than those in the lecture sections to take the less algorithmic hybrid approach ($p=0.0037$).

To explore research question 3, students in semesters 1 and 2 were asked "Which aspect of this course did you enjoy the most?" Four clusters emerged, as summarized in table 4.

Table 4. Cluster composition: "Which aspect of this course did you enjoy the most?"

Cluster	n Lecture	n Team-based inquiry learning	Representative comment
Content/teacher	5	10	"Dr. C is fantastic."
Standards-based grading	6	15	"Standard [based] grading. I think all math classes should go to this."
Teamwork	1	15	"I enjoyed being in teams the most. We were able to help each other out."
Lectures/activities	0	6	"Lectures weren't boring."

A Freeman-Halton test showed that there was not a significant difference in cluster membership between the students in team-based inquiry learning and lecture sections (p=0.125), but we do find it notable that all of the students commenting that the lectures or activities were the most enjoyable aspect were from the team-based inquiry learning sections.

Post-semester surveys contained several agreement questions posed to both team-based inquiry learning (n_1=69) and lecture students (n_2=18) in semesters 1 and 2. These were answered on a six-point Likert scale (strongly disagree to strongly agree). Table 5 presents the results of Mann-Whitney U tests conducted to determine if there were significant differences between the two groups.

Table 5. Agreement questions, six-point Likert scale

	Team-based inquiry learning		Lecture		
Prompt	Median	Mean	Median	Mean	*p*-value
"This course was a valuable learning experience."	5	4.56	5	5.00	0.16
"This course helped me improve my problem solving skills."	4	4.46	5	4.76	0.29
"This course helped me work more effectively as a member of a team."	5	4.52	4	3.59	0.003

Observational study of team-based inquiry learning (semesters 1–4)

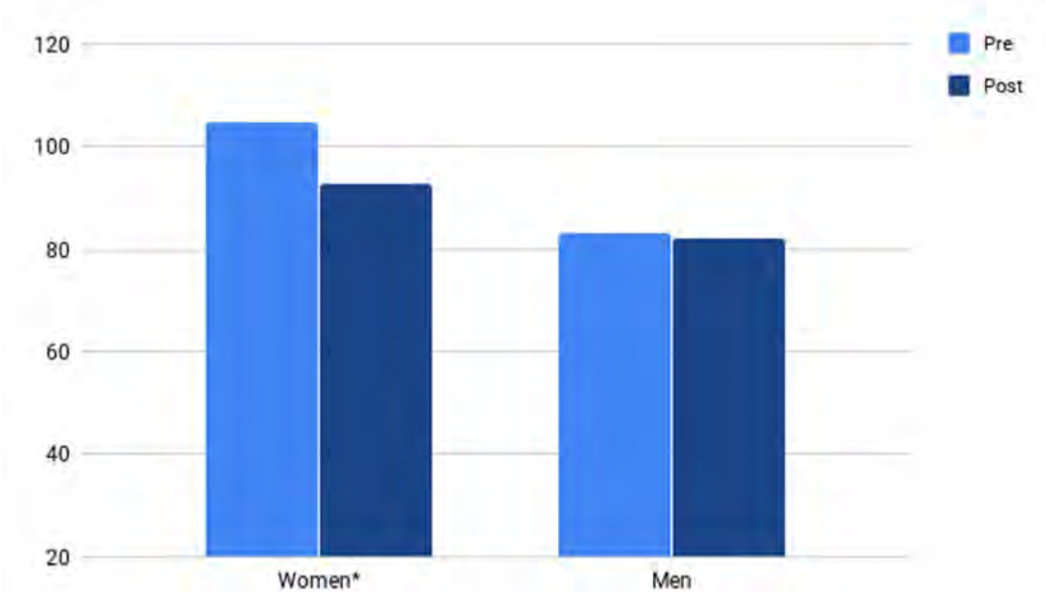
First, we compared content mastery in Linear Algebra across the four semesters (table 6). As noted above, in the first semester there were two lecture sections and two team-based inquiry learning sections, while in the subsequent semesters, all sections were entirely team-based inquiry learning. A Kruskal-Wallis test showed there was a difference across the four semesters (p=0.005). In particular, content mastery in the third and fourth semesters were significantly higher than in the first (p=0.001 and p=0.00001, respectively, which remain significant when applying a Bonferonni correction to account for the six possible pairwise comparisons). We note especially that in the fourth semester, the median student mastered each of the 21 standards tracked here.

Table 6. Number of content standards mastered in Linear Algebra, by semester

Semester	Number of Students	Median mastery	Mean mastery
1	120	19	15.8
2	114	19	16.4
3	100	20	17.7
4	94	21	19.56

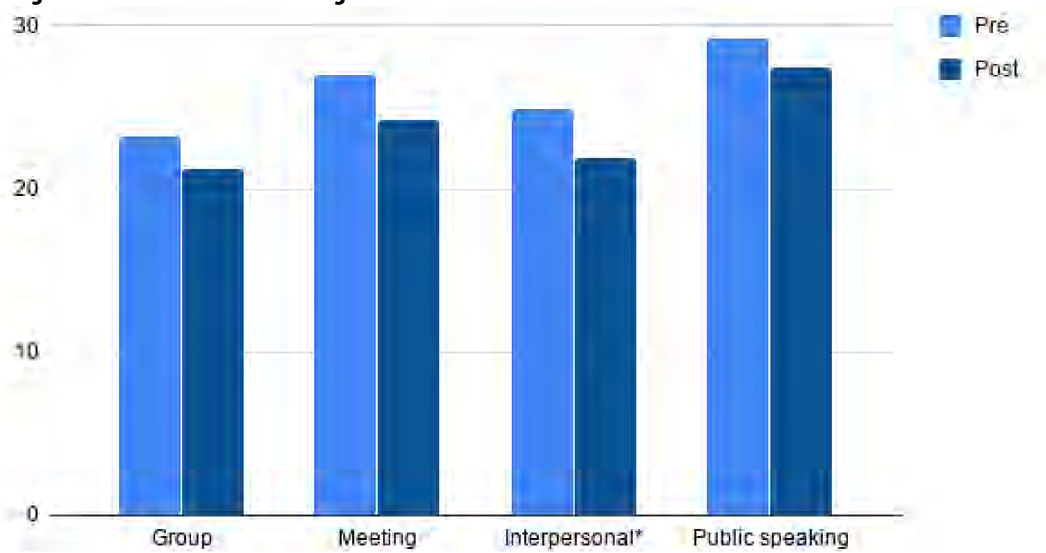
In semester 3, we administered the personal report of communication apprehension questionnaire (known as PRCA-24) both pre-semester and post-semester. Overall, there was no significant change (repeated measures ANOVA, p=0.070, n=73), but women showed a significantly larger decrease in communication apprehension than did men (repeated measures ANOVA, p=0.024), shown in figure 1. The decrease observed in the women was significant (p=0.016, n=16).

Figure 1. Change in communication apprehension over the semester, by gender



We also examined the change among women in the PRCA-24's four subscales. All decreased (see figure 2), with only the interpersonal scale reaching significance (p=0.034).

Figure 2. Change in PRCA-24 subscales among women



To examine the impact of various components of team-based inquiry learning on mastery, we used a convenience sample of one instructor (the first author) and computed the correlation of each component with number of standards mastered (table 7). Both attendance and the individual readiness assurance tests had significant, moderate correlations with the number of standards mastered.

Table 7. Correlations of team-based inquiry learning components with content mastery

Course	Number of students	Individual readiness assurance tests	Team readiness assurance test	Attendance	Peer evaluations
Linear Algebra	40	0.51***	0.01	0.48**	0.06
Differential Equations	39	0.55***	0.25	0.59***	0.31

*p<0.05, **p<0.01, ***p<0.001

In semesters 2 and 3, on post-semester surveys students were asked to rate their agreement with a series of statements on a five-point Likert scale (strongly disagree to agree); a total of 83 responses were recorded. A Wilcoxon signed rank test was used to determine if the medians were significantly different from the neutral response 3 (table 8). We note that in all student surveys, we used the phrase "team-based learning" rather than "team-based inquiry learning," as this was the language used by the instructors with their students.

Table 8. Median responses to agreement questions, five-point Likert scale

Prompt	Median	Mean
The use of team-based learning in this course helped me to learn more than in a traditional course.	3	3.2
The use of team-based learning during class time was a valuable learning experience.	4***	3.7
This course helped me improve my problem solving skills.	4***	3.7
This course helped me work more effectively as a member of a team.	4***	4.0
I generally felt prepared for the individual readiness assurance tests.	4***	3.5
The team readiness assurance test discussions allowed me to correct my mistakes and improve understanding of concepts.	4***	4.3
There was a connection between the readiness assurance tests and the team activities.	4***	3.9
I came to class prepared.	4***	4.1
Solving problems in a team was an effective way to learn.	4***	3.7
Team-based learning helped me improve my critical thinking skills.	4***	3.5
Team-based learning helped me improve my communication skills.	4***	3.7
Team activities had real-world applications.	4***	3.5

*$p<0.05$, **$p<0.01$, ***$p<0.001$

Students were also given an open-ended prompt to explain their reasoning for their response to "The use of team-based learning in this course helped me to learn more than in a traditional course." Five clusters, summarized in table 9, emerged in the concept map.

Table 9. Cluster composition: "The use of team-based learning in this course helped me to learn more than in a traditional course."

Cluster	Size	Representative comment
Deeper learning	10	"It helped me learn difficult topics faster than other classes."
Negative	7	"I don't like having to teach myself what's going on."
Peer instruction	8	"Having people explain things differently helped."
Actively engaged	3	"I feel I spend more time actively engaged with learning in class, and less time distracted or bored."
Requires good teammates	3	"Doesn't work if no one knows what is going on."

Students were also given the open-ended prompt "What was the most beneficial aspect of team-based learning?" Five clusters, summarized in table 10, emerged in the concept map (figure 3), in which nodes represent student responses, and edges are drawn between similar responses.

Figure 3. Concept map: Responses to "What was the most beneficial aspect of team-based learning?"

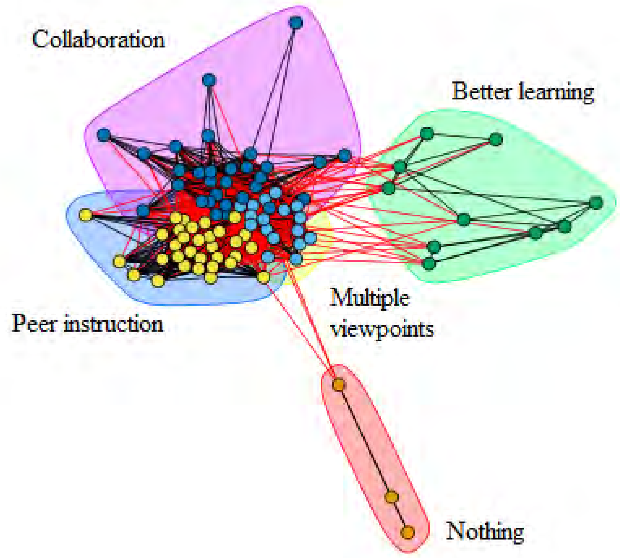


Table 10. Cluster composition: "What was the most beneficial aspect of team-based learning?"

Cluster	Size	Representative comment
Peer instruction	32	"Team members can teach each other, and members that understand concepts other members don't can try to explain it in a way that's different from how the teacher explained it."
Collaboration	30	"I like how when I work in a group everyone gets to combine their ideas and come up with the solution."
Multiple viewpoints	17	"Finding out how other people think about solving problems"
Improved learning	10	"I felt like I actually learned it as opposed to traditional where you just learn it for a test."
Nothing	3	"Nothing really"
Peer instruction	32	"Team members can teach each other, and members that understand concepts other members don't can try to explain it in a way that's different from how the teacher explained it."

Finally, students were asked, "What was the least beneficial aspect of team-based learning?" Six clusters, summarized in table 11, emerged in the concept map, as well as eight statements that neither author deemed similar to any others (aggregated in table 11 as "Singletons").

Table 11. Cluster composition: "What was the least beneficial aspect of team-based learning?"

Cluster	Size	Representative comment
Unproductive struggle	30	"Sometimes we would all be stuck on a problem and wouldn't get any progress done."
Teammates	15	"Some group members aren't prepared to do the work of the day and don't help"
More lecture	13	"Lack of lecture"
Nothing	9	"I can't think of any downsides"
Singletons	8	–
Prefer traditional	6	"Traditional learning is the way I learn better"

DISCUSSION

Below, we focus on our five research questions, with student comments from the open-ended survey questions and focus groups reported to triangulate the quantitative results presented above.

Q1: Does team-based inquiry learning increase students' content mastery?

There was not a significant difference between the sections using team-based inquiry learning and those using lecture during the quasi-experimental study, but aggregating the results for all students in the section of Linear Algebra taught via team-based inquiry learning across the four semesters showed that these students mastered more content than did the self-selected lecture students. We also find it instructive to look at the change in content mastery over the four semesters in the study (table 6). It is notable that content mastery increased over time; in particular, the students in the third and fourth semesters (all team-based inquiry learning) had significantly greater content mastery than did those in the first semester (half of the sections using team-based inquiry learning, the other using half lecture), with effect sizes of r=0.25 and r=0.45, respectively. Overall, we view this as fairly robust evidence that team-based inquiry learning leads to increased content mastery, as has been shown previously for both team-based learning (Haidet, Kubitz, and McCormack 2014; Liu and Beaujean 2017) and inquiry-based learning (Laursen et al. 2011).

We propose two causes for this increase in content mastery over time: (1) the instructors improved as facilitators with experience, and (2) the materials were revised over time. For example, one issue we encountered as facilitators was that because of the nature of the inquiry activities, students were often writing and documenting their solutions using poor, misleading, or incorrect notation, which they then replicated on assessments. Now, we know that while teams are working on an activity, one of our roles as facilitators is to circulate the room and point out errors in notation and help correct them. Additionally, when a team is reporting their reasoning, we find it helpful to play the role of scribe and document their reasoning on the board at the front of the room, clarifying and providing precise notation as needed. This provides students with a model of how to transcribe their thinking correctly and precisely for a particular problem. We refer the reader to Lewis, Clontz, and Estis (2019) for further discussion of facilitation in team-based inquiry learning classes.

The second, and in our view more impactful, factor in increasing content mastery was revision of the course materials over time. The highest mastery was in the third and fourth semesters of the study, which is when new instructors were brought in to teach: two new instructors taught the third semester and the fourth semester included one new instructor, one instructor from the previous semester, and one of the original instructors (the first author). However, the bulk of the changes to the materials occurred after the first and second semesters. With two instructors using these materials simultaneously in these first two semesters, we took notes after each class meeting about what went well, what did not go well, and implemented corresponding changes to the material. One metric illustrating this is the number of changes to the materials repository: 52 percent of changes were made during the initial semester, 31 percent in the second semester, and only 3 percent and 2 percent, respectively, in the third and fourth semesters. These changes included simple tweaks such as minor timing adjustments, improved phrasing to remove ambiguity, or the addition of an extra prompt of scaffolding, but also some more major changes were made between semesters, such as moving certain topics to different points in the semester, revising the readiness assurance materials, and even combining two modules into one.

Q2: Does team-based inquiry learning increase students' flexibility in solving problems?

During the quasi-experimental semester, we observed students in the team-based inquiry learning section were more likely than those in lecture-based sections to take a more flexible approach when computing determinants (p=0.0037). When interpreting this, it is important to note that students in the lecture section were shown multiple approaches to the problem by the instructor. However, it seems that merely being shown multiple techniques does not lead to students learning the concept at a deep enough level to flexibly use multiple techniques.

We propose that three aspects of team-based inquiry learning's framework support students' improved flexibility in solving problems. First, students work in teams on the activities, thus allowing them the opportunity to see how their teammates might approach problems differently (a form of peer instruction, which has previously shown to improve student learning in mathematics and other disciplines: Lasry, Mazur, and Watkins 2008; Miller, Santana-Vega, and Terrell 2006). This was pointed out by students in the focus group: one student observed, "A lot of times there is an easier way to go about it. Me and Jason are on the same team; if he does it one way and I see an easier way, I can show him that. And it'll make a little more sense to him. [Jason agreed]." This is also reflected in students' responses to the survey question "What was the most beneficial aspect of team-based learning?" Three overlapping clusters (peer instruction, multiple viewpoints, and collaboration: see figure 3) indicate that students broadly found value in learning from their peers and seeing how others approached problems.

Second, part of this pedagogy involves comparing responses across teams. This allows the instructor to highlight different approaches taken by different teams, even if they ended up at the same final answer. A priori, this may not seem very different from the instructor's presenting multiple approaches, as was done in the lecture sections of the quasi-experiment. However, research in secondary education has shown that this reflective and evaluative step (that is, evaluating their own and other teams' approaches) is beneficial to students developing flexibility (diSessa and Sherin 2000; Uesaka and Manalo 2006); students being presented multiple techniques in a lecture may not be engaging in an evaluative process. We note that in most of the students' survey responses indicating that they found seeing other students' thinking was valuable, it was unclear whether they were referring merely to their own teammates, or to other teams' thinking as well.

Finally, the realization of team-based inquiry learning as a mode of inquiry-based learning is also likely contributing to students' developing more flexible problem-solving skills. Indeed, Laursen, Hassi, Kogan, Hunter, and Weston (2011) in their multi-institution study report from student interviews that students felt inquiry-based learning helped them to approach solving problems more flexibly. However, we note that most interpretations of inquiry-based learning are also collaborative learning to some degree, so further research is likely needed to distinguish the effects of inquiry from the effects of collaboration.

Q3: How do the individual components of team-based inquiry learning support student learning?

Of the various graded components of the sections taught with team-based inquiry learning, we found that the individual readiness assurance tests and class attendance were both moderately correlated with the number of standards mastered, while the peer evaluations and team readiness assurance tests were not. This finding—that peer evaluations are not correlated with performance—replicates an earlier such finding (see Dingel, Wei, and Huq 2013). Student responses to survey questions and in the focus groups indicated that they found great value in the collaborative inquiry activities that made up the bulk of class time. We find the clusters of responses to the question "What was the most beneficial aspect of team-based learning?" (figure 3) illustrate this quite well: the opportunities to collaborate allowed students to learn from their peers and see multiple viewpoints and approaches to each problem; this in turn should lead to deeper learning.

The focus groups were asked, "Were there specific design aspects of the course that impacted your learning?" Several students pointed out the opportunity to struggle with new ideas, a key aspect of inquiry-based learning, led to deeper learning. One student said,

> I had a teacher in high school who said in order for you to really genuinely learn you have to struggle . . . [The professor] will put a question on the board that you may not recognize initially. So when you sit there and say I have no idea how to go about this it and it gets some gears turning that you may not have thought you actually had because you are going through the process like ok it's this, it's this it's not this . . . I don't know if he means to do it or not, but maybe putting some things up there that [are] foreign to everybody it just gets you brainstorming and actually struggling to learn.

Additionally, students in the focus group recognized the value of the readiness assurance process in reducing their cognitive load during class. One student noted, "It helped to have that refresher on that when you're learning, because the small things that you should already know are not taking away from you learning the other topics that we had to cover." To this, another student replied, "You do not have to have that refresher in class time, you can have it before class time so you can have more time in class."

Q4: How do students respond to team-based inquiry learning?

Overall, student response to team-based inquiry learning was positive, though students identified some concerns. Students broadly recognized the value of collaboration, peer instruction, and seeing multiple viewpoints, with some tying this to better learning. One student in the focus group noted, "You can go over things in lecture and see concepts, but when you stand up and do it hands on, that is probably the best learning experience that I had: doing it and seeing what needs to be done for each topic and concept."

There were student concerns. While some students merely indicated a preference for lecture (perhaps because they are used to it), others had more substantive criticisms. The largest concern (see table 11) seemed to be that students were sometimes engaging in unproductive, rather than productive, struggle. Indeed, one of the most difficult aspects of preparing the instructional materials for the sections using team-based inquiry learning was ensuring that the level of difficulty of the task was neither too difficult nor too easy. Our aim was to develop tasks that remained in the students' *zone of proximal development* (Vygotsky 1962, 103); that is, the team application activities were more challenging than students could do independently, yet they were at a level of difficulty that the students could achieve through collaboration and instructional support. This challenge of writing activities at the correct level is not unique to team-based inquiry learning, and it has similarly proved a challenge in related pedagogies such as peer-led team learning (Merkel and Brania 2015). Clearly, not all of our activities were within students' zone of proximal development, though the materials improved with revision between semesters, as evidenced by the monotonic growth in student mastery over time. However, it is important to note that this suggests instructors wanting to create materials for a course using team-based inquiry learning will likely need a few semesters of feedback and refinement to achieve optimal results.

Another explanation is that while students were struggling, their perception was that the struggle was unproductive, while in fact, it was productive. This interpretation suggests that instructors using the team-based inquiry learning need to pay close attention to ensure students know the purpose of the pedagogy. The success of this approach would then seem to rely on the establishment of a healthy classroom culture that provides a safe space for students to struggle and fail as part of the learning process. We note that these two explanations are not mutually exclusive: both are likely true, and thus they require attention by the practitioner.

The second major concern students had was that some felt that good teammates were required to succeed (although the size of this cluster, 15 students, was only slightly larger than the cluster who explicitly said nothing was least effective, 9 students). Although team-based inquiry learning includes several mechanisms to promote effective teamwork, such as peer evaluations and the readiness assurance process, students expressed challenges with working with their teammates. For example, students commented that sometimes teammates were absent or unprepared. Additionally, some students mentioned interpersonal issues affected their team performance. As one student said, "My team members NEVER let me participate because we had the overachieving guy who had to do everything HIS way. So I did not receive the opportunity to work as a 'team.'" These comments highlight a need for instructors to pay close attention to establishing a constructive and inclusive classroom culture. Additionally, instructors need to demonstrate effective facilitation skills, including all learners in the class discussions and clearly summarizing key ideas (Gullo, Ha, and Cook 2015; Lane 2008).

Q5: Does team-based inquiry learning have an effect on students' communication apprehension?

We found that team-based inquiry learning significantly decreased communication apprehension in women (p=0.016), but not men. Interestingly, all four subscales of communication apprehension decreased for women. While it certainly seems plausible that working in teams would reduce communication apprehension along the group subscale, it is somewhat unexpected that this carries over to all others, particularly the meeting subscale.

Moreover, while researchers have found women to have higher levels of communication apprehension than men (Simons, Higgins, and Lowe 1995; Williams 2000), it is unclear why team-based inquiry learning appears to reduce communication apprehension only in women. It is well established (e.g., Sadker and Sadker 2010, 43) that instructors call on male students more often than they do female students (which could, over time, increase communication apprehension); perhaps the reporting structure of team-based inquiry learning, in which instructors ask teams rather than individuals to share their reasoning, helps instructors reduce their (conscious or unconscious) bias.

This result takes on additional importance given the recent work of the first author (Lewis (2020), who studied how standards-based grading can be used to mitigate the impact of test anxiety on student performance. He found that the use of voluntary office hours for reassessments (rather than in-class written assessments) was an effective avenue for students with high test anxiety to demonstrate mastery of course content. However, there was a negative correlation between communication apprehension and the number of voluntary office hours reassessments attempted, indicating that these office hours reassessments are beneficial to students with high test anxiety but low communication apprehension. Thus, our findings suggest that using team-based inquiry learning in conjunction with standards-based grading could be particularly beneficial to women with high test anxiety and high communication apprehension. We conclude that in fields such as mathematics, in which women are traditionally underrepresented, team-based inquiry learning may be a way to mitigate some existing structural inequities.

Limitations and future work

The chief limitation of this work is that it is limited to intermediate-level post-secondary mathematics courses. Since inquiry-based learning has been used predominately in upper level mathematics courses (Laursen et al. 2011), the potential for applying team-based inquiry learning to introductory postsecondary and secondary mathematics courses, should be studied. The approach is readily adaptable to other disciplines with modes of inquiry-based learning, particular science courses such as physics and chemistry; further studies in these disciplines would be welcome.

A second limitation is that the study design required the use of standards-based grading in all of the courses. It is possible some of the positive benefits of team-based inquiry learning described here are instead attributable to standards-based grading, which has positive effects for students (Lewis 2020). Future work investigating team-based inquiry learning in the absence of standards-based grading could help distinguish the effects of the two.

One key question inviting future work is establishing the exact mechanism by which team-based inquiry learning is effective. While it is likely a combination of several components, we propose that the readiness assurance process is a key driver of the success of team-based inquiry learning. In particular, as suggested in the introduction, we believe our use of the readiness assurance process to review prerequisite material reduced students' cognitive load in class, allowing them to better learn new material; a more detailed investigation of this hypothesis is warranted. Indeed, the readiness assurance process alone may be valuable, for example in a lecture setting, but in light of the existing literature on the benefits of inquiry activities (e.g., Laursen et al. 2011), we believe the comprehensive pedagogy of team-based inquiry learning will yield the best results. Future work should also be conducted into the scalability of team-based inquiry learning. Studies with larger sample sizes may be able to determine how the findings described here might be differentiated among different groups of learners.

CONCLUSION

In summary, our study found that, over time, team-based inquiry learning led to increased content mastery in a mathematics course. In particular, we found that team-based inquiry learning improves students' flexibility in problem solving (as compared to that of students in a "traditional" lecture-based setting), which we interpret as evidence of deeper learning. Our findings suggest that team-based inquiry learning is an effective pedagogy suitable for application in a variety of disciplines with inquiry-learning traditions.

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