Inquiry-Based Calculus I: What is the impact on student performance?

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While active learning has been found to support student success, it has not yet emerged as the dominant instructional approach in undergraduate mathematics (Stains et al., 2018). This study focuses on student performance in undergraduate Calculus I where we compared the performance of students in inquiry-based (IBL) Calculus I with students in non-IBL Calculus I courses. Additionally, we examined the performance of first-year and upper-year students as well as students who were or were not pursuing a math-intensive major. Students in IBL Calculus performed on the final exam an average of nine percentage points higher than those enrolled in non-IBL Calculus. Differences in performance between first-year students and upper-year students and between students majoring in math-intensive fields and those in non-math-intensive narrowed in the IBL classes. This study aims to add to the ever-growing body of research showcasing the benefits of IBL in improving student course performance.

Keywords: inquiry-based learning, calculus, student performance

In 2016, the Conference Board of Mathematical Sciences (CBMS), a coalition of nineteen professional undergraduate mathematics organizations, issued a compelling statement urging "…institutions of higher education, mathematics departments, and the mathematics faculty, public policy-makers, and funding agencies, to invest time and resources to ensure that effective active learning is incorporated into post-secondary mathematics classrooms" (CBMS, 2016, p. 1). Research has consistently demonstrated the positive impact of active learning and student-centered approaches on improved student course performance (e.g., Abdi, 2014; Bruder & Prescott, 2013; Dunnigan & Harlow, 2021; Freeman et al., 2014), a deeper appreciation of challenging content (Cilli-Turner, 2017), and increased persistence and confidence in doing mathematics (Laursen et al., 2011).

Additionally, the attrition of students from STEM fields is a pressing concern, particularly when high-achieving students who are often successful in other subject areas are leaving STEM (Olson & Riordan, 2012). Troublingly, almost 90% of students cite poor instruction as a factor in leaving STEM (Kung & Speer, 2020). Moreover, Calculus has been noted as one of the largest gatekeepers and barriers for STEM majors, ultimately excluding students who would otherwise be successful (Bressoud et al., 2013; Rasmussen & Ellis, 2013). However, there are signs of improvement as active learning pedagogies have helped increase student performance (Freeman et al., 2014) and even significantly decreased achievement gaps for underrepresented students in STEM (Theobald et al., 2020).

Although mathematics departments have the support of organizations like the CBMS and MAA (Abell et al., 2018; CBMS, 2016), and there are many positive findings regarding the benefits of active learning in undergraduate STEM courses, active learning pedagogies are still not the dominant instructional method in undergraduate STEM (Stains et al., 2018). Because of active learning's overwhelmingly favorable results in supporting STEM students (e.g., Bruder & Prescot, 2013; Laursen et al., 2011), we studied the effects of inquiry-based learning (IBL), a specific type of active learning, on student course performance in an undergraduate Calculus I course. We contribute to the growing body of research on the effectiveness of IBL in improving student course performance. Additionally, this study explores the benefits of IBL on course performance for various groups of students who often struggle in STEM, such as upper-level students (Gregg-Jolly et al., 2016) and students majoring in fields that are not math-intensive such as the life sciences (Kokkelenberg & Sinha, 2010; Rasmussen & Ellis, 2013). In particular, we use final exam scores to measure differences in student performance between first-year students and upper-year students as well as between students in math-intensive majors and non-math-intensive majors. By shedding light on these aspects, we seek to contribute to the existing body of research on IBL implementation and, in turn, encourage other instructors to embrace active learning pedagogies. Specifically, this study seeks to answer the following research questions:

1. How does the final exam performance compare between students enrolled in inquiry-based (IBL) Calculus I and those in non-inquiry-based (non-IBL) Calculus I?
2. Do IBL and non-IBL final exam scores differ for first-year and upper-year students?
3. Do IBL and non-IBL final exam scores differ for students enrolled in math-intensive majors and students enrolled in non-math-intensive majors?

Inquiry-Based Learning

Inquiry approaches to undergraduate education have been gaining momentum (Laursen & Rasmussen, 2019) since the CBMS released their statement supporting active learning (CBMS, 2016). One such approach is IBL, where students work through a "carefully scaffolded sequence of mathematical tasks" (Ernst et al., 2017, p. 570) to construct their mathematical knowledge under the guidance of an instructor. In IBL, students actively communicate with their peers, posing questions and testing conjectures, fostering a collaborative and interactive learning environment. IBL differs from other active learning methods in three distinct ways. First, strategically sequencing tasks allows topics to build on each other throughout the semester instead of using a task unrelated to others. Second, IBL encourages students to actively reinvent mathematics they knew before or create mathematical ideas that are new to them. Third, IBL fosters critical reflection among students and instructors on their perceptions of mathematics and what it means to know, teach, and do math (Laursen & Rasmussen, 2019).

Table 1. The four pillars of inquiry.

	Mathematical Space	**Social Space**
Student Behavior	Engage deeply with meaningful tasks	Collaborate with classmates in processing ideas
Instructor Behavior	Inquire into student thinking and reasoning	Foster equity, respect, and responsibility

Adopted from Foley (n.d.).

The key tenets of IBL are built on the four pillars of inquiry (see Table 1), which consider the behaviors and actions of students and instructors mathematically and socially (Laursen & Rasmussen, 2019). In the mathematical space, students deeply engage with meaningful tasks and work collaboratively to process intricate mathematical concepts. Concurrently, the instructor tries to draw out and understand students' thinking and reasoning, aiming to acknowledge each individual's unique perspective. In the social space, students collaborate with their peers, exchanging mathematical ideas and collectively constructing their understanding of concepts, leading to deeper mathematics learning. The instructor's social role is to cultivate an inclusive learning environment where every student's voice is respected, and students take responsibility for their learning.

Methods

Context

In this study, we analyzed three consecutive semesters of implementation of IBL and non-IBL Calculus I courses at a large, public, midwestern university. Instructors of the IBL and non-IBL sections varied each semester, and instructors had the freedom to choose which type of section they wanted to teach. Importantly, no explicit indication in the course offerings differentiated the IBL and non-IBL sections. Therefore, students enrolling in these sections were unaware of the pedagogical style beforehand. All sections shared the same learning objectives, met for the same amount of time per week, had approximately the same number of enrolled students, and used the same final exam, making them suitable for comparing the pedagogical differences between IBL and non-IBL Calculus and their impact on student performance.

The non-IBL sections had a single instructor in class, while the IBL sections incorporated graduate and undergraduate students as learning assistants (LAs) to support group work (see Webb et al. 2014), aiming for an instructor-to-student ratio of 15:1. In the IBL sections, students took an active role in their learning and spent most of their time working collaboratively in small groups, engaging with *Active Calculus* tasks (Boelkins et al., 2018). Instructors and LAs provided support by addressing difficulties, asking questions, checking comprehension, encouraging discussion, and fostering independent problem-solving skills rather than providing direct answers to student questions. On the other hand, the non-IBL sections primarily relied on lecture-based instruction from the instructor. While some non-IBL sections included elements of IBL Calculus, such as small group work, they did not emphasize students' responsibility for developing strategies, procedures, or conceptual understanding. Instead, instructors primarily directly presented these procedures, strategies, and key concepts to students.

Data Collection & Analysis

The participants in this study were students enrolled in either non-IBL (n = 381) or IBL Calculus I (n = 310). In both IBL and non-IBL Calculus sections, all students completed the same standards-based final exam each semester, designed to align with specific course objectives and assess conceptual and procedural understanding. While the exams varied slightly across semesters, they were created by the same calculus coordinator, who adhered to the same exam guidelines, making it suitable to compare final exam performance across semesters. We used Welch's t-test ($\alpha = .05$), a robust test, to account for the unequal variances between the populations to compare exam scores for groups of students in both IBL and non-IBL sections. We also used Cohen's d (Cohen, 1988) effect sizes to help determine the practical significance of the differences observed by certain groups. For these analyses, we followed Cohen's recommended benchmarks for small (d = .20), medium (d = .50), and large (d = .80) effects. Finally, we ran these same tests on subgroups of students including first-year and upper-year students, in addition to students pursuing math-intensive (MI) majors, those that required a mathematics course beyond Calculus II, or non-math-intensive (NMI), majors where Calculus I or Calculus II was the terminal mathematics course required at our institution.

Results

Here, we present our findings organized by research question. First, we compare IBL and non-IBL participants' performance on a standards-based final exam. Then, we discuss how participants' scores differed based on whether they were first-year versus upper-year students or students majoring in a math-intensive field versus a non-math-intensive field.

IBL vs. Non-IBL Final Exam Performance

Overall, IBL students outperformed non-IBL students. As can be seen in Table 2, IBL participants' average final exam score was nearly a full letter grade higher than non-IBL participants' average final exam score. IBL participants' final exam scores (M = 68.37, SD = 16.82) were significantly higher, (t(687.21) = 6.59, p < .001), than the scores of non-IBL participants (M = 59.24, SD = 19.65). The effect size (Cohen's d = 0.50) indicated a moderate difference in the final exam performance of IBL vs. non-IBL participants. Thus, students in IBL scored significantly and noticeably better, on average, than their peers in non-IBL, averaging over 9 percentage points higher on the final exam.

Table 2. IBL vs. Non-IBL Participants' Exam Performance.

	n	*M*	*SD*	*t*	*p*	Cohen's d
IBL	310	68.37	16.82	6.59	<.001	0.50
Non-IBL	381	59.24	19.65			

First-Year vs. Upper-Year Final Exam Performance

The average final exam score of first-year students (M = 67.64, SD = 17.45) across both IBL and non-IBL sections was significantly higher (t(679.373) = 5.80, p < .001) than the average final exam score of students in their upper years of school (M = 59.49, SD = 19.29). The effect size (Cohen's d = 0.44) indicated a moderate difference in the final exam performance of first-year and upper-year participants. As seen in Table 3, first-year participants' final exam score average was nearly eight percentage points higher than upper-year participants' final exam average.

Table 3. First-Year and Upper-Year Participants' Exam Performance in IBL and Non-IBL

	First-Years	Upper-Years
IBL	71.58 (n=132)	65.42 (n=173)
Non-IBL	64.76 (n=181)	54.34 (n=199)
Total	67.64 (n=313)	59.49 (n=372)

We further examined the differences in exam scores of first-year and upper-year students between the IBL and non-IBL sections. We found that upper-year IBL students' average final exam score (M = 65.42, SD = 16.99) was significantly higher (t(300.572) = 3.54, p < .001) than upper-year non-IBL students' average final exam score. The effect size (Cohen's d = 0.60) showed a strong difference between the scores of upper-year students in IBL and non-IBL, indicating IBL may have better served upper-year students than did non-IBL. Additionally, first-year IBL students' average final exam score (M = 71.58, SD = 15.83) was significantly higher (t(300.572) = 3.54, $p < .001$) than first-year non-IBL students' average final exam score (M = 64.76, SD = 18.06). The effect size of (Cohen's d = .40) indicated a moderate difference in exam scores among first-year students, with those in IBL scoring about 7 percentage points higher on the final exam than the first years in non-IBL.

Furthermore, we compared final exam scores between first-year and upper-year students enrolled in the same type of section. The average final exam score for first-year non-IBL students (M = 64.76, SD = 18.05) was significantly higher (t(377.983) = 5.38, $p < .001$) than the average final exam score for upper-year non-IBL students (M = 54.34, SD = 19.72). The effect size (Cohen's d = 0.55) indicated a moderate difference in the final exam performance of first-year and upper-year students in non-IBL. In the IBL sections, the average final exam score for first-year students (M = 71.58, SD = 15.83) was significantly higher (t(291.193) = 3.26, $p < .001$) than the average final exam score for upper-year students (M = 65.42, SD = 16.99). Thus, in both IBL and non-IBL, first-year students were performing better than upper-year students. However, the effect size (Cohen's d = 0.37) was not as strong for IBL as it was for non-IBL (Cohen's d = 0.55), indicating a larger difference between first-year and upper-year students in non-IBL. This is evident in the percentage point gap of nearly 6 percent between first-year and upper-year students in IBL compared to over 10 percent between first-year and upper-year students in non-IBL. Therefore, it seems that IBL may have helped lessen the gap between first-year and upper-year students' final exam performance.

Math-Intensive vs. Non-Math-Intensive Final Exam Performance

Regardless of being in an IBL or non-IBL section, the average final exam score for MI majors (M = 63.34, SD = 19.55) was not significantly higher (t(477.703) = 0.39 p = .697) than the average final exam score for students in NMI majors (M = 62.74, SD = 18.50) (see Table 4). The effect size (Cohen's d = 0.03) indicated very little difference in the final exam performance based on whether students were required to take a course beyond Calculus II for their major. Thus, average exam scores did not differ based on the intensity of mathematics courses required for a major.

Table 4. Math-Intensive and Non-Math-Intensive Participants' Exam Performance in IBL and Non-IBL

	Math-Intensive	Non-Math-Intensive
IBL	67.18 (n = 104)	68.55 (n = 201)
Non-IBL	60.46 (n = 139)	57.77 (n = 235)
Total	63.34 (n = 243)	62.74 (n = 436)

We next examined the differences between MI and NMI majors' exam scores for students enrolled in IBL or non-IBL sections. Math-intensive IBL students' average final exam score was

(M = 67.18, SD = 18.54) significantly higher (t(299.453) = 2.72, p = .007) than the average final exam score for MI non-IBL students (M = 60.46, SD = 19.85). The effect size (Cohen's d = 0.35) indicated a small to moderate difference between MI majors in IBL and non-IBL, with a difference of about 7 percentage points on the final exam. Thus, the averages of MI majors in IBL were noticeably higher than MI majors in non-IBL. Similarly, NMI IBL students' average final exam score (M = 68.55, SD = 15.78) was significantly higher (t(433.295) = 6.428, p < .001) than the average final exam score for NMI non-IBL students (M = 57.77, SD = 19.22). The effect size (Cohen's d = 0.61) indicated a moderate and stronger effect than those students in MI fields. NMI majors in IBL scored an average of about 11 points higher on the final exam than NMI majors in non-IBL. These results indicate that IBL benefited both MI and NMI majors and it was not the case that MI majors outperformed NMI majors or masked poor performance from NMI majors.

Finally, we compared the exam scores of MI and NMI majors enrolled in courses with the same pedagogical approach. Within a type of instruction, typically MI majors and NMI majors performed about the same. The average final exam score for MI non-IBL students (M = 60.46, SD = 19.85) was not significantly higher (t(282.356) = 1.28, p = .201) than the average final exam score for NMI non-IBL students (M = 57.77, SD = 19.22). The effect size (Cohen's d = 0.14) indicated a small difference in the final exam performance of non-IBL MI and NMI participants. For IBL participants, the average final exam score for MI majors (M = 67.18, SD = 18.54) was not significantly lower (t(181.566) = – 0.64, p = .523) than the average final exam score NMI IBL students (M = 67.18, SD = 18.54). The effect size (Cohen's d = –0.08) indicated little difference in the final exam performance between the majors. The NMI majors scored over one percentage point higher than MI majors in IBL. In contrast, in non-IBL, NMI majors scored nearly three percentage points lower on average than MI students.

Discussion

This study provided insights into the effects of IBL on student performance in undergraduate Calculus I. We aimed to compare student performance on a common final exam between the following populations of interest: 1) students in IBL Calculus and those in non-IBL Calculus, 2) first-year and upper-year students, and 3) students in math-intensive majors and students in non-math intensive majors. We specifically choose to examine comparisons between year and major because both our own experience and research has shown that upper-years (Gregg-Jolly et al., 2016) and those not in math-intensive fields (Kokkelenberg & Sinha, 2010; Rasmussen & Ellis, 2013) struggle in calculus.

Overall, IBL participants outperformed non-IBL participants on the final exam, with a difference of nine percentage points (see Table 2). Although this study used a smaller sample than some prior studies (Freeman et al., 2014), the fact that the final exam was relatively consistent across semesters, made by the same course coordinator, using the same guidelines, and was administered to all Calculus I students in courses with similar student populations helped us draw strong conclusions about student performance. The significant difference and moderate effect size (Cohen's d = 0.50) reinforces the idea that IBL can improve student performance in Calculus I; students enrolled in IBL sections scored nearly a letter grade higher than students enrolled in non-IBL on the same final exam.

Unsurprisingly, overall, first-year students performed significantly better than upper-year students. However, the largest gap in final exam performance was between upper-year students in IBL and upper-year students in non-IBL. Thus, IBL significantly benefited both first-year and upper-year students' course performance. Moreover, we see these differences in performance between first-year and upper-year students narrow in IBL. The IBL structure provided a learning environment that focused on (1) deliberate practice, where students worked on scaffolded tasks and received immediate feedback from course instructors, and (2) a culture of inclusion that fostered respect among students and demonstrated confidence and interest in each student's individual success in calculus (Theobald et al., 2020). We claim this structure supported these upper-year students who often struggle in STEM courses as they feel the pressure of making academic and life decisions about their chosen career path (Gregg-Jolly et al., 2016) which helped lessen differences in performance between first-year and upper-year students.

In terms of the intensity of mathematics required for students' majors, we did not find a significant performance difference between whether or not a student's major required a mathematics course beyond Calculus II. However, both students who required a math course beyond Calculus II and students whose terminal math course was either Calculus I or Calculus II benefited significantly from the IBL pedagogical approach. Effect sizes indicated the largest difference to be between NMI majors in IBL and NMI majors in non-IBL with students in IBL scoring nearly 11 percentage points higher on the final exam, which is critical as NMI majors are those students who most frequently leave calculus (Rasmussen & Ellis, 2013). By incorporating IBL, students enrolling in these majors succeeded at a greater rate, and hopefully, in turn, persisted with their majors.

Conclusion and Limitations

Overall, our results indicate the potential for benefits of instruction informed by an IBL approach. Two groups of students in particular benefited: upper-year students and students in non-math-intensive majors, who are traditionally less successful in STEM (Gregg-Jolly et al., 2016; Kokkelenberg & Sinha, 2010; Rasmussen & Ellis, 2013). In some ways, we anticipated better performance of IBL students than non-IBL peers, as suggested by prior research (Freeman et al., 2014; Laursen et al., 2011). However, further data analysis revealed subtle differences in how those benefits played out. Notably, differences in performance between upper-year and first-year students was significantly smaller in the IBL classes than non-IBL. Similarly, there were no significant differences in performance for NMI majors and MI majors in IBL classes, debunking the notion that an IBL approach is only for mathematically strong students. Thus, not only was stronger course performance associated with the IBL approach, but an IBL approach may have also better supported students who traditionally leave STEM fields (Gregg-Jolly et al., 2016; Kokkelenberg & Sinha, 2010; Rasmussen & Ellis, 2013). By incorporating IBL, college math instructors can create a learning environment that supports overall student success in Calculus I and specific populations who traditionally struggle in STEM. Although we did not have adequate sample sizes for analyses in this study, future research could examine the effects of IBL on differences in performance of other traditionally underrepresented groups in STEM: women, black and Latinx students, first-generation students, and students of low socioeconomic status (Theobald et al., 2020).

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