Class Size, Course Spacing, and Academic Outcomes[*]

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Abstract

Using administrative data from a land grant university, we estimate how class size and waiting longer between courses impacts student grades using paired prerequisite and follow-up courses. We find that students in larger prerequisite classes earn lower grades in follow-up courses, although this effect is mitigated as the time between the two courses increases. This finding is consistent with the hypothesis that students learn less in larger class sections, leaving them with less knowledge to decay and that any increase in student maturity may more than make up for the forgotten material.

Key Words: Knowledge Decay, (Summer) Learning Loss, Class Size
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1. Introduction

A large and growing body of research documents mostly negative effects of larger classes on student outcomes. Much of this literature focuses on elementary school class size and finds that larger class sizes are associated with lower test scores.[2] Class size estimates in higher education are less common, but also suggest negative effects of class size on student outcomes, particularly for minority students and first-generation students.[3] Smaller classes often offer more opportunities for active, hands-on learning than larger ones, and allow the use of pedagogical tools that may improve student learning [Gleason 2012 and Lopesto and Slater 2016]. Some evidence suggests that larger classes may benefit more students because larger classes allow better teachers to teach more students; reducing class size may mean exposing students to lower-quality instructors as universities hire less experienced teachers [Sapelli and Illanes 2016].

This paper also contributes to the literature on knowledge decay. Much of the knowledge decay literature focuses on the debate in elementary and secondary schools over the effect of summer vacations—the long annual break—on student knowledge. This observed decline in test scores after the summer vacation has also been called the summer learning loss [Kneese 2000; Cooper et al., 2003]. Some studies estimate the summer learning loss to be as large as "…about one month on a grade-level equivalent scale, or one-tenth of a standard deviation relative to spring test scores" [Cooper et al. 1996].[4] This effect is also not equal across different types of students. For example, studies document larger declines for disadvantaged and minority students [O'Brien 1999; Burkam et al. 2003; Downey, Hippel, & Broh, 2004; Alexander, Entwisle, &

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[2] See, for example, Krueger (2003) on the Tennessee STAR study or Mathis (2017).
[3] See, for example, Diette and Raghav (2015), Beattie and Thiele (2016), and Bandiera, Larcinese, and Rasul (2010).
[4] The impact of knowledge decay has typically been applied to the debate of a traditional academic calendar vs. year-round schooling (Graves, 2010 and 2011; McMullen and Rouse, 2012; Graves, McMullen, and Rouse, 2013). Anderson and Walker (2013) extend this research to examine learning loss over the weekend, finding a positive effect for shorter weeks and longer breaks.

Olson, 2007]. McMullen and Rouse [2012] illustrate the importance of student fixed effects in estimating summer learning loss. At the college level, Dills et al. [2016) find that any observed knowledge decay is largely eliminated with the inclusion of student fixed effects. Even with the student fixed effects, some groups continue to experience knowledge decay: students in language courses, for students with below-median SAT Math scores, and for students with majors outside STEM fields.

We extend the evidence on class size effects in higher education by focusing on a different academic outcome, grades in what we call follow-up courses, a course that closely builds on the content of a course and lists it as a prerequisite. Using administrative data at a large public university, we examine pairs of prerequisite and follow-up courses. We consider how the characteristics of the prerequisite class and spacing between the courses in the course-pair affect student performance in the follow-up course. Specifically, we estimate three effects. First, we estimate how the class size of one's prerequisite class affects students' grades in the follow-up course. Second, as in Dills et al. [2016], we estimate the effect of more time between courses in a course-pair.[5] Third, we allow the effect of waiting longer to take a follow-up course to differ for students in different sized prerequisite courses.

We allow prerequisite class size to affect student performance in two ways. Class size may affect how much students learn, a question that has been studied previously. Class size may also affect how long students retain their knowledge. For example, more deeply held knowledge may depreciate more slowly and class size may affect that depth of learning. This is the first study to test this second hypothesis. If class size affects students' knowledge retention, we

[5] Dills et al. (2016) focused on the question of whether there is any measurable between semesters, and whether this loss is larger over the summer break relative to the winter break. Given the overlap of sample and course-pairing between the two papers, some language draws directly from Dills et al. (2016).

would observe different effects of waiting longer between courses for students taking larger and smaller prerequisite classes.

Our specifications include student fixed effects as well as a variety of course characteristics to control for differences across students and courses. In most cases, we also control for course-pair fixed effects. We estimate small, negative effects of prerequisite class size: adding one hundred students to a classroom lowers grades by 0.04 grade points.[6] The effect of waiting longer between courses somewhat differs for different sized prerequisite classes. For students enrolled in 116 person prerequisite section, the 75th percentile in the sample, waiting an additional two months to take the follow-up course results in grades that are 0.07 grade points higher. For students enrolled in 22 person prerequisite classes, the 25th percentile in the sample, waiting an additional two months to take the follow-up course results in grades that are 0.01 grade points higher. The overall pattern of results suggests that students enrolled in larger prerequisite courses may benefit from waiting longer to take the follow-up course.

2. Empirical Method and Data

Our sample comes from all grades earned by undergraduate students at Clemson University from 1982 to 2002. Clemson University is a selective, research-intensive, public land-grant institution in Clemson, South Carolina. Clemson is ranked in the top 100 national universities by U.S. News and World Report. We observe approximately 69,000 students during this period. The dataset includes individual characteristics for over 90% of the sample, including

[6] Figures from this table use the estimates from Column (3) of Table 2. The class size effect is calculated using six months between the start of each course.

SAT scores, race, sex, whether they are from South Carolina, and if they had a family member go to Clemson. The data include class size for every course observed in the sample.

The course catalog lists prerequisites for each course, allowing us to pair courses. Some common course pairs include the language sequences such as Spanish 101 and Spanish 102; science course sequences such as Chemistry 101 and Chemistry 102; and math course sequences such as Calculus I and Calculus II.[7] Some courses also list multiple prerequisite courses. When considering courses with multiple prerequisites, we define the initial course in a two-course sequence as the highest-numbered prerequisite course. In a robustness check, we limit the sample to follow-up courses with only one prerequisite and find similar results.[8]

The university is a land-grant institution with a strong focus on science and engineering. About half of the sequences in our sample are in the science, technology, engineering, or mathematics (STEM) courses. We also observe common sequences such as English 101-102 or longer sequences, such as the four-semester Spanish sequence of 101-102-201-202. Of the sequences analyzed, 80 percent of the students take sequences that are fall-spring. The remaining 20 percent of analyzed sequences are taking their first class in the spring and the follow-up course in the fall.

We measure the length of time between a student taking the prerequisite and taking the follow-up course as the number of months from the start of the first course to the start of the

[7] Dills and Hernández-Julián (2008) has a full list of the courses in the sample; we reproduce that table in Appendix Table A2. We match course pairs using one academic year's catalog. We check for but do not find evidence of changing patterns in course-taking plausibly associated with a change in prerequisites in the remainder of the sample. Please refer to that paper and to Dills et al. (2016) for more information on the construction of the course pairs.

[8] Results are available upon request.

second course in the sequence.[9] The main analysis sample includes only students taking a course-pair either fall then spring or spring then fall. The measured gap for a student taking a fall course followed by a spring course is five months; the measured gap for a student taking a spring course followed by a fall course is seven months. The average months between beginnings of courses is 5.4.

The main analysis sample comprises 117,610 course-pair observations for 47,250 unique students.[10] Table 1 presents summary statistics for this sample. Students can earn only full letter grades: A (4.0), B (3.0), C (2.0), D (1.0), or F (0.0). The prerequisite courses average a grade of 2.8 (what would roughly be a B-) and a class size of 70 students. The follow-up courses average a grade of 2.7 (what would be a B-) and a class size of 62.9. About 2 percent of students take the prerequisite twice. For these students, we use the more recent prerequisite course's characteristics in the estimation sample.

We estimate the following for student *i* who took an introductory course *k* during period *p* and then took follow-up course *j* during semester *t*:

$$\text{Grade}_{ikpjt} = \beta_1 \text{Months between}_{ikpjt} + \beta_2 \text{ClassSize}_{ikp} + \beta_3 \text{ClassSize}_{ikp} * \text{Months between}_{ikpjt} + \alpha\ \text{Prereq-Grade}_{ikp} + W'_{itj} + \Theta_t + \lambda_{jk} + \sigma_i + e_{itjkp} \quad (1)$$

[9] Note that this is the same as doing middle to middle or end to start (as the variation can only occur in the break length). There are other ways to measure this gap. However, the most accurate data is from the start of one semester to the start of the next semester. When measuring from the end of the first course to the beginning of the second course or the middle of the first course to the middle of the second course the results are robust. Thus, to keep our gap measure as clean as possible, we measure the gap from the beginning of the first course to the beginning of the subsequent course.

[10] For additional details on the sample, see Dills and Hernandez-Julian (2008) and Dills et al. (2016).

where $Grade_{ikpjt}$ is the students grade in the course measures as an integer from 0 to 4 (0 for F, 1 for D, etc.). Grades are one measure of student knowledge, albeit likely imperfect.

'Months between' measures the length of time between the start of the prerequisite course and the follow-up course. Waiting longer between courses allows more time for the depreciation of knowledge, likely leading to lower grades in follow-up courses. Waiting longer may have benefits, however. Students have more time to mature, to understand their mistakes in previous classes, and for incorrect knowledge to depreciate.

W_{itj} is a matrix of student characteristics and course characteristics including the course level (100-, 200-, 300-, or 400-level course), department indicators, and an indicator for students who are taking a course for the second time.[11] The department indicators control for differences in departmental grading policies. To control for time-varying grade differences, such as university-wide grade inflation, we include year dummies for the calendar year of the follow-up course.[12] Repeated observations for students allow us to include student fixed effects, σ_i, in the estimation model. These fixed effects account for time-invariant characteristics such as ability, socio-economic background, sex, and race. Other traits, such as motivation and maturity, may vary over time, so student fixed effects will not capture this change. In all specifications, we include the cumulative number of credits earned by the students, a measure of class year that captures some aspects of student maturity. In most specifications, we also include course-pair fixed effects, λ_{jk}.

[11] Tafreschi and Thiemann (2015) , using a regression-discontinuity design, estimate that students who are required to repeat all of their first-year courses are more likely to drop-out but also earn higher grades when they re-take a course.

[12] In samples expanded to include a wider variety of gap lengths between classes, we include semester-by-year fixed effects.

We focus on the coefficients on the prerequisite class size and the interaction of prerequisite class size and the time gap between courses. There are four potential outcomes. First, students learn more material while in a larger class, but in such a way that causes the information to fade more quickly ($\beta_2>0$, $\beta_3<0$). Second, students learn more material while in a larger class and learn it more deeply so that the information decays more slowly ($\beta_2>0$, $\beta_3>0$). Third, students learn less material while in a larger class and in such a way that causes the information to decay more quickly ($\beta_2<0$, $\beta_3<0$). Fourth, students learn less material while in a larger class but that the content that is learned decays more slowly ($\beta_2<0$, $\beta_3>0$). College students may continue to mature while at school and to take their studies more seriously. In both the second and the fourth potential outcomes listed above, the interaction effect (β_3) may also reflect positive maturing effects of the student over time.

Ideally, we compare the performance of students in the same follow-up course with differing prerequisite characteristics. We approach, but do not attain, this ideal because we do not observe the exact section in which a student enrolls. Although the student fixed effects and course-pair fixed effects control for time-invariant characteristics of the students and courses, we do not possess information on the courses' instructors. Professor experience and quality slightly improve student learning in higher education [Carrell & West 2010; Braga, Pacagnella, and Pellizari, 2014]. Carrell and West [2010] find that students of less qualified teachers earn higher grades in Calculus I but lower grades in Calculus II. They theorize that students may gain more "deep learning" in classes with a more experienced professor. If better instructors teach larger sections, this would bias the estimates of class size downwards. Bias in the estimated effect of time between courses requires that different quality instructors teach in the fall compared to in the spring. If better instructors teach prerequisites in the fall, their students experience shorter gaps before the follow-up course, biasing the estimate on the gap downwards; if better instructors teach prerequisites in the spring, their students experience longer gaps before the follow-up course, biasing the estimate on the gap upwards. Overall, we are unable to control for the instructor either through fixed effects or instructor traits, which may bias our estimates.

We do not observe how classes are taught, a factor that may be correlated with class size as well as student outcomes. Freeman et al. [2014] find that active learning increases student performance in STEM courses. The majority of our sample, however, is from the 1980s and 1990s, before active learning had become as common in college teaching as it is today. If professors in larger classes employ better teaching methods or are more experienced instructors, this would bias our class size estimates upward. Very small classes are less likely to be conducted in a lecture style, whereas the very large classes are very likely to be conducted in a lecture style, perhaps (at least in recent years) with active learning methods interspersed.[13] Further, cheating may be easier to get away with in a larger class, leading to less student learning, shorter retention of that learning, or both.

We stratify the sample by a variety of characteristics. We stratify the sample by the entering SAT score of the students and by sex. We also separately restrict the sample to 100- and 200-level follow-up courses. Diette and Raghav [2015] find that smaller class size predicts student success particularly for students in 200-level courses, for students with below-average SAT scores, and for freshmen. We extend their research to see how class size impacts learning as

[13] Results presented in Appendix Table 1 allow for the effect of prerequisite class size to be non-linear. In column (4) we present results using a quadratic in prerequisite class size; in column (5) we use the log of prerequisite class size. The results suggest some non-linearity in that the interaction of months gap with the squared class size is significant in column 4. In the specification using logged class size, we observe that a 10% increase in prerequisite class size lowers grades by 0.025 grade points that is offset by a 0.003 grade point increase for every month longer the student waits to take the follow-up course.

demonstrated by performance in subsequent courses. Beattie and Thiele [2016] find that increased class size is more likely to harm minority students and first-generation college students. In contrast, Bandiera, Larcinese, and Rasul [2010] find that smaller classes benefit the highest performing students. We separately consider language courses and STEM courses. Previous research suggests that class size may matter more for foreign language courses [Khazaei, Zadeh, & Ketabi 2012; Asqalan et al. 2016].

3. Results

Table 2 presents estimates using the sample of fall-spring and spring-fall course sequences only. In column (1) we estimate the specification without student fixed effects but with a variety of student characteristics. We include their SAT Math score, age entering Clemson, race, and dummy variables for whether the student is in-state, male, or a legacy student.[14] The coefficients on the gap between courses and the prerequisite's class size are negative and significant. Longer gaps between paired courses and larger prerequisite class sizes are associated with lower grades in follow-up courses. The coefficient on the interaction of these two variables is positive and statistically significant. These results suggest that larger prerequisite classes lead to slightly lower grades in follow-up courses although this effect is offset when the courses are separated by a longer gap. The interaction term also implies that although a longer gap is associated with lower grades, this effect is slightly smaller when the prerequisite's class size was bigger.

[14] Legacy students are students that have a family member that went to Clemson. The results for these controls are not reported but available upon request.

Column (2) presents the results including the student fixed effects. As seen in Dills et al. [2016], including student-level fixed effects reduces the magnitude of the coefficient on months between courses and turns it insignificant. The estimates for prerequisite class size and its interaction with months between are somewhat smaller and still statistically significant. Column (3) adds course-pair fixed effects to the student fixed effects. We continue to find class size effects that are negative and significant with the interaction of the class size and months between to be positive and significant. Larger prerequisite classes lower student performance in the follow-up course. The effect is somewhat offset by students waiting longer for the follow-up course.[15]

The magnitude of these results is modest. We consider the effect of increasing class size from 22 students to 116, a move from the 25^{th} to 75^{th} percentile of class size in the sample. The results in column (3) imply that the effect of the larger class size for fall-spring students is a statistically significant decline in grades of 0.1 grade points (p-value = 0.000); for spring-fall students, the class size effect is an increase in grades of 0.016 grade points (p-value = 0.413). The effect of a two-month longer gap is small and statistically significant increase for students in a prerequisite class of 22 students (0.03 grade points p-value = 0.064); the effect is a larger and statistically significant increase of 0.15 grade points for students in a prerequisite class of 116 students (p-value = 0.000).

The specification includes the class size of the follow-up course. Interestingly, the estimate on this class size tends to be positive, small, and statistically significant. An increase

[15] Given the ordinal nature of grades, we also estimate columns (2) and (3) of Table 2 using an ordered logit. These results are available in Appendix Table A3. The pattern of estimates is similar: larger prerequisite classes lead to lower grades unless students wait at least seven months between classes. Waiting longer between courses lowers grades when prerequisite classes are small; for a prerequisite class size larger than 77 students, waiting longer raises grades in the subsequent course. The coefficients are more likely to be statistically significant in the ordered logit.

from the 25th percentile of follow-up class size (21 students) to the 75th percentile (98 students) results in grades that are 0.04 grade points *higher* (p-value = 0.001), evidence that time to mature in collegiate coursework may have a substantial impact on student grades.

In columns (4) and (5) we add students who took the courses more than one semester apart but not more than 18 months apart. A concern with allowing longer gaps between the courses is that the delay now becomes endogenous: instead of taking the follow-up in the next available semester, students are deciding how long to spend between the courses. Students may choose longer gaps to provide more opportunities to learn material in other courses, better adapt to college, and mature before the next course. The estimates using the longer sample continue to show a significant, but smaller, impact of class size and the interaction of class size and months between when including student level fixed effects and course-pair fixed effects. However, when adding course-pair-semester fixed effects the significance goes away.

In Table 3, we split the sample by types of courses. This table uses the same specification as column (3) of Table 2. Column (1) presents results for foreign language courses. Dills et al. (2016) estimate higher rates of knowledge decay for language courses. Controlling for class size turns the estimated effect of months between courses is to raise grades. The average language prerequisite class enrolls 20 students; at this class size, waiting two additional months for the follow-up course increases follow-up course grades by 0.12 grade points (p-value = 0.029). Larger prerequisite classes lead to lower grades in follow-up courses. Although the class size effect is not statistically significant, effects are larger for students in spring-fall sequences. Column (2) presents results for STEM courses. The effect of class size is similar for STEM classes as in the full sample: larger prerequisite classes lower student grades in follow-up classes, but less when the student waits longer.

We then limit the sample in ways that target course-pairs where the follow-up course more likely directly relies on the prerequisite knowledge. First, we limit the sample to only 100- and 200-level courses. These results, in column 3, are similar to the full sample results in Table 2. We also consider only those sequences numbered as 101 and 102. The smaller sample size leads to less precise estimates although the pattern of the point estimates is similar.

In our sample, some students do not follow the prescribed course sequence. If many students take a sequence out of order, the implication is that taking them in sequence may not be that important. We limit the sample to course sequences which most students take in the catalog-listed order; these courses are more likely to have direct ties to each other. In column (5), we require more than 90 percent of students to take the pair of courses in the prescribed order. In columns (6) and (7), we require more than 95 percent of students to take the pair of courses in the prescribed order. The results here follow the same pattern: grades are lower for students enrolled in larger prerequisite classes and this effect is smaller for the summer gap than for the winter gap. Column (7) also restricts the sample to course-pairs where only one follow-up course lists a particular course as a prerequisite. If one course serves as the prerequisite to many courses, the links between the course pairs may be weak. The pattern of results is qualitatively similar. Students in larger courses have lower grades and this effect is dampened by waiting longer between courses.

The estimates in Table 4 split the sample by the students' math SAT scores and by gender.[16] The class size and months gap results are somewhat larger for students who have lower SAT scores and the students who are female. In results not presented here, we also stratify the

[16] We denote a student as above or below median based on the median SAT score in the semester the student first appears in the sample.

sample by the nine reported race categories. The sample sizes are significantly smaller. Almost all estimates on the coefficients of interest are statistically insignificant.

We stratify the sample by grade earned in the prerequisite class.[17] These estimates appear in Table 5. The source of identification is more limited as, with the student fixed effects, estimates require the student to earn the same grade in a prerequisite for more than one course sequence. Results for A and C students follow the general pattern of results for the full sample although the effects are smaller and statistically insignificant.

4. Conclusion

Using pairs of courses at a university, we estimate the effects of class size and the time, measured in months, between the courses on grades in the follow-up course. We expand the literature by allowing for a variety of ways class size can impact academic outcomes. First, we allow prerequisite class size to affects grades in a later course. Second, we allow the class size effect to differ for students waiting longer between courses. Our results suggest that students earn lower grades in follow-up courses when enrolled in large prerequisite classes. This decline is somewhat offset when students wait longer to enroll in the follow-up course. Previous research demonstrates the effects of class size on contemporaneous outcomes; we show on-going effects of class size on future course grades.

Given these results, one possible policy response would be to reduce class size. We provide a back-of-the-envelope calculation of the costs and benefits of reducing class size from 300 students to 100 students by hiring an adjunct to teach the two additional sections. Data from the Chronicle of Higher Education suggests that two sections taught by adjuncts cost a total of

[17] We also estimate the Table 2 specifications include the grade earned in the prerequisite. The results are similar to those presented in Table 2.

$6,000.[18] Our estimates imply an effect on course grades of 0.026 grade points, raising average GPA by (0.026/40=) 0.00065 grade points. Higher GPAs experience a return in the labor market. Wise [1975] estimates a 1 percent return for an additional letter grade; Jackson and Jones [1990] estimate a 10 percent return. This implies a benefit in their first working year from reducing class size of $0.28 to $2.80 per student and $83.85 to $838.5 for the 300 affected students.[19] With no discount rate and a working life of 40 years, the benefit is $3,354 to $33,540. One estimate in the literature is that military personnel have a discount rate of 25 percent [Pleeter and Warner 2001]. This discount rate implies a benefit of $420-$4,200, insufficient to offset the cost of additional instructors.

Another possible policy response is to schedule larger sections of prerequisites in the spring than in the fall, providing for longer wait times between the courses. Alternatively, institutions could advise students performing poorly in large prerequisite sections to delay taking the follow-up course. To the extent that students are able to do so without lengthening the number of semesters they enroll in college, this option can increase the students' average GPA and is relatively costless.

Larger classes affect academic outcomes in follow-up courses. The effect of waiting longer between courses depends on class size. Students from larger prerequisite classes benefit from waiting longer to take a follow-up course. One possible mechanism is that waiting longer between courses has offsetting effects: any depreciation in knowledge is mitigated by the increase in maturity gained in that period. This is particularly true for students with below average test scores. Gleason [2012], however, suggests that the negative effect of class size can

[18] https://data.chronicle.com/217882/Clemson-University/adjunct-salaries/
[19] Average salary for a Clemson graduate is $43,000 (https://www.collegefactual.com/colleges/clemson-university/outcomes/return-on-investment/).

be mitigated by providing students with various study tools such as WebAssign, self-checking online quizzes, and recorded video lectures. How these innovations impact learning in large classes and knowledge retention over time is left for future research.

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Table 1: Sample Summary Statistics
(N=129,206)

Variable	Mean	Std. Dev.	Min	Max
Grade in follow-up	2.7	1	0	4
Grade in prerequisite	2.8	0.9	0	4
Gap	5.4	0.8	5	7
Class Size in Prerequisite	70.03	61.6	5	253
Class Size in follow-up	62.6	55.5	5	236
Took prerequisite twice	0.0	0.1	0	1
SAT Math	56.6	8.5	24	80
Entering Age	19.7	2.0	15	47.6
Instate	0.7	0.5	0	1
Male	0.5	0.5	0	1
Family	0.3	0.5	0	1

Table 2: Months between sequential courses, class size, and student grades

	(1)	(2)	(3)	(4)	(5)
	Fall-Spring or Spring-Fall only			gap up to 18 months	
Months between courses	-0.0538***	0.0059	0.0013	0.0043**	0.0076***
	(0.006)	(0.008)	(0.009)	(0.002)	(0.002)
Prerequisite Class Size	-0.0041***	-0.0022***	-0.0042***	-0.0008***	-0.0001
	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)
Months between*Prereq Class Size	0.0006***	0.0002**	0.0006***	0.0001***	-0.0000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Follow-up Class Size	0.0003**	0.0005***	0.0008***	0.0002*	0.0016***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Took Prerequisite Twice	-0.7585***	-0.1865***	-0.1133***	-0.0818***	-0.1108***
	(0.024)	(0.036)	(0.035)	(0.022)	(0.017)
Cumulative credits to date	0.0035***	-0.0003	-0.0004**	-0.0005***	-0.0005***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
student demographics?	YES	NO	NO	NO	NO
student fixed effects?	NO	YES	YES	YES	YES
course-pair fixed effects?	NO	NO	YES	YES	YES
course-pair-semester fixed effects?	NO	NO	NO	NO	YES
Observations	117,610	117,610	117,610	149,765	139,951
R-squared	0.190	0.683	0.698	0.651	0.663

Characteristics included in column (1) are the student's SAT math score, age at entry to Clemson, indicators for student's race, whether the student in an in-state student, male, or a legacy. All specifications include department fixed effects, course-level fixed effects, and semester of follow-up course fixed effects. Robust standard errors clustered by student in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 3: Splitting the sample by course characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	languages	STEM	100 or 200 level	101-102 sequences	Less than 10% take out of order	Less than 5% take out of order	<5% take out of order; no duplicate prereqs
Months between courses	0.118*	-0.016	-0.0056	0.0330	0.0014	0.0029	-0.0075
	(0.063)	(0.019)	(0.0101)	(0.0390)	(0.0091)	(0.0092)	(0.0107)
Prerequisite Class Size	0.013	-0.005***	-0.0044***	-0.0041*	-0.0042***	-0.0041***	-0.0056***
	(0.017)	(0.001)	(0.0006)	(0.0022)	(0.0006)	(0.0006)	(0.0008)
Months between*Prereq Class Size	-0.003	0.001***	0.0006***	0.0003	0.0006***	0.001***	0.001***
	(0.003)	(0.0002)	(0.0001)	(0.0004)	(0.0001)	(0.0001)	(0.0001)
Follow-up Class Size	0.012***	0.0006**	0.0008***	0.0001	0.0008***	0.001***	0.001***
	(0.004)	(0.0003)	(0.0002)	(0.0005)	(0.0002)	(0.0002)	(0.0002)
Took Prerequisite Twice	-0.003***	-0.001**	-0.0006**	-0.0007	-0.0004**	-0.0005**	-0.0002
	(0.001)	(0.0004)	(0.0002)	(0.0008)	(0.0002)	(0.0002)	(0.0002)
Cumulative credits to date	0.441*	0.056	-0.1087***	-0.2072	-0.1134***	-0.116***	-0.197***
	(0.251)	(0.056)	(0.0394)	(0.1277)	(0.0354)	(0.0359)	(0.0438)
Observations	13,823	59,509	108,361	55,660	117,562	115,473	94,483
R-squared	0.849	0.825	0.714	0.838	0.698	0.700	0.731

All specifications include student fixed effects, course-pair fixed effects, and semester of follow-up course fixed effects. Robust standard errors clustered by student in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 4: Stratifying the sample by student characteristics

	(1) above median SAT	(2) below median SAT	(3) males	(4) females
Months between courses	0.0043	-0.0045	0.0104	-0.0163
	(0.0120)	(0.0143)	(0.0124)	(0.0133)
Prerequisite Class Size	-0.0033***	-0.0061***	-0.0035***	-0.0048***
	(0.0008)	(0.0010)	(0.0008)	(0.0009)
Months between*Prereq Class Size	0.0005***	0.0009***	0.0005***	0.0007***
	(0.0001)	(0.0002)	(0.0001)	(0.0002)
Follow-up Class Size	0.0008***	0.0010***	0.0009***	0.0008***
	(0.0002)	(0.0003)	(0.0002)	(0.0002)
Cumulative credits to date	-0.0004	-0.0006*	-0.0004	-0.0000
	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Took Prerequisite Twice	-0.1227**	-0.0621	-0.1109***	-0.0993
	(0.0492)	(0.0512)	(0.0429)	(0.0618)
Observations	63,036	54,574	64,337	53,273
R-squared	0.695	0.699	0.689	0.705

All specifications include department fixed effects, course-pair fixed effects, and semester of follow-up course fixed effects. Robust standard errors clustered by student in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 5: Stratifying the sample by grade in prerequisite

	(1) A in prereq	(2) B in prereq	(3) C in prereq	(4) D in prereq
Months between courses	-0.0133	0.00518	0.0197	0.0747
	(0.0211)	(0.0251)	(0.0358)	(0.212)
Prerequisite Class Size	-0.00195	-0.00197	-0.00442*	-0.00296
	(0.00120)	(0.00164)	(0.00240)	(0.0121)
Months between*Prereq Class Size	0.000333	0.000333	0.000593	0.000286
	(0.000203)	(0.000278)	(0.000403)	(0.00222)
Follow-up Class Size	3.93e-05	0.000168	0.00130**	0.00249
	(0.000375)	(0.000452)	(0.000623)	(0.00343)
Cumulative credits to date	-0.000510	-0.000863	-0.00185**	-0.00256
	(0.000539)	(0.000613)	(0.000887)	(0.00473)
Took Prerequisite Twice	-0.369	-0.136	-0.0255	0.353
	(0.245)	(0.110)	(0.0948)	(0.424)
Observations	28,725	45,699	33,970	8,964
R-squared	0.802	0.776	0.814	0.931

All specifications include department fixed effects, course-pair fixed effects, and semester of follow-up course fixed effects. Robust standard errors clustered by student in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Appendix Table 1: Table 2 using fall-spring indicator and allowing for non-linearities

	(1)	(2)	(3)	(4)	(5)
	Fall-Spring or Spring-Fall only			non-linear	
Fall-Spring?	0.108***	-0.0118	-0.0026		
	(0.011)	(0.016)	(0.018)		
Prerequisite Class Size	0.0002	-0.001***	0.0002	-0.004**	
	(0.000)	(0.000)	(0.000)	(0.0018)	
Fall-spring*Prereq Class Size	-0.001***	-0.0004**	-0.001***		
	(0.000)	(0.000)	(0.000)		
Follow-up Class Size	0.0003**	0.0005***	0.001***	0.001***	
	(0.000)	(0.000)	(0.000)	(0.0002)	
Took Prerequisite Twice	-0.759***	-0.187***	-0.113***	-0.115***	-0.117***
	(0.024)	(0.036)	(0.035)	(0.034)	(0.034)
Cumulative credits to date	0.004***	-0.0003	-0.0004**		
	(0.000)	(0.000)	(0.000)		
Months between courses				0.008	-0.09***
				(0.011)	(0.024)
Months between*Prereq Class Size				0.0001	
				(0.0003)	
Prerequisite Class Size^2				-0.000002	
				(0.00001)	
Months between*Prereq Class Size^2				0.000002	
				(0.000001)	
ln(prerequisite class size)					-0.243***
					(0.039)
months between*ln(prereq class size)					0.032***
					(0.006)
ln(follow-up class size)					0.0303**
					(0.012)
student demographics?	YES	NO	NO	NO	NO
student fixed effects?	NO	YES	YES	YES	YES
course-pair fixed effects?	NO	NO	YES	YES	YES
Observations	117,610	117,610	117,610	129,206	129,206
R-squared	0.190	0.683	0.698	0.693	0.693

Characteristics included in column (1) are the student's SAT math score, age at entry to Clemson, indicators for student's race, whether the student in an in-state student, male, or a legacy. All specifications include department fixed effects, course-level fixed effects, and semester of follow-up course fixed effects. Robust standard errors clustered by student in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Appendix Table A2: List of course-pairs included in sample

Subsequent Course	Prerequisite Course
Accounting 301	Accounting 204
Accounting 303	Accounting 204
Accounting 301	Accounting 201
Accounting 303	Accounting 201
Accounting 307	Accounting 202
Applied Economics 302	Applied Economics 202
Applied Economics 303	Economics 211
American Sign Language 102	American Sign Language 101
American Sign Language 201	American Sign Language 102
American Sign Language 202	American Sign Language 201
Anthropology 301	Anthropology 201
Anthropology 320	Anthropology 201
Architecture 152	Architecture 151
Architecture 251	Architecture 152
Architecture 252	Architecture 251
Architecture, Arts, and Humanities 102	Architecture, Arts, and Humanities 101
Architecture, Arts, and Humanities 203	Architecture, Arts, and Humanities 102
Architecture, Arts, and Humanities 204	Architecture, Arts, and Humanities 203
Architecture, Arts, and Humanities 205	Architecture, Arts, and Humanities 102
Architecture, Arts, and Humanities 206	Architecture, Arts, and Humanities 205
Astronomy 302	Physics 221
Astronomy 303	Physics 221
Biochemistry 210	Chemistry 102
Biochemistry 211	Biochemistry 210
Biological Science 100	Biology 103
Biological Science 101	Biology 110
Biological Science 102	Biology 103
Biological Science 102	Biology 110
Biological Science 205	Biology 103
Biological Science 223	Biological Science 222
Biology 102	Biology 101
Biology 104	Biology 103
Biology 111	Biology 110
Ceramics and Material Engineering 222	Ceramics and Material Engineering 221
Chemical Engineering 220	Chemical Engineering 211
Chemical Engineering 311	Chemical Engineering 211
Chemical Engineering 312	Chemical Engineering 220
Chemical Engineering 312	Chemical Engineering 311
Chemical Engineering 319	Chemical Engineering 211

Chemical Engineering 319	Chemical Engineering 223
Chemical Engineering 319	Chemical Engineering 220
Chemical Engineering 321	Chemical Engineering 220
Chemistry 102	Chemistry 101
Chemistry 106	Chemistry 105
Chemistry 201	Chemistry 102
Chemistry 205	Chemistry 102
Chemistry 223	Chemistry 102
Chemistry 224	Chemistry 223
Chinese 102	Chinese 101
Chinese 201	Chinese 102
Chinese 202	Chinese 201
Chinese 204	Chinese 203
Computer Science 102	Computer Science 101
Computer Science 220	Computer Science 120
Computer Science 270	Computer Science 120
Construction Science Management 202	Construction Science Management 201
Construction Science Management 205	Construction Science Management 203
Construction Science Management 301	Construction Science Management 202
Design 152	Design 151
Design 251	Design 152
Design 252	Design 251
Design 351	Design 252
Design 352	Design 351
Economics 314	Economics 200
Economics 314	Economics 211
Economics 315	Economics 200
Economics 315	Economics 212
Electrical and Computer Engineering 212	Electrical and Computer Engineering 211
Electrical and Computer Engineering 262	Electrical and Computer Engineering 202
Electrical and Computer Engineering 321	Electrical and Computer Engineering 320
Engineering Mechanics 202	Engineering Mechanics 201
English 102	English 101
Experimental Statistics 311	Experimental Statistics 301
Finance 312	Finance 306
Finance 312	Finance 311
Forestry 102	Forestry 101
Forestry 205	Forestry 102
French 102	French 101
French 201	French 102
French 202	French 201

French 221	French 102
Geology 102	Geology 101
Geology 103	Geology 102
Geology 112	Geology 101
German 102	German 101
German 201	German 102
German 202	German 201
General Communications 207	General Communications 104
History 394	History 173
Industrial Engineering 201	Engineering 120
Italian 102	Italian 101
Italian 201	Italian 102
Italian 202	Italian 201
Japanese 102	Japanese 101
Japanese 201	Japanese 102
Japanese 202	Japanese 201
Landscape Architecture 152	Landscape Architecture 151
Latin 102	Latin 101
Latin 201	Latin 102
Latin 202	Latin 201
Legal Studies 313	Legal Studies 312
Management 315	Management 314
Marketing 302	Marketing 301
Mathematical Sciences 103	Mathematical Sciences 104
Mathematical Sciences 106	Mathematical Sciences 103
Mathematical Sciences 106	Mathematical Sciences 105
Mathematical Sciences 108	Mathematical Sciences 106
Mathematical Sciences 115	Mathematical Sciences 104
Mathematical Sciences 116	Mathematical Sciences 115
Mathematical Sciences 117	Mathematical Sciences 104
Mathematical Sciences 118	Mathematical Sciences 117
Mathematical Sciences 129	Mathematical Sciences 106
Mathematical Sciences 206	Mathematical Sciences 108
Mathematical Sciences 208	Mathematical Sciences 206
Mechanical Engineering 305	Engineering 120
Mechanical Engineering 303	Mechanical Engineering 203
Packaging Sciences 102	Packaging Sciences 101
Packaging Sciences 202	Packaging Sciences 102
Parks, Recreation, and Tourism Management 205	Parks, Recreation, and Tourism Management 101
Parks, Recreation, and Tourism Management 315	Parks, Recreation, and Tourism Management 314
Physics 208	Physics 207

Physics 221	Physics 122
Physics 222	Physics 221
Physics 311	Physics 222
Physics 321	Physics 221
Polymer and Textile Chemistry 304	Polymer and Textile Chemistry 303
Portuguese 102	Portuguese 101
Portuguese 201	Portuguese 102
Portuguese 202	Portuguese 201
Russian 102	Russian 101
Russian 201	Russian 102
Russian 202	Russian 201
Sociology 303	Sociology 201
Spanish 102	Spanish 101
Spanish 201	Spanish 102
Spanish 202	Spanish 201
Spanish 202	Spanish 201
Spanish 221	Spanish 102
Spanish 221	Spanish 121
Technology and Human Resource Development 160	Technology and Human Resource Development 110
Technology and Human Resource Development 220	Technology and Human Resource Development 110
Textile Engineering 201	Textile Engineering 175
Textile Engineering 201	Textile Engineering 176
Textile Engineering 202	Textile Engineering 201

Appendix Table A3: Months between sequential courses, class size, and student grades: Ordered Logit

	(1)	(2)
	compare to OLS estimates in Table 2	
	column (2)	column (3)
	Fall-Spring or Spring-Fall only	
Months between courses	-0.0956***	-0.1348***
	(0.013)	(0.015)
Prerequisite Class Size	-0.0078***	-0.0113***
	(0.001)	(0.001)
Months between*Prerequisite Class Size	0.0011***	0.0017***
	(0.000)	(0.000)
Follow-up Class Size	0.0008***	0.0021***
	(0.000)	(0.000)
Took Prerequisite Twice	-1.2869***	-1.1693***
	(0.054)	(0.055)
Cumulative credits to date	0.0064***	0.0068***
	(0.000)	(0.000)
course-pair fixed effects?	NO	YES
Observations	117,610	117,610

All specifications include student random effects, department fixed effects, course-level fixed effects, and semester of follow-up course fixed effects. Robust standard errors clustered by student in parentheses. *** p<0.01, ** p<0.05, * p<0.1