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Brief Report

Benefits for Women and Men of Inquiry-Based Learning in College Mathematics: A Multi-Institution Study

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Slow faculty uptake of research-based, student-centered teaching and learning approaches limits the advancement of U.S. undergraduate mathematics education. A study of inquiry-based learning (IBL) as implemented in over 100 course sections at four universities provides an example of such multi-course, multi-institution uptake. Despite variation in how IBL was implemented, student outcomes are improved in IBL courses relative to traditionally taught courses, as assessed by general measures that apply across course types. Particularly striking, the use of IBL eliminates a sizable gender gap that disfavors women students in lecture-based courses. The study suggests the real-world promise of broad uptake of student-centered teaching methods that improve learning outcomes and, ultimately, student retention in college mathematics.

Key words: Inquiry-based learning; Undergraduate; Women; Scale-up of reform

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Certain reforms of classroom practice improve undergraduate education in mathematics, engineering, and the sciences. Research in cognitive science and education offers persuasive evidence that students can and do learn better through active, student-centered forms of instruction in college science (Deslauriers, Schelew, & Wieman, 2011; Hake, 1998; Ruiz-Primo, Briggs, Iverson, Talbot, & Shepard, 2011; Springer, Stanne, & Donovan, 1999) and mathematics (Kwon, Rasmussen, & Allen, 2005; Rasmussen, Kwon, Allen, Marrongelle, & Burtch, 2006).

Evidence from secondary school mathematics lends further support to the effectiveness of student-centered instructional approaches (Boaler, 1998; Boaler & Staples, 2008; Clarke, Breed, & Fraser, 2004; Slavin, Lake, & Groff, 2009), yet relatively few students experience these proven, high-impact educational practices during college (Kuh, 2008). Slow faculty uptake of research-based, student-centered teaching methods (DeHaan, 2005; Fairweather, 2008; Walczyk, Ramsay, & Zha, 2007) limits large-scale implementation and institutional commitment. To date, the evidence base is slim about successful moves from proof of concept to implementation of such pedagogical reforms on a scale that broadly improves undergraduate student learning.

To examine the scale-up of student-centered methods to multiple courses and institutions, we studied the implementation of a student-centered approach known as inquiry-based learning (IBL) in undergraduate mathematics courses at four universities. Like other inductive teaching approaches (Prince, 2004), IBL methods invite students to work out ill-structured but meaningful problems (Yoshinobu & Jones, 2013). Following a carefully designed sequence of tasks rather than a textbook, students construct, analyze, and critique mathematical arguments. Their ideas and explanations define and drive progress through the curriculum. In class, students present and discuss solutions, alone at the board or via structured small group work, while instructors guide and monitor this process. In U.S. college mathematics, IBL approaches have grown not out of learning theory but through collegial sharing of the Socratic methods of topologist R. L. Moore (Coppin, Mahavier, May, & Parker, 2009), since modified to better incorporate peer interaction and serve diverse students. Today IBL practice is broadly consistent with modern understandings of human learning (Bransford, Brown, & Cocking, 1999).

Context of the Research

Independent, privately funded IBL Centers were established at four research universities to develop and promote IBL teaching in mathematics (http://eduadvance.org/centers.html). Our research study began after the IBL Centers' work had been ongoing for several years (for all study results, see http://www.colorado.edu/eer/research/steminquiry.html). Faculty at the IBL Centers developed and taught over 40 courses (e.g., analysis, number theory, cryptology, discrete mathematics, multivariable calculus, differential equations) to audiences from first-year honors students to upper-division mathematics majors and preservice elementary and secondary teachers. Each university independently recruited and prepared its instructors and selected courses for IBL treatment. The courses shared a general philosophy and a common set of teaching approaches but were diverse in structure, content, and local implementation. At the time of the study, each IBL course had been taught by several instructors with varied levels of teaching experience. Although these conditions posed challenges for the study design, they are typical of real-world contexts for educational reform.

In this brief report we document the implementation of IBL approaches on a broad scale and report selected student outcomes of IBL instruction as implemented at these institutions in courses where a comparison group of students in non-IBL sections was available. We highlight results that show differential outcomes by gender but include additional results to demonstrate that positive outcomes of IBL instruction are not limited to women.

Study Methods

Our study examined student learning and affective outcomes of IBL courses, their variation among student subgroups, and teaching and learning activities and processes. We used a quasi-experimental design because assignment of courses, instructors, or students to IBL or non-IBL approaches was outside our control. We labeled courses as IBL or non-IBL following each campus' designation of its courses but used classroom observations to establish that IBL courses in fact used instructional practices that were problem-driven, student-centered, and clearly different from those used in non-IBL courses. To mitigate possible student self-selection effects, we controlled for preexisting differences that could be measured. Also, due to the large range of courses and audiences as well as variability in how faculty implemented IBL, we used general measures to examine student outcomes—surveys, interviews, and grades—rather than course-specific content assessments. Data were gathered from over 100 course sections at four campuses in 2008–2010. The report by Laursen, Hassi, Kogan, Hunter, and Weston (2011) offers a very detailed exposition of our methods.

To characterize the educational intervention and its variability, we observed 42 course sections that represented the full span of IBL courses and comparable non-IBL courses at the IBL Centers. These courses represented a variety of content domains and student populations, including mathematics majors and preservice teachers. Each course was observed by trained observers 4–8 times through the term (averaging 313 minutes each), using a protocol focused on real-time documentation of various classroom activities, rather than instructors' skill in implementing them (Laursen, Hassi, Kogan, Hunter, & Weston, 2011). Observers also rated their perceptions of classroom atmosphere and interactions. Descriptive statistics were used to compare the frequency of different classroom activities, both as a fraction of all class time observed and by the number of distinct episodes of activity bounded by a change to a new activity type.

Survey measures included a pre- and post-course survey of students' attitudes, beliefs, and approaches to learning mathematics (which include constructs of confidence and interest), using items based on a detailed literature review (Laursen et al., 2011). On the postsurvey, students also reported their learning gains on a mathematics-focused version of the Student Assessment of their Learning Gains, hereafter referred to as SALG-M. The SALG survey (Seymour, Wiese, Hunter, & Daffinrud, 2000) is a self-report instrument with psychometric properties similar to other validated self-report instruments (Falchikov & Boud, 1989; Kuh, 2001). Learning gains items used a 5-point scale and attitudinal items a 7-point Likert scale.

The survey data were analyzed for students in *math-track* courses only; these courses targeted students majoring in mathematics or mathematics-intensive fields such as engineering and science, as distinguished from courses that targeted preservice elementary and secondary teachers (for more information about preservice teacher data, see Laursen, Hassi, & Hough, 2014). The same survey was given to students in all courses, thus all students in math-track courses reported on their interest and confidence in mathematics as well as their interest and confidence in teaching mathematics, regardless of their major. Sample sizes for the post-only survey (*N* = 902) and pre- and post-surveys (*N* = 573) are unequal because not all students completed precourse surveys. Statistical analyses included both descriptive and inferential statistics using parametric and nonparametric tests; methods for the propensity analysis and modeling study of gains are detailed below. Interviews (*N* = 110) with students, faculty, and teaching assistants triangulated the survey data. Results from other parts of the full study (Laursen et al., 2011), in particular data on student grades and course-taking patterns, are introduced in order to point out student outcomes more broadly or to help interpret results in the following sections.

Findings

Characterization of Classroom Practices

Observation data show clear differences between IBL courses and comparable non-IBL sections (Table 1). On average, over 60% of IBL class time was spent doing and discussing mathematics through student-centered activities including problem presentations, discussion, small group work, and computer work, while students in non-IBL courses spent 87% of class time listening to their instructors talk. IBL courses also showed greater student leadership, more student question-asking, and greater variety in classroom activities. They were rated more highly for a supportive classroom environment, students' intellectual contributions, and feedback to students on their work. Ratings of instructor behaviors (e.g. instructors expressing their own ideas) differed less between IBL and non-IBL courses. Overall, despite variation from course to course (as reported in Laursen, 2013), the IBL courses offered students notably different learning experiences from the lecture-based, non-IBL courses.

Table 1

Mean instructional characteristics of IBL (N = 31) and non-IBL (N = 11) classrooms

Observation variable	**IBL sections**[a]	**non-IBL sections**
I. Use of Class Time		
IBL classes spend more time in student-centered activities (student presentation, whole-class discussion, small group work, computer work) (% of observed class time)	62.4%	8.1%
IBL students spend less time listening to instructors (prepared lecture, spontaneous explanation) (% of observed class time)	27.0%	87.1%
IBL students frequently engage in student-centered activities (episodes/hour)	4.54	0.6
IBL classes change gears more often (all activities, episodes/hour)	8.61	3.28
IBL instructors give shorter lectures (minutes/lecture episode)	9.2	43.2
IBL class sizes were modestly but not significantly smaller.	19	48
II. Classroom Leadership Roles		
IBL instructors yield leadership to students for significant amounts of class time (% of class time with student, group, or class leading)	57%	6%
IBL students more frequently take a leadership role (episodes/hour)	4.0	0.4
III. Question-Asking Behaviors		
IBL students ask more questions (questions/hour)	13	5
More students ask at least one question in IBL classes (% of students/class period)	33%	14%
IV. Classroom Interactions and Atmosphere mean observer rating (standard deviation) for all observed class sessions; scale: 1 = *never*, 5 = *very often*		
Supportive work environment: composite of 6 ratings (students ask questions, review others' work, work together, get help; instructor gives help, tries to set positive atmosphere)	3.52 (0.61)	2.10 (0.56)
Student intellectual input: composite of 3 ratings (students express own ideas, set pace; instructor listens)	3.57 (0.37)	1.88 (0.66)
Instructor authority: composite of 3 ratings (instructor expresses own ideas, sets pace, summarizes material)	3.19 (0.40)	4.20 (0.43)
In-class assessment and feedback: composite of 2 ratings (students get feedback in class, instructor gives feedback)	3.38 (0.64)	1.61 (0.50)

Note. All differences are statistically significant at the $p < 0.001$ level (t-test, chi-square) except for class size, which is not significant. Standard deviations are given for categorical data in Section IV.

[a]Includes 18 math-track and 13 preservice teacher course sections, each observed multiple times; there is no significant difference between these groups. All non-IBL sections were math-track courses as no non-IBL courses were taught for preservice teachers..

Overall Student Outcomes

These instructional differences were mirrored by differences in student outcomes. On the SALG-M, students in IBL math-track courses reported greater learning gains than their non-IBL peers on every measure: cognitive gains in understanding and thinking; affective gains in confidence, persistence, and positive attitude about mathematics; and collaborative gains in working with others, seeking help, and appreciating different perspectives (Figure 1). In Laursen et al. (2011), we reported on qualitative analyses that corroborate the nature of these gains.

Separately, on the pre- and post-attitudinal survey, among IBL students, most interest and confidence measures remained flat or increased modestly from pre- to post-course, while the confidence of non-IBL students declined (Laursen et al., 2011). These modest changes overall serve to emphasize the differences that are revealed when data are disaggregated by gender (discussed below). Finally, data from separate samples of students who had previously taken these courses showed that IBL students earned as good or better mathematics grades than their non-IBL peers and took as many or more mathematics courses after participating in an intervention or comparative course (Kogan & Laursen, 2013). Overall, across all three types of measures, student outcomes from IBL classes were better or equal to those from non-IBL counterparts.

Gender differences. Particularly striking are the learning gains disaggregated by gender (Figure 1). Women in non-IBL courses reported substantially lower cognitive and affective gains than did their male classmates. In contrast, in IBL courses, women's cognitive and affective gains were statistically identical to those of men, and their collaborative gains were higher. Furthermore, in both types of course, women's subsequent grades were as good as those of their male peers (as reported in Kogan & Laursen, 2013). This suggests that learning gains reported by women in non-IBL classes reflect their weaker sense of mastery, rather than a real gap in performance.

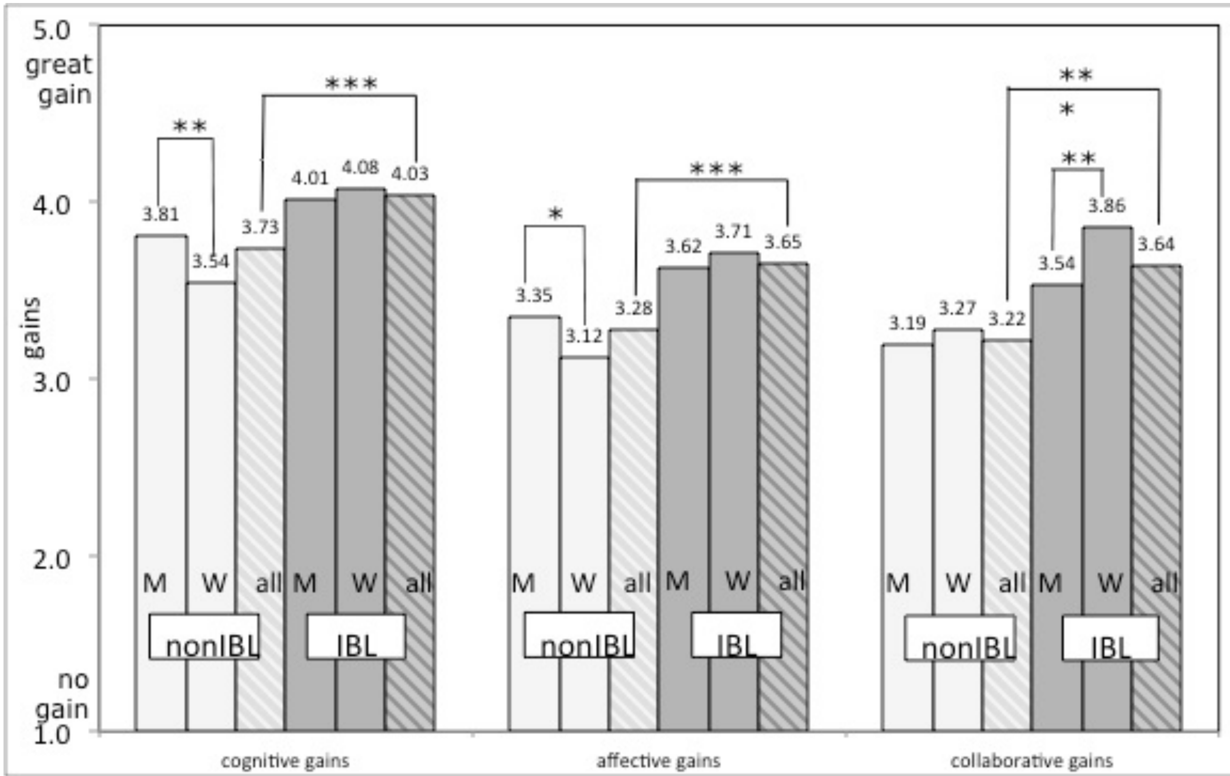

Figure 1: Mean learning gains reported by students in IBL and non-IBL courses, by gender. Sample sizes: Non-IBL—250 men (M), 108 women (W), 358 all; IBL—366 men, 178 women, 544 all. Brackets indicate statistically significant differences: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Pre- to post-course changes in students' interest and confidence, while modest overall, differed more sharply by gender (Figure 2). Women in non-IBL classes reported substantial decreases in their confidence and intent to pursue more mathematics (take more math courses), compared to more minor decreases reported by their male classmates. In IBL courses, however, women's attitudes improved: on average, their interest in pursuing mathematics (math as personal interest) increased, like that of their male IBL classmates, and their confidence in doing mathematics and teaching mathematics increased even more than men's. Together, these data suggest that IBL approaches leveled the playing field by offering learning experiences of equal benefit to men and women, while non-IBL courses were more discouraging and less effective for women in particular.

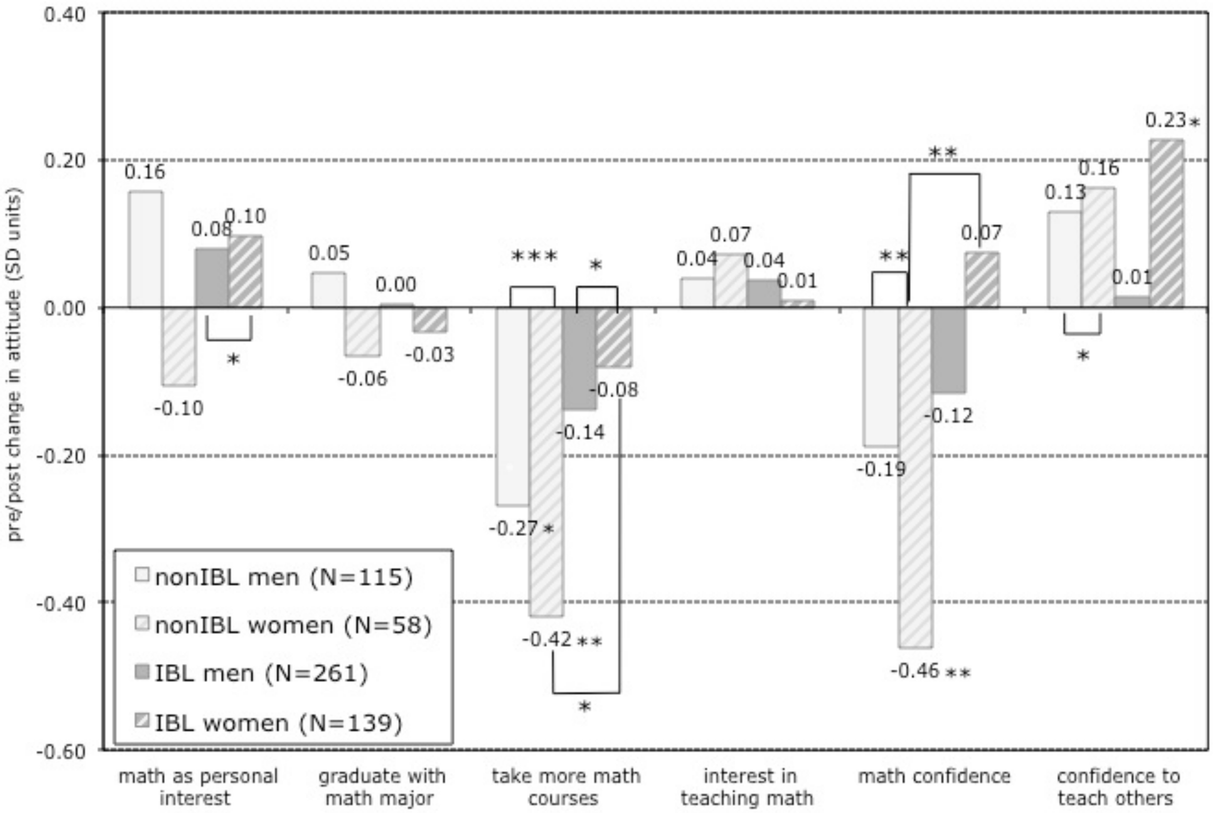

Figure 2. Mean changes in attitude (in *SD* units) from individually matched items on pre- and post-course surveys for students in IBL and non-IBL courses by gender. Within sub-groups comparisons pre- to post-course were made using paired *t*-tests and Wilcoxon signed rank tests; between-group comparisons of attitudinal change (*t*-test) are indicated by brackets. Statistical significance: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Statistical model for gains as outcome variables. To test these apparent gender differences more rigorously, we explored factors that could explain these differential student responses by course type and gender. Because presurvey data from IBL and non-IBL students suggested some institutional and self-selection of students into particular course sections, we conducted a propensity analysis (Pearl, 2009) to statistically adjust for differences in the composition of the IBL and non-IBL groups. Students' academic background, prior mathematics experience, and their mathematics attitudes and beliefs as measured on the presurvey were used to adjust for differences in student characteristics between groups; there may be other group differences that we did not measure. We also used attitudinal covariates that were derived from a factor analysis (Maximum likelihood, Varimax). The variables represented three main factors: preference for collaborative learning, preference for independent learning, and interest and motivation to pursue mathematics. The resulting propensity analysis revealed only modest group differences in class composition (8% more seniors in the IBL group) and expected grades (approximately 0.2 letter grade higher for the IBL group) and almost no difference for the three factor variables. Although the differences were not large, we nonetheless used this analysis to generate a propensity variable for use as a covariate in regression; this method holds any observed differences between groups constant in the analysis.

To account for the possibility that preexisting differences among students explained the differences in their postcourse gains, we constructed ANOVA models using each of the three SALG-M gains composites as the dependent variable, IBL course status and student gender as factors, and the four covariates including the propensity variable and the three covariates for students' learning preferences and beliefs as assessed on the presurvey. Table 2 shows that, for *Cognitive Gains*, the results showed significant main effects for IBL status and gender and for the IBL by gender interaction. The same model for *Affective Gains* showed similar effects. ANOVA for *Collaborative Gains* showed a significant main effect for IBL status but none for gender or IBL by gender. Significant two-way factor interactions for course status by gender showed large gains for IBL females with no significant gain for males in either group.

Overall, even after controlling for differences in achievement, preparation, and attitudes, women's outcomes were much less positive than those for men in non-IBL courses but much more positive in IBL courses and equivalent to those of male classmates. Table 2 summarizes the effect sizes for course type, gender, and their interaction.

Table 2

ANOVA results and effect sizes on learning gains for IBL course status, student gender, and their interactions, from non-adjusted means and total sample standard deviation

					Effect size[a]		
Dependent variable	Main effect, IBL status	Main effect, gender	Interaction, IBL status x gender	Description of interaction	IBL status (regardless of student gender)	Gender (regardless of IBL status)	Male gender in non-IBL course
Cognitive gains	$F = 7.2$, $p = 0.007$**	$F = 9.6$, $p = 0.009$**	$F = 6.9$, $p = 0.0009$**	IBL women and men nearly equal; Non-IBL women below non-IBL men	0.24	0.14	0.46
Affective gains	$F = 8.6$, $p = 0.003$**	$F = 6.5$, $p = 0.01$**	$F = 6.8$, $p = 0.009$**	IBL women and men nearly equal; Non-IBL women below non-IBL men	0.26	0.08	0.40
Collaborative gains	$F = 11.5$, $p = 0.0001$**	NS	NS	NS	0.31	-0.16	—

Note. Statistical significance: ** $p < 0.01$, * $p < 0.05$, NS not significant. Degrees of freedom for all comparisons: 1, 554.

[a]IBL course and male gender are scaled as positive effect sizes.

Discussion

From observation, corroborated by survey items on classroom experiences and student and instructor interviews, we identify twin pillars that support student learning in IBL classes: deep engagement with meaningful mathematics and collaborative processing of mathematical ideas (Laursen et al., 2011). Deep engagement begins with instructors' choice of meaningful problems whereby students explore or discover mathematical ideas. Because homework is not just "busy work" but central to class time, students prepare seriously and feel accountable to their classmates. They report regularly spending time on assignments, not just right before tests. Collaboration may include formal small group work or whole-class discussion of student-presented work as peers offer refinements, critiques, or alternate solutions. Collaborative work develops communication skills, fosters peer interdependence and a positive atmosphere, and provides insights that math is "not just one way only," as one student put it. Another linked collaboration and deep engagement as mutually reinforcing: "Once you spend time alone with it, then talking to other people really helps solidify it." For many students, IBL mathematics experiences were personally empowering (Hassi & Laursen, 2014).

Such classroom learning environments seem central to the positive effects of IBL on women. IBL does not appear to alter women's intellectual achievement—in our samples, as in larger studies (Lindberg, Hyde, Petersen, & Linn, 2010), they were as capable as the men—but rather their own perceptions of their competence (Goetz, Bieg, Lüdtke, Pekrun, & Hall, 2013). In non-IBL courses, women reported gaining less mastery than did men, but these differences vanished in IBL courses. That this apparent deficit can be so readily erased shows that its cause is not a deficit among female students, but rather that non-IBL courses do selective disservice to women. That is, IBL methods do not "fix" women but fix an inequitable course. IBL courses offer several features that may be particularly effective for women, including collaborative work (Springer et al., 1999), and emphases on problem-solving and communication (Du & Kolmos, 2009). In our study, these elements of IBL courses are called out in women's reports of strong collaborative gains and greater confidence to teach mathematical ideas to others. Moreover, women's strong confidence and intended persistence after an IBL course are consistent with psychological explanations of academic persistence and belonging. For example, public sharing and critique of student work may enhance self-efficacy through vicarious experiences (van Dinther, Dochy, & Segers, 2011). Seeing that everyone succeeds and struggles at times links effort, not innate talent, to success in mathematics (Good, Rattan, & Dweck, 2012). Educational approaches that improve women's success with and confidence to pursue mathematics may address their persistent underrepresentation in mathematically intensive fields (Goetz et al., 2013; Shen, 2013).

Conclusion

This study exemplifies both the challenges and promise for implementation of IBL. We detect robust, meaningful differences in self-reported gains and attitudes among students in IBL relative to those in non-IBL courses. Rigorous statistical modeling linked student gains clearly to the pedagogy, showing that IBL benefits all students even as it levels the playing field for women, who are often underserved by college mathematics courses (Hill, Corbett, & Rose, 2010). The general lack of differences in students' grades later in the curriculum is notable because it belies instructors' common concern that reduced content "coverage" in IBL courses will disadvantage students later on (Yoshinobu & Jones, 2012). Elsewhere, we document the benefits of IBL to preservice teachers (Laursen et al., 2014), low-achieving students (Kogan & Laursen, 2013), and first-year students (Laursen, 2013).

Studies like this are a necessary type of scale-up from proof-of-concept studies that demonstrate the effectiveness of these instructional approaches in highly controlled but perhaps educationally unrealistic conditions (e.g., Deslauriers et al., 2011). A pattern of good student outcomes emerged despite high variety in instructors' implementation (Laursen, 2013). This speaks to the robust nature of the outcomes and suggests that a crucial element is instructors' choice to use class time for activities that foster deep mathematical engagement. Collectively, the IBL Centers' efforts approached a scale that can make a substantive difference in mathematical outcomes for students that are crucial for their retention in and contributions to the discipline.

These findings should encourage practitioners to scale up institutional and collaborative initiatives to broaden the use of research-based teaching and learning methods. As with scale-up in K-12 education (Schoenfeld, 2002), professional development and collegial support are key in developing college instructors who can share good ideas and elevate the profile of teaching, especially among early-career instructors (Laursen, 2013). Future work should probe the origins of the gender differentials observed here, investigate the impact of IBL methods on students from under-represented minority groups and in other higher education contexts, and examine the processes by which these reforms do or do not take hold in institutional and disciplinary settings.

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