Robert H. Tai, Philip M. Sadler, Adam V. Maltese

A Study of the Association of Autonomy and Achievement on Performance

The authors find that autonomous learning activities in high school science interact with high school mathematics grades to produce a significant association with college science grades.

Inquiry-based instructional practices are a mainstay of the National Science Education Standards (National Research Council, 1996). The National Research Council (NRC) teachers' guide asks the critical question, "How does a teacher decide how much guidance to provide in an inquiry?" (NRC, 2000, p. 30). Another primary concern is the quality of student work produced in these activities. For many teachers who assign inquiry activities, the reality is that while some students may produce good work, others languish (O'Neill & Polman, 2004; Polman, 2000).

A major finding of prior interaction research was that higher achievers responded better in less-structured learning environments, such as student designed projects and labs, while lower achievers responded better to more-structured environments, as in labs using worksheets and detailed directions (Cronbach & Snow, 1977; Tobias, 1981). Based on this finding, optimal levels of academic performance would be expected if instructional methods were chosen to more closely match students' backgrounds. Will matching a student's academic achievement with particular teaching practices have a long-range impact on their academic performance? A review of existing literature shows that these types of studies are not common (e.g. Cronbach & Snow, 1977). With more students going to college (Bureau of Labor Statistics, 2005) than during the past few years, and most high school science teachers naturally emphasizing college preparation (Hoffer, Quinn, & Suter, 1996), one option for a long-range measure of performance is introductory college science. Research linking high school preparation to college performance may provide some insight into best practice.

This study investigated the interaction between students' academic background (high school grades, standardized exams, and enrollment in advanced high school courses) and how much autonomy they reported having in high school science through labs and projects. Our objective was to see if students who reported experiencing more or less self-directed projects and labs performed differently in college science when we took into account their prior academic background. To provide a more solid foundation for our conclusions, we performed the same analysis on three different data sets in biology, chemistry, and physics.

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Methodology

The data used in this study is a subsample taken from a national survey entitled *Factors Influencing College Science Success* (Project FICSS, NSF-REC 0115649). A sample of 67 four-year colleges and universities was selected from a comprehensive list of nearly 1,700, using stratified random sampling based on size to insure that the sample spanned the range from small colleges to large universities. Of the selected schools, 55 schools from 31 states participated.

Faculty in 29 biology departments, 31 chemistry departments, and 37 physics departments participated and data was collected from college science students in 128 different first semester introductory college science courses all taught exclusively in the Fall Semesters of 2002 and 2003. Insti-

Table 1: Summary of Institutional Characteristics of Participating Schools

Field (# of Schools)	Participant	Affiliation		Avg. ACT	Avg. SAT	School Size [a]			# of States
	Totals	Public	Private	Range of Avg. ACT	Range of Avg. SAT	S	M	L	
Physics (37)	1903	24	13	17-30	830-1320	18	12	7	26
Chemistry (31)	3521	20	11	17-27	830-1210	16	11	4	22
Biology (29)	2749	19	10	17-30	840-1320	13	9	8	23

[a] Small schools < 5,000 student enrollment (full-time equivalent student enrollment totals, FTE), medium-size schools between 5,000 and 15,000 FTE, and large schools >15,000 FTE.

tutional data is displayed in Table 1. To check for institutional "self-selection" bias, we compared participating and non-participating schools across measures such as school size, admissions selectivity, and geographic location and found no indications of bias.

For continuity in comparison across courses, we chose to include only courses with the ubiquitous large lecture format, by far the most likely to be experienced by high school students who take introductory college science. All courses in this survey filled program requirements for majors within their respective disciplines. All 67 schools originally selected for the survey used this class format. The total sample sizes were: 2,754 biology surveys, 3,521 chemistry surveys, and 1,903 physics surveys. These sample sizes offer a high degree of statistical power (Light, Singer, & Willett, 1990).

The survey instrument was designed by the researchers to collect information about a large number of curricular issues in high school science. The survey was vetted through a series of focus group interviews and pilot surveys. For retrospective self-report surveys, limitations of accuracy and reliability are important considerations. A review of research (Kuncel, Credé, & Thomas, 2005) concluded that self-report surveys of college students are reasonably accurate and produce valid information. To improve accuracy and reliability, the survey was designed with characteristics associated with improving recall (Niemi & Smith, 2003; Sawyer, Laing & Houston, 1988; Schiel & Noble, 1991; Valiga, 1987). The reliability of the questionnaire was assessed through a separate test-retest study of 113 introductory college chemistry students, not included in the sample analyzed here. The reliability study required students to complete the survey on two separate occasions, two weeks apart. The resulting reliability coefficients ranged from 0.46 to 0.69, which were considered reasonably high for analyses of groups of 100 students (Thorndike, 1997). Finally, to further enhance accuracy, the surveys were administered during college science class sessions, (i.e. lectures, recitation meetings, or lab sessions) and the students' final grades were reported by professors.

As is common in many surveys, not every participant answered every question. Many students left blanks, or marked multiple responses to the same question. Recommended research practice favors data imputation over the more commonly used tactic of list-wise deletion (Peugh & Enders, 2004). We employed the Expectation – Maximization (EM) Algorithm[1] to impute missing data for the predictors: SAT-Mathematics, SAT-Verbal, Last High School Mathematics Grade, Last High School Science Grade, and Last High School English Grade (Allison, 2002; Little & Rubin, 2002; Scheffer, 2002). With data imputation, 88% of the surveys were retained for the analysis. The final sample sizes were 2,430 students for biology; 3,187 students for chemistry, and 1,577 students for physics.

The first step in data analysis was a descriptive comparison across different demographic and general educational background variables. Next, multiple linear regression models were fitted to the outcome variable, final college science course grades, hereafter referred to as GRADES. Controlling for differences in demographic and general educational backgrounds, this analysis included students' academic background measures (high school grades, standardized exams, and patterns of advanced course taking), and students' experiences with inquiry-related pedagogies (Student-designed Projects and Level of Freedom in laboratory exercises).

Research linking high school preparation to college performance may provide some insight into best practice.

College science grades are a common choice to gauge science performance (Gainen & Willemsen, 1995; Ozsogomonoyan & Loftus, 1979; Spencer, 1996). A review of course syllabi shows that college grades are not a single measure, but a composite

[1] An extended explanation of the process of data imputation is available upon request from the corresponding author.

Structured learning activities are essential to building the knowledge-base necessary for understanding more advanced scientific concepts, while autonomous learning forms the foundation of scientific inquiry.

of several different measures (e.g. tests, quizzes, homework sets, and exams) collected over months, and as a result, are collectively more indicative of student performance than a single achievement test. In addition, college-level content subsumes high school content, often in just a few weeks. Therefore, one would expect that students with a deeper conceptual understanding of the fundamental science topics would have an advantage and earn higher college grades. To address concerns about comparability across courses and institutions, college effects variables were included to account for these differences (Pike & Saupe, 2002).

The academic achievement predictors included SAT-Quantitative and Verbal scores; Last High School grade in Mathematics, Science, and English; high school enrollment in calculus (regular, Advanced Placement® Calculus A/B, and Advanced Placement® Calculus B/C); and enrollment in Advanced Placement® science courses. The inquiry-type learning activity predictors included Number of Student-designed Projects and Level of Freedom in Designing/Conducting Labs.

The demographic background predictors included gender, racial/ethnic background, parental education levels, average county household income, and high school type (i.e. public or private) which past studies have shown to be important (e.g. Bryk, Lee, & Holland, 1993; Burkam, Lee, & Smerdon, 1997).

Results and Discussion

The descriptive statistics for the predictor variable, Number of Own Projects, were very similar across all three data sets, with the average number reported by students in all three disciplines at about one per high school course (see Table 2). However, Level of Freedom in Designing/Conducting Labs varied widely between students in biology and the two physical sciences. The biology ratings appear to be nearly half of a standard deviation below the other averages. This result suggests that college chemistry and physics students reported more freedom in their corresponding high school classes than college biology students reported about their high school biology classes.

The mathematics achievement measures show some differences

Table 2: Descriptive Statistics for Continuous Predictors

		Min	Max	Biology Mean (s.d.)	Chemistry Mean (s.d.)	Physics Mean (s.d.)
Number of Student-designed Projects (None = 0, More than 3 = 4)		0	4	1.2 (1.2)	1.0 (1.2)	1.2 (1.3)
Level of Laboratory Freedom (None = 0, Complete = 4)		0	4	1.2 (1.2)	1.6 (1.3)	1.7 (1.2)
SAT Score	Quantitative	220	790	580 (100)	590 (100)	620 (90)
	Verbal	200	800	570 (100)	570 (100)	580 (100)
Last HS Grade in … (A = 5, F = 1)	Mathematics	2	5	4.3 (0.8)	4.3 (0.8)	4.5 (0.7)
	Science	1	5	4.4 (0.8)	4.4 (0.8)	4.5 (0.7)
	English	1	5	4.6 (0.6)	4.6 (0.6)	4.6 (0.6)
Highest Parent Education Level (Attended HS = 0, Grad. School = 4)		0	4	2.8 (1.1)	2.7 (1.1)	2.9 (1.0)

Table 3: Frequency Statistics for Categorical Predictors

Predictors		Number of Students					
		Biology		Chemistry		Physics	
AP® Science	Did Not Enroll	2428	88%	3155	90%	1747	92%
	Enrolled	326	12%	366	10%	156	8%
HS Calculus	No HS Calculus	1775	65%	2000	57%	842	44%
	Regular	373	14%	518	15%	351	18%
	AP® A/B	473	17%	792	22%	526	28%
	AP® B/C	133	5%	211	6%	184	10%
Race/Ethnicity	Native American	33	1%	36	1%	27	1%
	Black	207	8%	202	6%	102	5%
	Hispanic	134	5%	177	5%	89	5%
	Asian	167	6%	293	8%	151	8%
	Multi-racial	73	3%	93	3%	38	2%
	Not Reported	53	2%	95	3%	106	6%
	White	2087	76%	2625	75%	1390	73%
Year in College	Freshman	1496	54%	2103	60%	234	12%
	Sophomore	691	25%	811	23%	733	39%
	Junior	404	15%	393	11%	579	30%
	Senior	127	5%	143	4%	273	14%
	No Response	34	1%	64	2%	82	4%

across the three samples. As one might expect, physics students report having taken more mathematics and also report generally higher mathematics achievement. The percentage of students reporting high school calculus enrollment varied across the three disciplines: 35.4 % for biology, 43.2 % for chemistry, and 55.8 % for physics students. The average SAT-Mathematics scores (see Table 2) for biology and chemistry students were 580 and 590, respectively; while the average SAT-Mathematics score for physics students was 620. Also, biology and chemistry students' average high school mathematics grades were the same at 4.3 (A = 5; B = 4), while the average for physics students was 4.5, roughly one quarter of a standard deviation higher. In general, introductory college physics students were higher math achievers than introductory college biology and chemistry students.

Autonomous learning is the seed of scientific research.

In other measures, we found very similar results across the three separate samples. A comparison of the averages for SAT-Verbal, Last HS Grades in Science and English, and Highest Parental Educational Level found them all to be similar. Fewer than 12% of the students in all disciplines enrolled in the corresponding Advanced Placement® science course in high school. A comparison of gender differences showed more females than males in biology and chemistry, and more males than females in physics. Students enrolled in introductory sciences are overwhelmingly white, comprising three quarters of the sample in each discipline (see Table 3). For Year in College, biology and chemistry students were primarily freshman, while physics student were primarily sophomores, which may be due to the calculus co-/prerequisite for some physics courses. In general, the descriptive data is consistent with well-known educational trends. This consistency is important, since our analysis is intended to produce generalizable findings.

Regression Models

The main focus of this study was to investigate the interaction between differences in students' academic achievement and their high school learning experiences. We wanted to study what influence the level of autonomy students reported experiencing in high school had on their college science performance when taking into account their academic background, specifically with respect to mathematics achievement. The analysis found a significant interaction between Last High School Mathematics Grade and Level of Lab Freedom for the biology (α – level = 0.05) and chemistry (α – level = 0.05) analyses, but not for the physics analysis. Figure 1 presents a comparison of the results of the multiple linear regression analysis. All three regression models accounted for roughly one third of the overall variance, a strong result for such large-scale analyses.[2]

At first glance, these findings may seem inconsistent with results for physics lacking a significant interaction. However, looking back at comparisons of the students' backgrounds in Tables 2 and 3, the average college physics student appears to have higher levels of mathematical achievement than his or her peers in chemistry or biology. This artifact suggests that fewer students with low and very low Last High School Mathematics Grades enrolled in college physics. Therefore, it seems reasonable to argue that the interaction was not found in the physics data because students with weaker mathematics achievement in high school may choose not to enroll in physics courses.

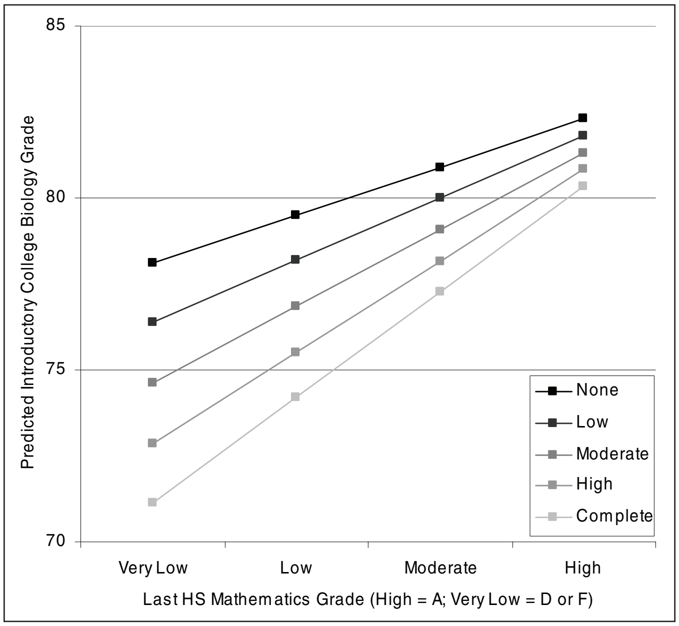
At first glance, the graphs in Figure 1 appear to indicate that students who reported complete freedom in designing and conducting labs were at a disadvantage in all disciplines. However, a closer look shows that large differences are mainly for students reporting low to very low Last High School Mathematics Grades in the biology and chemistry. For the students in the high and moderate groups, the differences are much more modest with results similar to the physics analysis which showed no interaction. The regression results predict that students earning low and very low Last High School Mathematics Grades who also reported Complete Lab Freedom were predicted to have college biology and chemistry grades approximately one half of a letter grade lower than their peers who reported no freedom. These results imply that higher autonomy in high school labs may not be the best way for students with low mathematics grades to learn science in high school.

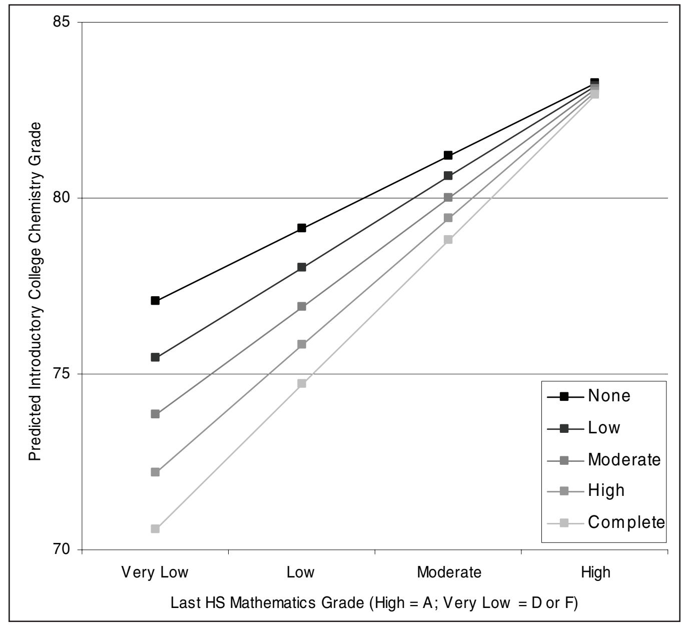
Conclusions

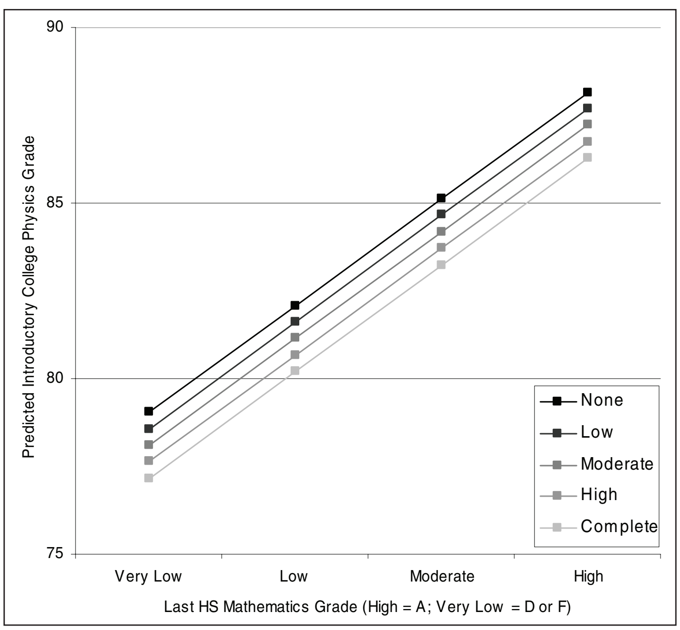
The results from this study suggest that decisions about how much freedom to give students in high school science activities such as labs and projects should also include considerations of students' achievement in mathematics. Structured learning activities are

[2] Tables comparing the three replicate multiple linear regression models are available from the first author upon request.

Figure 1: Association of Level of Lab Freedom (None to Complete) and Last HS Mathematics Grade on Predicted Introductory College Science Grade







essential to building the knowledge-base necessary for understanding more advanced scientific concepts, while autonomous learning forms the foundation of scientific inquiry. The findings from this study suggest that students with lower levels of high school mathematics achievement had greater success in college science when they reported more structured high school lab experiences. Students with higher levels of high school mathematics achievement did not reveal much variation with differences in lab structure. These results agree with earlier research and extend these conclusions to longer range outcomes.

This study compelled us to think more deeply about teaching and learning science, and the outcomes. Final course grades were chosen for this analysis primarily because of their clear impact on students' career paths; however, other outcomes are also important to consider. While some forms of teaching may be highly effective in building students' background knowledge and enhancing their performance in science, other methodologies seem to raise students' interest in learning science and spark their imagination, possibly contributing to their continuance in the study of science.[3] Performance and continuance may be two different dimensions of science pedagogy. Other studies have found important positive impacts of instructional methods on student interest and attitudes (e.g. Hofstein, Shore, & Kipnis, 2004; O'Neill & Polman, 2004).

[3] The term "continuance" is used here rather than the term "persistence," which refers to long-term student commitment in the pursuit of an educational goal (e.g. Seymour & Hewitt, 1997). This study captures only shorter-term course-taking. Science course-taking is but one step in science persistence. We wish to acknowledge Mary M. Atwater for her insight (Personal correspondence, May 16, 2005).

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If freedom in laboratory design is associated with lower college science performance for many students, should this approach to instruction be abandoned in high school science courses? Abandoning freedom for students to design and conduct their own experiments in science labs is very shortsighted. Autonomous learning is the seed of scientific research. Scientists must achieve some level of research independence in order to make contributions to the knowledge-base. Certainly, there have been questions raised about the authenticity of students' laboratory work as a reflection of scientific practice (Hodson, 1996). However, laboratory work in school science is a pedagogical tool to teach both content and practice in scientific inquiry, thus a balance must be struck between structure and autonomy in inquiry-type learning activities.

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