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Research Article

Concurrent Enrollment in Lecture and Laboratory Enhances Student Performance and Retention

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Abstract: Laboratories have been a cornerstone in teaching and learning across multiple scientific disciplines for more than 100 years. At the collegiate level, science laboratories and their corresponding lectures are often offered as separate courses, and students may not be required to concurrently enroll in both. In this study, we provide evidence that enrolling in an introductory laboratory concurrently with the corresponding lecture course enhances learning gains and retention in comparison to students who enroll in the lecture alone. We examined the impact of concurrent versus nonconcurrent enrollment on 9,438 students' withdrawal rates from and final grades in the general chemistry lecture at the University of Michigan at Ann Arbor using multiple linear and binary logistic regression analyses, respectively, at a significance level of 0.05. We found that concurrent enrollment in the lecture and laboratory positively impacts (1) the odds of retention in the lecture by 2.2 times on average and (2) final lecture grades by up to 0.19 grade points on a 4.0 scale for the lowest-scoring students according to university-level mathematics and chemistry placement exam scores. These data provide important results for consideration by curriculum advisors and course planners at universities that do not require concurrent enrollment in general chemistry as well as other science courses. In the face of current budget cuts that threaten to shorten or eliminate laboratory experiences altogether at multiple educational levels, this study demonstrates the value of laboratories in promoting science learning and retention. © 2012 Wiley Periodicals, Inc. J Res Sci Teach 49: 659–682, 2012

Keywords: college/university; concurrent enrollment; final course grades; general chemistry; lecture and laboratory; withdrawal/retention rate

Laboratories have historically been important tools for teaching and learning in the natural sciences; for more than 100 years, laboratories have been employed to help students interact with scientific phenomena (Hofstein & Lunetta, 1982, 2004). In multiple disciplines as well as across educational levels, laboratories have been shown to improve creative thinking

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and problem-solving abilities (Hill, 1976), scientific thinking (Raghubir, 1979; Wheatley, 1975), intellectual development (Renner & Fix, 1979), and practical skills, and increase favorable attitudes towards science (Ben-Zvi, Hofstein, Samuel, & Kempa, 1976; Bybee, 1970). Because laboratory experiences have been found to promote learning in so many disciplinary contexts, the laboratory has truly become a cornerstone of science education.

Recently, the National Research Council defined a core set of seven science learning goals for students that laboratories should advance in *America's Lab Report* (2006): "enhancing mastery of subject matter, developing scientific reasoning, understanding the complexity and ambiguity of empirical work, developing practical skills, understanding the nature of science, cultivating interest in science and interest in learning science, and developing teamwork abilities" (p. 76–77). The general goals for science education are similar, but laboratories are especially and uniquely suited for helping students develop practical skills and understand the complexity and ambiguity of empirical work (Millar, 2004). The extent to which these goals are attained in laboratories at any educational level differs according to instructor competence, available resources, integration with other instructional activities, and students' prior knowledge and experiences. The specific rationale for each goal in learning science necessarily varies. For example, scientific reasoning skills, such as developing scientific arguments and models, are indispensable for examination of the material world and are not easily learned without structured education (Zimmerman, 2000). Decades of studies have shown that both students' and the general public's understanding of the nature of science is oftentimes naïve and inaccurate (Driver, Leach, Millar, & Scott, 1996; Lederman, 1992), therefore another goal of laboratories is to improve understanding of the nature of science. Student achievement of these seven goals in concert is vital for fostering general scientific literacy and training future scientists, engineers, and citizens at large.

For as many years as laboratories have been lauded for achieving science-learning gains, however, they have also come under fire for being expensive in terms of materials and personnel as well as time-consuming (Baker & Verran, 2004). Budget restrictions, safety concerns, increased attention to test scores on state- and nation-wide standardized exams, and lack of adequate instructor preparation for teaching laboratories have all contributed to the reduction in time students are able to spend doing laboratory experiments, and, in some cases, these factors have been instrumental in the elimination of laboratories altogether at the high school level (National Research Council, 2006; Washam, 2007, Autumn). Indeed, one of the key conclusions of *America's Lab Report* is "the quality of current laboratory experiences is poor for most students" (p. 6). Students at schools with low socioeconomic status and/or high proportions of non-Asian underrepresented ethnic groups are especially likely to experience a lack of adequate laboratory space, equipment, and materials, and these circumstances play a role in these students spending less time doing laboratory activities than others (Banilower, Green, & Smith, 2004). This is problematic because the balance of remaining laboratory instructional time may not reflect established educational design principles. Laboratories may lack explicit learning goals or adequate connection to other instructional activities, for example, and this can reduce laboratory experiences to "cookbook" procedures where coverage of long lists of science topics takes precedence. In these weak (or nonexistent) laboratory environments, students may pick up some subject matter, but are unlikely to attain other important science learning goals for laboratories, namely developing scientific reasoning, understanding the nature of science, and cultivating interest in science (National Research Council, 2006).

The high financial, time, and personnel commitments required for running laboratories has for decades motivated research studies comparing laboratory instruction with other modes of teaching with the goal of identifying equally beneficial but more cost-effective methods, and some have fought for the removal of wet laboratories altogether (see (Hofstein & Lunetta, 1982, 2004) and references therein). Some of these studies concluded that laboratory experiences are no more beneficial to students than other types of instruction such as viewing a movie, doing group work, or having a class discussion, with the exception that students in traditional laboratory settings have better abilities to perform practical manipulations in the laboratory. However, the usual method of student evaluation in these studies was paper-and-pencil tests that did not measure many of the important science learning goals described above. Given, then, that the laboratory is uniquely suited for helping students achieve some specific learning goals, but also that it is expensive and time-consuming, current studies are needed to assess the value of laboratories in terms of encouraging science learning. Here, we demonstrate that enrolling in an introductory college-level laboratory concurrently with the corresponding lecture course promotes learning gains and retention in comparison to students who enroll in the lecture alone.

Rationale and Research Question

Most scientists and educators agree that laboratory experience is imperative for learning science (Carnduff & Reid, 2003); teaching general chemistry apart from the laboratory has even been considered "pedagogically and philosophically unsound" (Wojcik, 1990). Even so, a survey of the most recent available course guides at 40 public, U.S. universities with high undergraduate enrollment revealed that 38%, 43%, and 33% offer general biology, chemistry, and physics lectures and laboratories, respectively, as separate courses without requiring concurrent enrollment (Table 1). This separation does provide some perceived benefits. Practically, it can act to ease students' scheduling conflicts. Oftentimes these general science courses act as service courses for other disciplines, so offering the lecture and laboratory separately can also "benefit" students who are required to take only one of them for a particular course of study (Long, McLaughlin, & Bloom, 1986) and may ease the financial burden of the laboratory on the department (Dubravcic, 1979). Additionally, universities may not have sufficient physical laboratory space for all of the lecture students in a given term to enroll in the laboratory. The separation of lecture and laboratory courses may also help deconvolute a student's grades; in other words, a student who performs well in the laboratory but has trouble in the lecture earns separate lecture and laboratory grades that more accurately reflect the student's abilities than a single, all-inclusive grade (Cawley, 1992). Similarly, as a department chair at the university studied aptly stated, it allows students to fail one course while still receiving credit for the other; that is, it reduces the risk of taking a four- or five-credit course by dividing the class into three- and one- or two-credit segments.

Offering collegiate-level lectures and laboratories in the sciences as separate courses is typical and may have some benefits for the practical issues of scheduling and finances. There are, however, advantages to offering the lecture and laboratory as a single course or, at least, requiring concurrent enrollment. In particular, encountering the same scientific concept in multiple contexts has been shown to promote deeper conceptual understanding and facilitate transfer (Bransford & Schwartz, 1999). Also, isolated laboratory experiences have not been compelling in effecting mastery of specific scientific subject matter, whereas laboratory experiences combined with other instructional activities have promoted science learning (Hofstein & Lunetta, 2004). When laboratories are paired with other types of instruction such as lectures and group discussion, students are more apt to demonstrate interest in and positive attitudes towards science, and integrated instruction has been shown to specifically benefit lower ability students' scientific reasoning skills (White & Frederiksen, 1998). These and

Table 1

Introductory Science Lecture and Laboratory Enrollment Requirements at 40 NCAA, Public Universities

		Biology		Chemistry		Physics	
NCAA Conference	University	C[a]	NC[b]	C[a]	NC[b]	C[a]	NC[b]
Atlantic Coast	Clemson University	×		×			×
	Florida State University	×			×	×	
	Georgia Institute of Technology	×		×		×	
	North Carolina State University	×		×		×	
	University of Maryland	×		×			×
	University of North Carolina		×		×	×	
	University of Virginia		×	×			×
	Virginia Polytechnic Institute	×			×	×	
Big Ten	Indiana University		×		×	×	
	Michigan State University		×		×		×
	Ohio State University	×		×		×	
	Pennsylvania State University	×			×	×	
	Purdue University		×	×		×	
	University of Illinois		×		×	×	
	University of Iowa	×		×		×	
	University of Michigan		×		×		×
	University of Minnesota	×		×		×	
	University of Nebraska		×	×			×
	University of Wisconsin	×		×		×	
Pacific-10	Arizona State University	×			×		×
	Oregon State University	×			×	×	
	University of Arizona		×	×		×	
	University of California (Los Angeles)	×		×			×
	University of California (Berkeley)	×			×	×	
	University of Colorado		×	×			×
	University of Oregon	×			×	×	
	University of Utah		×	×			×
	University of Washington	×		×		×	
	Washington State University	×		×		×	
Southeastern	Auburn University	×			×	×	
	Louisiana State University		×		×		×
	Mississippi State University	×			×	×	
	University of Alabama		×	×		×	
	University of Arkansas	×		×		×	
	University of Florida	×		×			×
	University of Georgia	×		×		×	
	University of Kentucky		×		×		×
	University of Mississippi	×			×	×	
	University of South Carolina		×	×		×	
	University of Tennessee	×		×		×	
Total		25	15	23	17	27	13

Note: The most recent available course guides (either 2010–2011 or 2011–2012) from flagship campuses were surveyed.

[a] Concurrent enrollment is required.

[b] Concurrent enrollment is not required. We considered an institution to offer nonconcurrent enrollment if the lecture was listed as a corequisite for the laboratory but the laboratory was not listed as a corequisite for the lecture, or if multiple introductory tracks were offered and any allowed for nonconcurrent enrollment.

other positive outcomes of integrated instructional methods support a concurrent approach to teaching science lectures and laboratories.

Although literature support exists for the role of laboratories in learning science at the collegiate level, comparatively little has been published on the impact of the timing of laboratory enrollment in comparison to the lecture, that is, concurrent versus nonconcurrent enrollment; only a few studies that support concurrent enrollment have been reported. In the community college context, concurrently enrolled general biology students achieved higher learning gains on exams and reported more positive attitudes on attitude inventories than nonconcurrent students (Saunders & Dickinson, 1979). Concurrent enrollment in general physics lecture and laboratory courses was found to increase the lecture grades of students with intermediate grade point averages (GPAs) by approximately one third of a letter grade, though no significant effect was found for students with the highest and lowest GPAs (Long et al., 1986). Here, we sought to understand the impact of concurrent enrollment in general chemistry lecture and laboratory on the withdrawal rates and final grades of students in the lecture at University of Michigan, a large, public university with high undergraduate enrollment. We hypothesized that concurrent enrollment would positively impact students in terms of both withdrawal rates and final grades because of the aforementioned goals of laboratories, particularly enhancing mastery of subject matter.

General chemistry at University of Michigan is an interesting context in which to investigate this issue of enrollment because of the strong emphasis on collaborative learning and teamwork in the laboratory studied; we suspected that concurrent enrollment would benefit students in part for this reason. Across many years and disciplines, collaborative work has been shown to enhance student achievement, retention, and attitudes, among other outcomes (Bowen, 2000; National Research Council, 2006; Springer, Stanne, & Donovan, 1999). Proposed causal mechanisms for this relationship include that students working in groups perform metacognitive processes when they explain their reasoning to other group members (Hogan, 1999; White & Frederiksen, 1998), and ensuing peer interaction and argumentation enhances students' cognitive development by requiring students to validate their ideas (Chin & Osborne, 2010; Driver, Newton, & Osborne, 2000; Lumpe & Staver, 1995; Richmond & Striley, 1996). More broadly speaking, productive argumentation can promote science literacy (Cavagnetto, 2010). In the specific context of college-level chemistry courses, collaborative work has been shown to positively affect students' attitudes and perceptions (Cooper & Kerns, 2006; Tien, Roth, & Kampmeier, 2002), problem-solving strategies and abilities (Cooper, Cox, Nammouz, Case, & Stevens, 2008), overall achievement level (Bowen, 2000; Tien et al., 2002), and has even been implicated in increasing retention among females in general chemistry laboratories (Cooper, 1994).

As compared to what is currently available in the literature, our data set is unique, covering 6 years and nearly 10,000 students. Of the studies we found specifically pertaining to concurrent versus nonconcurrent enrollment in science lecture and laboratory settings, one observed ~2,500 students over 5 years, but the other studied only 500 students over a single year, and both studies are dated (Long et al., 1986; Saunders & Dickinson, 1979). Also, much time and attention has recently been paid to reforming "traditional" learning settings into "studio-style" settings. In this closely related set of literature, the majority of studies are current; yet report on usually <1,000 students over 1 or 2 years (DiBiase & Wagner, 2002; Hoellwarth, Moelter, & Knight, 2005; Oliver-Hoyo, Allen, Hunt, Hutson, & Pitts, 2004). Our study is additionally based on relatively current student demographics; as the proportions of female, Hispanic, Asian/Pacific Islander, and Black students in post-secondary classrooms have steadily increased since the 1970s (U.S. Department of Education, 2011), this research probes a fundamentally different population of students than those in studies from the 1970s, 1980s, and 1990s.

Withdrawal rates were specifically examined in light of the national need to encourage retention of post-secondary students in the natural and physical sciences (Committee on Prospering in the Global Economy of the 21st Century, 2007; Maltese & Tai, 2011). As general chemistry is a "gateway course" to many scientific disciplines, withdrawal at this introductory level not only increases time-to-degree but is also a serious barrier to progression in the sciences and engineering (Seymour & Hewitt, 1997; Strenta, Elliott, Adair, Matier, & Scott, 1994). In the data described herein, for example, there were 260 students who withdrew from general chemistry lecture. Of these students, only 109 (42%) returned to take the course a second time. The retention of nonscience majors in science courses is also an important issue due to the need for a scientifically literate and critical public (Glynn, Taasoobshirazi, & Brickman, 2007; Martens, 2007; National Research Council, 1996, 2006). Considering only the 3,359 general chemistry students in this study who had graduated by the time the data was obtained, we found that 35% (1,172) did not major in a science or engineering field (Table 2).

We also specifically examined final grades because exam and overall course grades are routinely used as measures of cognitive outcomes, that is, student performance, achievement, and/or learning (Dubravcic, 1979; Long et al., 1986; Marshall & Dorward, 2000; Saunders & Dickinson, 1979). A student's college grades are also useful as a gauge of how well they have adapted to the college environment, and are a strong predictor of earning a bachelor's degree (Pascarella & Terenzini, 2005). We recognize that there are significant pitfalls in blindly assuming that grades reflect real learning (Pascarella & Terenzini, 2005; Walvoord, 2004), however, grades are generally useful as tools for approximating cognitive results.

Methods

Study Context: General Chemistry at University of Michigan

This study was performed at a large, public, midwestern university where general chemistry consists of separate lecture and laboratory courses, each one semester in length. Students have the option to enroll in the lecture and laboratory either concurrently or nonconcurrently, and some students enroll in the lecture without ever enrolling in the laboratory. In this data set, 63% of students were concurrent, 22% were nonconcurrent (though neither course is a prerequisite for the other, the vast majority of these students—97%—enroll in the lecture first), and 15% enrolled in the lecture only. Because the majority of nonconcurrent students enroll in the lecture first, the students who enrolled in the lecture only were considered nonconcurrent students in this research. Students have the option of taking the lecture in one of three different formats, and in any given year, approximately 91% of students enroll in the traditional lecture format with the remaining 9% roughly evenly split between the other two formats. For all courses, the content was generally stable from year to year, and technological advances mainly influenced changes in structure. Based on the students for whom we have degree information, 66% of students in the traditional lecture format eventually completed science and/or engineering majors, the highest percentage of all three lecture formats (Table 2). Additionally, in the traditional format, the majority of students were concurrently enrolled regardless of whether they completed a science/engineering or nonscience/nonengineering degree (59% and 53% concurrently enrolled, respectively) (Table 2). A quasi-experimental design was employed in which the assignment of students to (1) the concurrent or nonconcurrent group or (2) a particular lecture format was uncontrolled because of the

Table 2
Summary of Student Characteristics

	Lecture Format[a]			
Characteristic	Traditional	Extra time	Studio	Total
Total	8,624	466	348	9,438
Laboratory enrollment				
Concurrent	5,390	232	348	5,970
Nonconcurrent	3,234	234	0	3,468
Gender				
Female	3,930	324	192	4,446
Male	4,694	142	156	4,992
Ethnicity				
Asian	1,276	29	63	1,368
Black	525	165	24	714
Hispanic	394	50	14	458
Native American	69	12	1	82
White	5,609	192	222	6,023
None	615	13	21	649
Missing	136	5	3	144
Age[b]				
Freshman (≤2)	7,519	395	339	8,253
Sophomore (2< × ≤4)	820	54	6	880
Junior (4< × ≤6)	158	10	1	169
Senior (>6)	115	7	2	124
Missing	12	0	0	12
Degrees earned[c]				
Science or engineering (total)	2,077	55	55	2,187
Concurrent	1,228	26	55	
Nonconcurrent	849	29	0	1,172
Nonscience or –engineering (total)	1,047	81	44	
Concurrent	551	34	44	6,079
Nonconcurrent	496	47	0	
Missing	5,500	330	249	

[a] Lecture formats are fully described in the Study Context section.

[b] Student's ages are reported according to the cumulative number of terms they had been enrolled at the university prior to and including the term in which they first enrolled in the lecture.

[c] Describes students who had completed a major (minors not included) in a science or engineering field by the time that this data was collected in 2008.

disruption to the students' education that using random assignment in a true experiment would have caused, and we have attempted to control for resultant confounding variables.

The first lecture format is a traditional course that meets three times weekly for 50 minutes; 63% of students who take the lecture in the first format are concurrently enrolled. This course is a general introduction to chemistry, considering the following major topics: measurement, atomic theory and structure, stoichiometry, types of chemical reactions, gas laws, thermochemistry, quantum theory, electron configurations and periodicity, bonding, molecular orbital theory, states of matter, equilibrium, and acid–base chemistry. In addition to lecture time, students have a 50-minute discussion once per week with a graduate student teaching assistant. Discussion attendance is not explicitly required, but most students attend most discussions because weekly quizzes are administered there, and these eventually count for 20% of the final grade. The grading scheme places a large emphasis on exams with 70%

of the final grade derived from the two midterms plus the final exam. All exams are multiple-choice, whereas quizzes require work to be shown, and the online homework is a hybrid that requires student-generated responses. Of all the courses described here, this version has the most variance in terms of the number of instructors involved, with 12 unique instructors having taught one or more sections (each section is ~400 students) over the years of this study. A single instructor has served as the course coordinator throughout this time, providing continuity in course structure and content. The average total class size during this period was ~1,400 students. This format serves the largest number of students by far, so the results presented here should be interpreted as mainly reflective of the effect of enrollment for students' final grades in and withdrawal rates from this lecture format.

The second lecture format is designed for students who were expected to benefit from extra in-class time and office hours, generally underrepresented ethnic groups, first-generation college students, and students from low socioeconomic status backgrounds and/or very small high schools. In this format, students meet with an experienced instructor four times weekly for 50 minutes each, and 50% of these students are concurrently enrolled. As in the first lecture format, students attend one 50-minute discussion once per week with a graduate student teaching assistant and have the same structure for quizzes, though the number of students per discussion is smaller compared to the traditional format. The extra class period as well as extra faculty and teaching assistant office hours are provided for in-depth analysis of central concepts and extra practice time for students. The content of this lecture format is the same as that of the traditional format, and the syllabi, grading schemes, homework, quizzes, and exams are uniform across the two formats. The primary difference between this format and the traditional format is pacing, having 200 and 150 minutes per week of contact time, respectively, to teach the same material. The instructor for this lecture format was the same across all years of this study, and average class size was ~80 students. Students can gain access to this lecture format in one of a few different ways. Firstly, based on the factors described above, the Office of Undergraduate Admissions (OUA) identifies incoming students as eligible for participation in a comprehensive academic support program, which includes access to extended forms of introductory courses such as this general chemistry lecture format. Students in the comprehensive program are encouraged to enroll in this lecture format but may elect not to do so. Secondly, students who are not identified by OUA as eligible for the comprehensive program may apply to become an affiliate of the program and thus gain access to the resources that the program offers, including this lecture format of general chemistry. Thirdly, students who are not at all affiliated with the comprehensive program may be able to register for this format if they demonstrate a scheduling conflict with all sections of the traditional format of the course. In this data, the percent of students who are affiliated with the comprehensive academic support program in this lecture format and the traditional format is 52% and 7%, respectively.

The general chemistry laboratory course is offered in a single format; students who enroll in either of the lecture formats described above may take this laboratory course. Students attend one 3-hour laboratory/discussion session and one 50-minute lecture per week. The topics of experiments in this course include solubility, solution analysis, redox reactions, acid–base chemistry, metal complexes, and analysis of reactions, and though the topics are obviously similar to those taught in the lecture, the laboratory content is not explicitly linked to or aligned with the lecture content in any way. The pacing of the two courses is uncorrelated, and lecture exams do not intentionally test understanding of phenomena encountered in the laboratory. The laboratory course is inquiry-based and the experiments have evolved from requiring mostly individual work to teamwork in the last decade. Heterogeneous groups of generally four students are formed by the instructor based on factors such as prior chemistry knowledge, familiarity with computers, gender, age, and location on campus, and all group members receive the same grade for team assignments which discourages competition among students, with team points accounting for ~50% of the final grade. Students receive instruction regarding how to productively work in teams, such as strategies for conflict resolution, and rotate amongst well-defined roles for each experiment: team manager (keeps group on task, presents the team answers to oral discussion questions), recorder (documents team data, records abstract and outline for answers to oral discussion questions), chemist/safety officer (measures reagents, responsible for proper disposal and monitoring safety of all group members), and technologist (operates instruments, records group data into class data banks). Other major features of this course are that students produce group laboratory reports, give team oral presentations, and the experiments are designed such that students evolve concepts from their observed data. The exams include both multiple-choice questions and computational and conceptual problems that require students to show their work. A single instructor taught the laboratory course over the years of this study, and average class size was ~1,300 students with lecture sections averaging ~400 students and laboratory sections averaging ~20 students.

The third format integrates the lecture and laboratory into one five-credit "studio" course that explicitly aligns all "lecture" and "laboratory" topics. Therefore, unlike the first and second formats, the third format requires concurrent enrollment. With enrollment capped at 96 students per term, this format is also characterized by a small class size yielding more personal attention in comparison to the traditional lecture format. Students attend three 50-minute lectures and 5 hours of laboratory/discussion time per week. These 5 hours were fluidly allocated to laboratory or discussion time, so though points were not given for attendance, students were essentially required to attend all 5 hours each week due to the course design. The studio course is an intimate and creative version of general chemistry that is completely isolated from the lectures and laboratory described above, and enrollment in this format is completely determined by self-selection. The same subject matter is covered in approximately the same order, but both the lecture and laboratory/discussion incorporate more hands-on activities and small group discussions. This course is also project-based, with the major group project (27% of the final grade) culminating in a group paper and poster presentation. The overall grading scheme deemphasizes exam grades (35% of the final grade) in comparison to the first and second lecture formats, and the exams are different from those administered in the other formats. Points from online homework, class participation, and individual laboratory reports make up the balance of the grades. For the fall terms in 2006 and 2007, this course was taught in a (then) new undergraduate science building with innovative laboratory and "dinner theater" classroom space, whereas all other courses described here have always been held in the chemistry building. Designed to facilitate both small-group collaboration and large-group interaction, the "dinner theater" classroom is tiered with each level containing four to five small tables, each accommodating up to four students. There were two unique instructors for this course over the years of this study, and the average class size was ~60 students.

Data Collection

Data was collected from the Office of the Registrar for the 9,438 students who enrolled in the general chemistry lecture during the fall terms between 2002 and 2007, inclusive. The data consists of various demographics (e.g., gender, ethnicity, age), high school GPA, SAT, and ACT scores, mathematics and chemistry placement exam scores, participation in honors programs, degrees earned, and other factors (see Table 2 for a breakdown of some student characteristics according to lecture format). We also collected information about any general chemistry laboratory and organic chemistry laboratory and lecture courses in which students had enrolled between Fall 2002 and Spring 2008, including term enrolled, section number, final grade (measured on a 4.0 scale), and the drop date if the student withdrew from the course. Students who withdrew before the "normal" drop/add deadline, which is the end of the third week of class, were not considered in this study as withdrawals occur for a broad range of reasons early on each term. Students' names were not used; rather, they were identified by eight-digit numbers.

Data Analysis

The data was imported into the statistical software package PASW Statistics (version 18.0). Students were partitioned into four clusters according to their standardized (Z) scores on the university's mathematics and chemistry placement exams by pairwise K-means cluster analysis, a method that attempts to identify the centers of natural, homogeneous clusters in the data; Table 3 describes the clusters. There was a significant effect of cluster number on final lecture grade, $F(3, 3815) = 665.63$, $p < 0.05$, $\omega = 0.44$, and the *post hoc* Games–Howell procedure revealed that all clusters are significantly different from one another (Welch's F was used because the homogeneity of variance assumption was broken). Doing the cluster analysis pairwise means that students are assigned a cluster number if they have a mathematics placement exam score, a chemistry placement exam score, or both. Only students who are missing scores for both the placement exams (5.4%) will not be assigned a cluster number. Most students (91%) have valid data for both their mathematics and chemistry placement exam scores. This clustering technique was used because these two variables are positively correlated with each other ($r = 0.34$ [8538], p [two-tailed] < 0.01, representing a medium-sized effect). Using the variables separately in multiple regressions can lead to multicollinearity where the accuracy of individual predictors may be compromised, though the predictive power of the whole model is usually unaffected (Field, 2009; Hutcheson & Sofroniou, 1999). Therefore, the regressions were also performed using the placement exam scores as separate, continuous variables, and we found results (Tables S1–S4) similar to those reported here. Differences in final lecture grades according to enrollment status (i.e., concurrent vs. nonconcurrent) by cluster number are also reported (Table 4); this data is consistent with previous work in physics education research that has shown strong, positive correlations between preinstructional measures, and normalized learning gains (Coletta, Phillips, & Steinert, 2007; Meltzer, 2002).

Table 3
Summary of Student Clusters Based on K-Means Cluster Analysis

Cluster no.	No. of Students		Avg. Mathematics Placement Exam Score[b]	Avg. Chemistry Placement Exam Score[b]	Final Grade[c]	
	Total	Retained			*M*	*SD*
0	1,681	1,551	10.9	13.6	2.29	0.81
1	1,743	1,712	14.0	20.8	2.77	0.68
2	3,848	3,811	21.2	17.8	2.99	0.66
3	1,657	1,650	22.3	27.5	3.36	0.58
—[a]	509	454	—	—	—	—

[a] Students who were missing both placement exam scores were not assigned a cluster number.
[b] The mathematics and chemistry placement exams were scored out of 25 and 40, respectively.
[c] These statistics do not include withdrawn students.

Table 4
Differences in Final Lecture Grades According to Enrollment Status By Cluster

	Concurrent			Nonconcurrent			Difference		
Cluster no.	*M*	*SD*	*N*	*M*	*SD*	*N*	*M*	*t*	p^{a}
0	2.42	0.73	888	2.11	0.87	663	0.31	−7.48	0.00
1	2.83	0.67	1,107	2.66	0.70	605	0.17	−4.83	0.00
2	3.05	0.62	2,597	2.86	0.71	1,214	0.19	−8.03	0.00
3	3.37	0.58	1,065	3.34	0.57	585	0.03	−0.99	0.32

Note: These statistics do not include withdrawn students.

[a] The significance of differences in final grades between concurrent and nonconcurrent students was determined by independent-samples *t*-tests.

It is noted that without having access to placement exam scores from other universities, it is difficult to quantitatively comment as to whether other students would cluster in a similar fashion as students at University of Michigan. The nature of these particular placement exams also complicates comparison to other universities' exams. Here, the chemistry placement exam is designed to generate a normal bell-shaped distribution centered on a mean score of 50% whereas the mathematics placement exam is designed to generate a negatively skewed distribution with a mean score of 70% and, of course, placement exams at other universities may not be designed with such intended outcome distributions. One of the reasons we employed the clustering technique was to generate a handle for thinking about different types of students, broadly speaking. We wanted to have a method for assessing how concurrent enrollment affected the highest performing versus the lowest-performing students, and suspected that placement exam scores would generally reflect the students' abilities well. That being the case, we reasonably expect that students at any university would exhibit a similar distribution according to ability as the students in this study, with overall low-, medium-, and high-performers.

Binary logistic and linear regressions were used to evaluate the impact of concurrent enrollment on withdrawal rates and final course grades in the lecture, respectively, at a significance level of 0.05. Because of the major differences in assessments and grading systems between the studio and other lecture formats, we have excluded the studio students from the main analyses and instead report results for these students in a separate section. Although it is nonideal to use *post hoc*, observational data to identify outcomes of an educational experience (e.g., due to hindsight bias), we also find support for these descriptive and inferential statistical procedures as common and accepted for empirical studies in this discipline (Creswell, 2008; Fayowski & MacMillan, 2008; Goldstein & Perin, 2008; Long et al., 1986; Shavelson, 1996). Both binary logistic and linear regressions use covariates (independent variables) to predict the value of an outcome variable (dependent variable). Binary logistic regression is used when the outcome variable is dichotomous (e.g., withdrawn or not withdrawn) and linear regression is used when the outcome variable is a scale variable (e.g., final course grades).

Five covariates were used in the regressions: (a) the student's high school GPA, (b) the student's comprehensive SAT score (scores for students who had taken the ACT but not the SAT were converted using a concordance table published by The College Board (The College Board, 2006)), (c) the student's cluster number, (d) whether or not the student concurrently enrolled in the general chemistry lecture and laboratory, and (e) the product of (c) and (d) which was included in order to elucidate any interaction between them. High school GPA and comprehensive SAT scores were used as covariates because they have been found to be good predictors of freshman college achievement in multiple contexts (Daugherty & Lane, 1999; Fincher, 1974; Wolfe & Johnson, 1995), though they do not have equal predictive power across racial groupings (Sue & Abe, 1988; Ting & Robinson, 1998) and, thus, we treated them independently. The correlations between covariates do not represent large effect sizes, with the exception that the product term (e) is, as expected, highly correlated with (c) cluster number and (d) enrollment status (Table 5). Additionally, variance inflation factors for all covariates are <10, implying that multicollinearity due to covariate correlations does not substantially bias the regressions (Field, 2009).

Both types of regressions were performed listwise, which means that in order for students to be included in the analysis, they were required to have valid data for all of the covariates used. Because of this stipulation, 91.6% of all nonstudio students ($N = 9{,}090$) were included in the binary logistic regression where withdrawal rate was the outcome variable, and 92.1% of retained nonstudio students ($N = 8{,}834$) were included in the linear regression where final grades was the outcome variable. There was no way to determine whether the missing data is missing completely at random with respect to the outcome variables (Little & Rubin, 2002). If a student took the lecture or laboratory more than once, only the first time that they enrolled in the course(s) was analyzed. Finally, these analyses were based on an observational study and we attempted to design predictive models that would adjust for differences in students, and, in particular, the analytic form of the equations were selected specifically to work for these data. In other words, we sought to disentangle the effect of concurrent enrollment from a student's GPA, SAT, and mathematics and chemistry placement exam scores using these variables as covariates in our models. Of course, subsequent analyses may reveal other functional forms and other functional variables that may be more effective at describing the already substantial variation in student scores.

Results

Final Course Grades

The linear regression model revealed a systematic relationship between concurrent enrollment and final course grades. Specifically, concurrent enrollment positively affected students' final grades in the lecture by up to 0.19 grade points (Table 6). This linear model predicts that a student who enrolls concurrently in the lecture and laboratory can earn almost one third of a letter grade higher (e.g., B to B+) than a student who takes the lecture first and the laboratory in a later semester or not at all. A simple point-biserial correlation between enrollment status and final grade points reveals $r_{\text{pb}} = 0.14$ [8822], p [two-tailed] < 0.01, representing a small-sized effect.

Table 5
Correlation Coefficients for Covariates Used in Regression Models

	(a) HS GPA	(b) SAT	(c) Cluster	(d) Enrollment	(e) $(c)^*(d)$
(a) HS GPA	1	0.13	0.11	0.10	0.12
(b) SAT	8,932	1	0.43	0.08	0.27
(c) Cluster	8,666	8,919	1	0.07	0.56
(d) Enrollment	8,938	9,346	8,929	1	0.75
(e) $(c)^*(d)$	8,666	8,919	8,929	8,929	1

Note: All correlations are significant at the 0.01 level (two-tailed).

Table 6

Impact of Concurrent Enrollment on Final Grades in the Lecture

Covariates	*B*	*SE B*	*t*	*p*
Constant	−2.43	0.128	−19.0	0.00
(a) High school GPA	0.86	0.029	29.4	0.00
(b) Comprehensive SAT score	0.00[a]	0.000	18.4	0.00
(c) Cluster number	0.27	0.012	22.0	0.00
(d) Concurrent or nonconcurrent enrollment	0.19	0.027	6.9	0.00
(e) Interaction of (c) and (d)	−0.04	0.015	−2.5	0.01

Note: The proportion of variance (R^2) in final grades accounted for by this linear regression model is 0.32.

[a] The coefficient *B* is positive for this covariate but rounds to zero.

Importantly, the interaction covariate (e) term in this model reveals a differential impact of concurrent enrollment on final grades that is dependent on cluster number. For example, students in cluster three, those with the highest average mathematics and chemistry placement exam scores, benefited from concurrent enrollment on average by 0.07 grade points. This difference is due to the interaction covariate (e) term in the linear equation (since, in the linear equation, the coefficient *B* is multiplied by the interaction term for concurrent students in cluster three: $0.07 = 0.19 + (-0.04 \times 3)$). However, students in cluster zero, those with the lowest average mathematics and chemistry placement exam scores, benefited from concurrent enrollment on average by 0.19 grade points in their lecture grade (here, in the linear equation, the coefficient *B* is multiplied by the interaction term for concurrent students in cluster zero: $0.19 = 0.19 + (-0.04 \times 0)$). In summary, the average increase in final lecture grades for concurrently enrolled students according to cluster number was 0.19 for cluster zero, 0.15 for cluster one, 0.11 for cluster two, and 0.07 for cluster three. This shows that in terms of final grades in the lecture, the lowest-scoring students according to mathematics and chemistry placement exams receive the most benefit from concurrent enrollment.

Although we have controlled for differences in high school GPA, comprehensive SAT scores, and mathematics and chemistry placement exam scores, we may not have accounted for other important measures of student quality. Motivation, for example, has been found to foster science achievement in large, introductory biology courses (Glynn et al., 2007), and logical thinking skills have positively predicted student performance in physical chemistry courses (Nicoll & Francisco, 2001). These and/or other measures could contribute to the result that concurrent students earn higher final grades in the lecture than nonconcurrent students. Though the analysis works well for these practical measures that are routinely employed, it is important to ascertain the extent to which these results are confounded.

Determining the regression equation for one group of students and applying it to a second group can address this issue of prediction bias (Sue & Abe, 1988). The modeling described here deals with the issue of stronger students potentially self-selecting into concurrent enrollment by isolating the effect that concurrent enrollment has on increasing final lecture grades. First, we selected only concurrently enrolled students and, based on their data, calculated a linear regression model that shows the progression of performance (final lecture grade) as a function of covariates. The covariates used in this model were the student's high school GPA, cumulative SAT score, and cluster number. Then, this model was applied to the nonconcurrent students. This process essentially applies the "treatment" of concurrent enrollment to the nonconcurrent students. After applying the concurrent enrollment "treatment" to the nonconcurrent students, we observed the difference in mean final grades for each of the two groups

Table 7
Descriptive Statistics of Linear Regression Models Addressing Uncontrolled Variables

	N	Min	Max	Mean	*SD*
Concurrent					
Average final lecture grade	5,538	0.00	4.00	2.95[a]	0.72
Predicted average final lecture grade with nonconcurrent treatment applied	5,253	1.11	3.77	2.83[a]	0.40
Nonconcurrent					
Average final lecture grade	3,284	0.00	4.00	2.73[b]	0.84
Predicted average final lecture grade with concurrent treatment applied	2,887	1.15	3.83	2.85[b]	0.44

[a] The difference between the concurrent students' average final lecture grade and the average grade that the concurrent model predicts for nonconcurrent students is 0.10 (0.10 = 2.95–2.85).

[b] The difference between the nonconcurrent students' average final lecture grade and the average grade that the nonconcurrent model predicts for concurrent students is 0.10 (0.10 = 2.83–2.73).

to be 0.10 units on average (Table 7). This implies that the concurrent treatment may not be entirely responsible for the increase in final lecture grades that concurrently enrolled students have. To check the quality of this linear model, we calculated the linear regression model based on nonconcurrent students only and applied it to the concurrent students. Again, this process essentially applies the "treatment" of being nonconcurrently enrolled to the concurrent students. Here, the observed difference in mean scores for each of the two groups is again 0.10 final grade units on average (Table 6). That the difference found in this model is similar to the average difference found in the first model is confirmation that the models themselves are reasonable and accurate.

This modeling exercise affirms that the highest-performing students, according to the preinstructional measures used as covariates in the regressions, are not randomly distributed between concurrent and nonconcurrent enrollment. Rather, these students are more often concurrently than nonconcurrently enrolled, perhaps due to self-selection, advising, and/or other reasons. In fact, for an average of 0.10 final grade units out of the 0.19 potential increase in final grade, we cannot deconvolve the contribution of concurrent enrollment and other factors that we have not measured about the students in this data set. Because the magnitude of the mean final grade difference (0.10) is greater than or very similar to the effect of concurrent enrollment determined for clusters two (0.11) and three (0.07), it is untenable to claim that concurrent enrollment is exclusively responsible for the increase in final grades in these clusters. However, this does not necessarily imply that concurrent enrollment has no positive effect for the two highest clusters. In reality, concurrent enrollment may benefit students in the two highest clusters, but we cannot know this with statistical certainty. Regardless, the significant positive effect of concurrent enrollment for the students in clusters zero and one remains. Furthermore, considering the number of students with "borderline" final grades in clusters zero and one for a representative term of data and that enrollment in general chemistry exceeds 2,000 students annually, we find that the final grades of approximately 400 students (20%) would be positively impacted on an annual basis by concurrent enrollment.

Withdrawal Rates

Concurrent enrollment in general chemistry lecture and laboratory was found to systematically decrease the withdrawal rate from the lecture according to the binary logistic regression model, with concurrent and nonconcurrent students' retention rates being 99% and 95%,

Table 8

Impact of Concurrent Enrollment on Withdrawal Rate from the Lecture

Covariates	*B*	*SE B*	*Exp*(*B*)	*p*
Constant	−5.41	0.98	0.00	0.00
(a) High school GPA	0.94	0.23	2.56	0.00
(b) Comprehensive SAT score	0.00[a]	0.00	1.00	0.00
(c) Cluster number	0.70	0.12	2.02	0.00
(d) Concurrent or nonconcurrent enrollment	0.79	0.21	2.19	0.00
(e) Interaction of (c) and (d)	0.19	0.19	1.20	0.32

Note: The proportion of variance (R^2) in withdrawal rate accounted for by this binary logistic regression model is 0.19.

[a] The coefficient *B* is positive for this covariate but rounds to zero.

respectively (χ^2 (1) = 101.87, $p < 0.001$). Overall, the odds of a concurrent student being retained in the lecture were 2.2 times higher than students who took the lecture and laboratory separately, or those who never took the laboratory at all (Table 8). In this regression, the interaction covariate (e) term of cluster and enrollment status was nonsignificant ($p > 0.05$), therefore, there is no significant differential effect of enrollment status according to cluster number. The odds of concurrent students from any cluster being retained in the lecture are 2.2 times higher than nonconcurrent students, according to this model. Practically speaking, increasing the retention rate of nonconcurrent students to 99% translates into approximately 125 more students being retained in the lecture course over the years of this study. It is noted that other features of students reflecting their overall quality were unavailable; therefore, self-selection may bias our estimate of the impact of concurrent enrollment on withdrawal rates.

Lecture Format Designed for Additional Academic Support

Students have the option of enrolling in general chemistry lecture in one of three different formats (delineated in the Study Context section), and one format is designed for students who may benefit from extra academic support. Even though 75% of the students who enrolled in this lecture format are in cluster zero (they have the lowest average placement exam scores), and the difference in average final grade between the students, taking into account all clusters, in the academic support section ($M = 2.36$, $SD = 0.84$, $SE = 0.04$, $N = 418$) and those not enrolled in this format ($M = 2.89$, $SD = 0.76$, $SE = 0.01$, $N = 8404$) is significant $t(452) = 12.94$, $p < 0.05$, our analyses indicate that there is no significant difference between the two groups in the amount that concurrent enrollment helps students' final lecture grades. Statistically, students in the lecture format designed for additional academic support are no more likely to be helped by concurrent enrollment than students in the traditional format. The same conclusion holds true when withdrawal rates are the outcome variable. Also, in performing regression analyses to explore whether enrollment in this lecture format influenced final grades or retention, regardless of concurrent versus nonconcurrent enrollment, we found no significant effect for either metric, indicating that comparable students who enroll in this format and the traditional format would not be predicted to have different final grades or retention outcomes.

Studio-Style Course Format

The students who enrolled in the studio-style format of general chemistry were required to register for a single five-credit course, meaning nonconcurrent enrollment was not an option for these students. Enrollment in the studio format was found to have no significant effect on withdrawal rates from the lecture when compared to nonstudio students, whether nonconcurrent students were included in the analyses (χ^2 (1) = 3.48, $p > 0.05$) or not (χ^2 (1) = 0.19, $p > 0.05$).

The studio instructors sought to generate similar final grade distributions as in the traditional and extra support formats, however the studio assessment techniques do differ from the other formats, and the following direct comparisons of final grades across the different formats should, accordingly, be cautiously interpreted. Considering both concurrent and nonconcurrent students, studio students had significantly higher final grades ($M = 3.10$, $SD = 0.65$, $SE = 0.04$, $N = 344$) than those in the nonstudio lecture courses ($M = 2.87$, $SD = 0.78$, $SE = 0.01$, $N = 8{,}822$) $t(382) = -6.45$, $p < 0.05$. Comparison of the studio students to the group that most closely mimics their experience, the concurrent students in the traditional lecture format ($M = 2.97$, $SD = 0.72$, $SE = 0.01$, $N = 5{,}322$), reveals a mean difference of 0.13 grade point units $t(5{,}663) = -3.35$, $p < 0.05$. Though this represents a statistically significant positive effect of the studio course on final grade, the uncertainty about how the differing assessments across the formats could impact the statistics as well as the results regarding withdrawals implies that, overall, there is no benefit to enrollment in the studio course over concurrent enrollment in a nonstudio format based on these metrics.

Limitations

Our objective was to analyze the first experience of each student in the lecture and laboratory courses. However, because data was collected between Fall 2002 and Spring 2008, we cannot exclude cases where students enrolled prior to Fall 2002. The overall number of students in this data set who enrolled more than once in the lecture (65 students or 0.7% overall) or laboratory (38 students or 0.4% overall) is small. Therefore, we reasonably expect that the number of students who are affected by this limitation is minimal, and we do not think the bias is substantial. Similarly, general chemistry lecture data was collected for the fall terms between 2002 and 2007, inclusive, however, any student who enrolled in the lecture more than once could have enrolled during a winter or spring term. In this case, we could have compared outcomes of a student's second enrollment in the lecture with that of other students' first enrollment. One guard against this potential error is that the bulk of general chemistry students regularly enroll in the lecture in the fall term. Average enrollment in the lecture during the fall, winter, and spring terms between Fall 2002 and Spring 2008 was 1,589, 518, and 50 students, respectively; in a given academic year, then, approximately 74% of general chemistry lecture students enroll in the course in the fall. Additionally, this study does not attempt to make comparisons between students who enrolled in the laboratory only and any other group, primarily because the number of students who enroll in the laboratory without ever enrolling in the lecture is very small. Finally, the instructors of the lecture courses were uncontrolled.

Discussion and Implications

The key findings of this study are that concurrent enrollment in general chemistry lecture and laboratory positively impacts (1) retention in the lecture for all students, and (2) final lecture grades for the students who score lowest on mathematics and chemistry placement exams. Considering that increasing retention of students, especially in science courses, is a consistent challenge in post-secondary education (Committee on Prospering in the Global Economy of the 21st Century, 2007; Daempfle, 2003–2004) and that educators fear driving students permanently away from the sciences, these findings provide an important guide to practice at universities that do not require concurrent enrollment in introductory science lectures and laboratories. These findings could, for example, impact students by means of curriculum advisors. Personal communication with a prehealth advisor (P. K. Zitek, September 13, 2009) at University of Michigan revealed that some advisors encourage students to enroll in lectures and laboratories concurrently if at all possible. Other advisors, however, do not prioritize concurrent enrollment, and students who do not feel comfortable with their science abilities may be disinclined to concurrently enroll. Understanding that empirical data supports a significant increase in retention and final lecture grades could certainly impact both advisors' practices and students' choices, and result (2) substantiates a relatively easy and financially viable route for universities to better assist students who may require more academic support.

Decades of research have been published concerning improving student performance, learning, and attitudes in college-level introductory science courses. Topics include utilizing student response systems (Hall, Collier, Thomas, & Hilgers, 2005, August), requiring writing assignments (Horton, Fronk, & Walton, 1985), individualized, self-paced instruction (Paul, 1983), and lecturing based on student-generated questions (Teixeira-Dias, Pedrosa de Jesus, & Neri de Souza, 2005), among many other categories of innovation. According to the data presented here, student performance is significantly positively affected by enrolling in the lecture and laboratory during the same term. Similarly, increasing student retention has been found to be affected by implementing cognitive task analyses (Feldon, Timmerman, Stowe, & Showman, 2010), supplemental instruction (Peterfreund, Rath, Xenos, & Bayliss, 2007–2008), computer-assisted instruction (Wrensford & Wrensford, 2003), and more appropriate placement strategies (Edwards, Roberts, & Pitter, 2010, November), among other methods. The data presented here, though, supports concurrent enrollment as a method for significantly increasing retention in the lecture. In short, unlike previous studies, this data provides evidence that significant increases in both student performance and retention can be brought about by relatively simple actions on the parts of students and the university.

We argue that the reasons for the observed results, though they are coupled with the issue of "time on task," are related to the design of the laboratory course itself, especially because the sequencing of topics in the lecture and laboratory are unrelated. "Time on task" is truly an important factor in achieving learning gains, but student's problem-solving strategies have been shown to stabilize after a small number of related problems (Stevens, Soller, Cooper, & Sprang, 2004, August). Cooper et al. (2008) has also shown that when students problem-solve as a group, they are able to arrive at efficient strategies more quickly than when working individually. Therefore, the design of the learning environment in the laboratory must be considered when interpreting these results. The laboratory course exemplifies some of the principles that purportedly support effective learning environments as outlined in the National Research Council studies *How People Learn: Brain, Mind, Experience, and School* (1999) and *How Students Learn: Science in the Classroom* (2005), that is, the laboratory is knowledge- and community-centered. Specifically, the course is comprised of guided inquiry experiments in which students are not presumed to know the expected results prior to collecting and analyzing their data, and prelabs are not intended to give away the outcomes (Minner, Levy, & Century, 2010; Wilson, Taylor, Kowalski, & Carlson, 2010). Students' resultant confusion facilitates development of their scientific reasoning skills and addresses the ambiguity of the scientific process (Kerner & Penner-Hahn, 2010). Students are encouraged in exploration, organization, and application in each experiment, with the overall goal of deriving concepts and principles from authentic, empirical data and, interestingly, students have access to a bank of many years of prior students' data to aid in pattern discernment. The cumulative curricular design also promotes more cohesive knowledge than a disconnected, traditional curriculum. Finally, this course challenges students with several forms of assessment, very few of which are multiple-choice.

Though the design principles described above contribute to the excellent quality of the laboratory course, we conjecture that the heavy emphasis on collaborative work in the laboratory is the most important causal element related to the outcomes described here. The laboratory is community-centered as the majority of the coursework is done in teams, and productive management of the differences among group members encourages positive learning outcomes (Heller & Hollabaugh, 1992). Team-learning environments have been repeatedly found to be superior to individualized problem solving in terms of student learning, development of interpersonal skills, and promoting student enjoyment of a course (Johnson & Johnson, 1989; Totten, 1991), perhaps cultivating student interest in learning science. In college-level chemistry courses, many studies have lauded various benefits of collaborative work (Bowen, 2000; Cooper, 1994, 1995; Cooper et al., 2008; Cooper & Kerns, 2006; Tien et al., 2002). The collaborative aspects of the specific laboratory studied here are numerous. Most notably, the team lab reports encourage students to come to consensus on all aspects of performing the experiments, and the team discussion presentations require that students confer about the implications of an experiment, including resolving differences of opinion within the group and explaining to the whole class how they did so. Additionally, in the beginning of the term, teams spend time identifying the strengths and previous experiences of their group members with the goal of recognizing skills they may be lacking as a group, and each team member evaluates the contributions of other members to the experiments, team reports, discussion presentations, and team as a whole throughout the semester.

The metacognitive and peer interaction (including argumentation) features of collaborative work may constitute the mechanism that yields the observed results both here and in other studies that explore group work as an intervention. Students engage in metacognitive practices when they must explain their thinking to another group member, and in this laboratory, there are multiple contexts in which students share their ideas with one another, which has been shown to enhance learning by leading to cognitive development (National Research Council, 1999, 2006); these contexts include performing the experiment, writing the team report, and giving oral presentations as a group to the whole class. Sharing and constructing ideas with another student, as well as listening to a student explain something to himself, are metacognitive and peer interaction methods that have been proposed to lead to learning gains (Hausmann, Chi, & Roy, 2004, August). White and Frederiksen (1998) have also shown that metacognitive activities can specifically help lower-achieving students, which may explain the observed disproportionate effect of concurrent enrollment on final grades that depends on students' placement exam scores. The collaborative design of the laboratory facilitates these metacognitive and peer interaction processes that may lead to the described benefits for concurrently enrolled students.

Despite the large laboratory and lecture courses not being explicitly linked in format or content (other than that they are both general chemistry courses), concurrent enrollment positively impacts student performance and retention in the lecture. These results beg the question as to what outcomes might be observed if the laboratory and lecture were explicitly aligned and taught synergistically, especially in light of studies that have reported advantages of integrated course structures (Bailey, Kingsbury, Kulinowski, Paradis, & Schoonover, 2000; Oliver-Hoyo et al., 2004). Recall that in the studio-style course, the laboratory and lecture were integrated and aligned in a five-credit course, yet our results indicated no practical benefit in terms of final grades or withdrawal rates over concurrent enrollment in a nonstudio format. This may seem confusing in light of the number of universities that have reported benefits of studio-style courses, but the findings are understandable considering that many pedagogical methods that render studio courses beneficial to students are already present in the laboratory course studied here. It is also possible that the particular metrics employed in this study are not sensitive enough to differentiate between the two student populations given the differences in how studio students were evaluated. In summary, though content alignment is a useful technique, our data indicates that educational benefits can be achieved in unaligned courses as well.

Our survey of large, public universities (Table 1) demonstrates that a substantial portion are not requiring concurrent enrollment in introductory-level science lectures and laboratories. The data presented herein indicates that requiring concurrent enrollment may be a viable path for improving student performance and retention in the lecture, and, considering the sheer magnitude of undergraduates who take these introductory science courses, the number of students who could be affected is substantial. Though we focused our attention here on large, public universities, there is potential for similar results to be found at any college or university that does not require concurrent enrollment, regardless of size. Additionally, these results could be extremely influential at the high school level. Consider the potential implications on graduation rates and the scientific pipeline of more students being retained in high school science classes!

Similar results may be found in higher-level courses such as organic chemistry, as well as in disciplines such as physics and biology in which it is evidently fairly common for lectures and laboratories to be offered separately. Comparable effects may also exist across disciplines. For example, based on previous research that has established college math scores as a predictor of good general chemistry scores (Angel & LaLonde, 1998), does a student who enrolls in college algebra and general chemistry do better with regard to some outcome than a comparable student who enrolls in general chemistry but not algebra? The link between general physics and calculus would also be interesting to explore. As is, the results presented here may have impact at the course-level, but similar findings in other disciplines could generate significant impact in pedagogical practice at the college- and university-level; these levels of application are oftentimes neglected in Scholarship of Teaching and Learning research (McKinney, 2007).

Because of the high cost of science laboratories, there is an ever-present need to justify their value, and this is especially true in the face of budget restraints. This research, in summary, supports the laboratory as a valuable method for achieving learning gains and increasing retention in the lecture. The collaborative design of the laboratory provides an important element of practice for metacognitive development and peer interaction, and we surmise that this collaborative nature of the laboratory is the most important feature related to the observed results. We anticipate that this work will be of interest to a broad range of teachers, professors, and educational researchers, especially those involved in course design, as this study is realistically applicable to any discipline that offers a course with separate lecture and laboratory components. Further research is needed as to the particular reasons why the laboratory benefits students' final grades in and withdrawal rates from the lecture, as well as the rationale behind the choice that students make to nonconcurrently enroll, as we fully expect that the reasons why students nonconcurrently enroll are nonuniform.

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