CAPR | CENTER FOR THE ANALYSIS OF POSTSECONDARY READINESS

# Computer-Based Math Remediation: Evidence from Technology-Centered Instruction in Two-Year and Four-Year Colleges

## A CAPR Working Paper

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## Abstract

Under a hybrid emporium instructional model, students primarily learn content and skills at their own pace through a computer-based platform; during class time, faculty serve more as tutors facilitating individual learning rather than as traditional lecturers. This study evaluates the adoption of this technology-centered instructional model in developmental math courses at public two- and four-year colleges in Tennessee. Using nine years of student enrollment and transcript data (2006–07 to 2015–16) provided by the Tennessee Board of Regents, this paper examines the effects of technology-centered instruction in developmental math courses on students' course pass rates, persistence rates, and completion rates, compared to students' outcomes in traditional lecture-based developmental math courses. While much of the prior research on the effects of technology-centered instruction has applied to students from a wide range of academic backgrounds, the primary objective of this paper is to discern whether technology-centered instruction is helpful (or harmful) for students who are academically underprepared for college.

Using a difference-in-differences analytic model to exploit variations in institutions' timelines in adopting the hybrid emporium model, I find that, for community college students, being assigned to a technology-centered developmental math course led to lower pass rates in their first college-level math course, fewer cumulative credits earned over time, and a lower likelihood of earning an associate degree within six years, as compared to students assigned to traditional developmental math courses. At four-year colleges, the adoption of this new instructional model resulted in a higher percentage of students passing their developmental math courses and thus spending fewer terms in developmental math. However, the pass rates of these students in their first college-level math courses were lower than those of students who were assigned to traditional developmental math courses. The magnitude of the effects varied by gender, age, and ACT math score.

# Contents

# 1. Introduction

Academic readiness remains one of the primary challenges to college student success. Colleges often place students who are not academically ready for college into developmental education courses to improve their math, reading, or writing skills and prepare them for college coursework. However, only half of all students who enroll in a developmental course successfully complete the course (Chen, 2016). Students who fail developmental math are less likely to ever earn a degree or credential compared to those who pass (Le, Rogers, & Santos, 2011). Over the past several years, an increasing number of states and institutions have received financial support from government and private sources to develop and assess alternative approaches to developmental education; others have begun to do so on their own. A 2018 national survey of state-level developmental education policies found that 20 states authorize the use of "innovative developmental education instructional methods and interventions" (Whinnery & Pompelia 2018). Newly redesigned developmental programs attempt to better target students' academic needs, often through the use of learning technology such as self-directed learning labs, computer-based instructional models, and high-tech classrooms (Epper & Baker, 2009; Means, Toyama, Murphy, & Baki, 2013). The use of technology in postsecondary teaching has grown rapidly over time, particularly in developmental math courses (Allen & Seaman, 2007, 2010; Means, Bakia, & Murphy, 2014).

Tennessee, the site for this study, is a national leader in the implementation of technology-driven instruction in developmental math. In the year 2000, more than 70 percent of students enrolled at one of the state's 13 community colleges were being placed into developmental math courses, along with more than 50 percent of students at one of the state's six four-year public universities (Gray-Barnett, 2001). The drop/failure/withdrawal rate in developmental math courses averaged 45 percent, compared to 26 percent in college-level math courses. In 2005, in response to the high number of students in need of developmental math and the high course failure rates, the Tennessee Board of Regents (TBR), the governing body overseeing these 19 colleges,[1] provided small grants to four institutions "to support technology-supported active learning strategies aimed at improving student learning outcomes, accelerating time to credit-bearing courses, and

[1] For the years of this study, TBR was the governing body of the state's 13 community colleges, six state universities, and 27 Tennessee colleges of applied technology (TCAT). Across these 46 public colleges, TBR served more than 200,000 students. In 2017, the six universities separated and are now governed by local boards. TBR, now known as The College System of Tennessee, currently enrolls nearly 120,000 students across the 13 community colleges and 27 TCATs.

reducing instructional costs" as part of the state's Developmental Studies Redesign Initiative (Crandall & Soares, 2015, p. 11).

Each of the pilot colleges introduced a variation on a new instructional model at the time, known as the emporium model. The model was developed at Virginia Tech in 1997, and the term "emporium model" was later broadly adopted by the National Center for Academic Transformation (NCAT) to describe a course in which traditional lectures are replaced with instructional software (National Center for Academic Transformation, 2013). The term "hybrid" emporium model is often used to emphasize that instructors still play a key role in a course even when they do not function as traditional lecturers. Under the hybrid emporium model, students typically spend all their class time in a computer lab learning the course content online at their own pace and are allowed to continue their work at home or outside of class by logging into the course interface with their unique ID and password. During class, faculty float around the computer lab, serving more as tutors who deliver individualized instruction as opposed to traditional lecturers who address the entire class. Instead of grading homework assignments and assessments, faculty rely on the software to automatically grade student work and track student progress. This gives the faculty more time to answer students' questions individually, both in the lab and through messages sent through the course site. This technology-based instruction is made possible through an online interface created by third-party providers such as Pearson or ALEKS (McGraw-Hill). Within the interface, the course content is divided into small blocks, or modules, which are taught using tutorials, short (3–5 minute) video lectures, sample problems, practice exercises, and quizzes and tests. When students fail a quiz or exam, they are allowed to complete the module again, with new sample problems. While the amount of class time spent in the computer lab can vary across institutions, the pedagogy under the hybrid emporium model is consistent: Whole-class instruction, including lectures, are eliminated and replaced with personalized instruction, mostly using interactive software.

Following the adoption of these technology-based pilot courses in four Tennessee institutions from 2005 to 2008, observational research and descriptive summaries from developmental math redesigns at NCAT partner institutions suggested that the new model was highly successful (National Center for Academic Transformation, 2009; Twigg, 2011). Comparing the pass rates of students before and after implementing the model showed that the percentage of students successfully completing a developmental math course increased 51 percent on average across the NCAT institutions, and the percentage of students successfully completing a college-level math course increased 25 percent on average (ranging from 7 to 63 percent) (Twigg, 2011). In 2012, TBR voted in favor of increasing the adoption of "substantially technology-driven instruction" to all public institutions. Colleges had until the fall of 2013 to adopt technology-driven instruction into their developmental math, reading, and writing courses.

Such use of learning technology could potentially have both positive and negative effects on college students. Technology can be used to expand and strengthen the delivery of developmental math instruction (Epper & Baker, 2009). One benefit is the consistency it provides across sections and institutions in the delivery of math content, the means of practice and application, and the assessment of math knowledge. This consistency across students could potentially result in more even levels of academic preparation for future college-level courses. Another benefit concerns the use of faculty time. Because the hybrid emporium model is computer-based, faculty are freed up to give more individualized instruction to students, as little time is spent directing the class as a whole (Herried & Schiller, 2013). Students are also able to receive more on-demand assistance by individually asking questions of the faculty during class or messaging faculty through the online interface (Trenholm, 2006). There are also clear expectations for progress, including deadlines for completing exams designed to measure mastery of a given topic. Opportunities for practice are also a fundamental component of the model; these can help faculty to identify problematic areas for students and to address these concerns with them one-on-one. Students are able to work at their own pace, allowing some to move more quickly into their college-level courses. Finally, students may feel more connected or engaged with faculty, perceiving them as more approachable due to the more informal computer lab setting (Boatman & Kramer, 2019).

Alternatively, not all students are comfortable using learning technology as an instructional tool, particularly in a self-driven manner. The model assumes that students have the ability to regulate their timing throughout the semester in order to achieve course milestones. It also assumes students will not be bored and become distracted by other websites or freedoms that come with self-driven, computer-based work. For those who have struggled to learn math content in the past, this independent model of learning may prove challenging. Students may also choose to “game” the quizzes and problem sets, repeatedly answering questions until they eventually land on the correct response, thus raising concerns about the actual level of mastery and engagement with the course content. Some students may also find it more difficult to establish rapport and common ground with instructors in the absence of direct instruction.

In this study, I explore the relationship between technology-based developmental math instruction and student outcomes. I examine the academic success outcomes for college students who were assigned to developmental math under the hybrid emporium model compared to students who were assigned to developmental math under the traditional, lecture-based model. Using site-specific variation in the implementation of the hybrid emporium model across Tennessee colleges, I ask**:**

1. Do technology-based developmental math courses result in higher course pass rates and persistence rates for students than the traditional version of these courses?

2. Do these results differ between two-year (community) colleges and four-year colleges and by prior level of academic preparation, age, and gender?

The results from this study are important to better understand what works in developmental education and for whom, particularly as states and systems look to incorporate technology in the student experience in new ways. As colleges turn to technology to help reduce instructional costs, the question remains whether technology improves student outcomes, particularly for students in developmental education. Technology-centered instruction remains a largely unexamined topic in the higher education literature, with much of the research base on computer-based instruction focused on middle and high schools. Given the desire for improved developmental education results nationwide, other states and institutions will benefit from research on technology-based developmental instruction in a state where the adoption of the hybrid emporium model has been widespread.

# 2. Prior Literature

Classroom interventions involving instructional technology can be conceptualized along a continuum based on the degree of reliance on technology. On one end are lighter technological interventions, in which instructional software is used as a supplemental tool in otherwise traditional courses, as opposed to using software as a primary instructional tool. On the other end are asynchronous online courses in which a software platform completely replaces all instruction. Students in these online courses have the freedom to complete the work when and where they wish. In between these two extremes are hybrid emporium courses—computer-based courses in which the instructional software delivers individualized instruction to students in a classroom, with an instructor in the room. Students are allowed to continue the work outside of class but are required to meet regularly together in a computer lab setting.

While the use of technology in traditional college classrooms is not new, the research base on the effectiveness of its use as an instructional method remains limited. High school is one sector where the use of technology in classrooms has been both implemented and thoroughly studied. Reviewing research from both the secondary and postsecondary literature reveals mixed effects of the use of technology in the classroom on student outcomes, depending on the degree of reliance on technology. Below I summarize the findings from research in both the secondary and postsecondary sectors, organized by the degree to which technology is used for instruction.

## Research on Technology as a Supplemental Tool to Traditional Instruction

Research examining the effectiveness of instructional software as a supplemental tool to traditional instruction finds generally positive impacts on middle and high school student outcomes. A review of these interventions in middle and high schools summarizes generally positive findings in terms of students passing the assigned math course (Tamin, Bernard, Borokhovski, Abrami, & Schmid, 2011; Waxman, Lin, & Michko, 2003). In a randomized controlled trial involving eight middle school teachers, students in math courses taught with Cognitive Tutor supplemental software scored higher on a common end-of-course algebra test and also received higher course grades than students in courses taught without the supplemental software (Morgan & Ritter, 2002).

Mobile learning is one example of how technology can be used to supplement in-class learning that is gaining popularity in the college context. (Chen & deNoyelles, 2013). In a randomized study of adult learners in Los Angeles, those who used a Spanish literacy mobile app to supplement their course content reported reading scores that were significantly higher than those of the comparison group (Aker, Ksoll, Miller, Perez, & Smalley, 2015). A similar study was conducted using mobile apps for developmental math students at a community college in Louisiana. Students who received access to the apps reported higher course grades in their developmental math courses compared to students in the control group, who did not get access to the apps. Treatment students received grades that were, on average, 0.15 grade points higher in pre-algebra and 0.23 points higher in algebra (Giani & Martin, 2019). Results from these studies suggest that technology, when used as a supplemental tool to traditional instruction, can have positive impacts on students' academic success.

## Research on Technology-Centered Instruction in Hybrid Courses

In hybrid emporium courses, technology functions as more than a supplemental tool, replacing traditional lectures with individualized software alongside an in-class teacher. Across the secondary and postsecondary sectors, several studies have investigated the effects of "hybrid" or "blended learning," usually defined in much the same way as the "hybrid emporium" model, but which may include time (typically less than 50 percent) spent in a traditional classroom. Only one study, conducted across three large urban school districts, found positive results for hybrid learning, with students randomly assigned to computer-based instruction scoring significantly higher on pre-algebra and algebra tests than students randomly assigned to traditional instruction, with larger test score gains for students far behind their peers academically (Barrow, Markman, & Rouse, 2009). The authors found no differences in the effect of hybrid learning by sex or race/ethnicity.

The majority of studies on hybrid or blended learning have found null to negative effects on student academic outcomes. In a 2003 study, the U.S. Department of Education contracted with Mathematica Policy Research, Inc., and SRI International to conduct an experimental study of the effects of technology-based instruction in high school algebra. The study found that test scores in treatment classrooms (with the math technology) did not differ from test scores in control classrooms by statistically significant margins. These effects were uncorrelated with classroom and school characteristics (Dynarski et al., 2007). Two large-scale field experiments using computer-based instruction also found null effects on student test scores in math courses at secondary school levels (Cavalluzzo, Lowther, Mokher, & Fan, 2012; Pane, Griffin, McCaffrey, & Karam, 2013), with no evidence of positive or negative impacts for student subgroups defined by gender, enrollment cohort, or rurality of the school setting (Cavalluzzo et al., 2012). A randomized controlled field trial of high school geometry courses taught using technology-based instruction versus traditional instruction found strong negative effects on test scores for students in the hybrid courses (Pane, McCaffrey, Slaughter, Steele, & Ikemoto, 2010). The study also found no statistically significant impact on students' attitudes toward mathematics or technology. In the community college context, Ryan, Kaufman, Greenhouse, She, and Shi (2016) concluded that students enrolled in hybrid courses perform similarly to students in a traditional instructional setting.

In a descriptive study comparing the learning outcomes for introductory psychology students in hybrid and traditional sections at a four-year university, Powers, Brooks, Galazyn, and Donnelly (2016) found that exam and homework grades were lower in hybrid sections over the semester than in traditional sections. Similarly, in a study of hybrid sections of intermediate algebra at a private four-year college, Spradlin and Ackerman (2010) found no statistically significant differences in the posttest scores of students receiving traditional instruction and those receiving computer-assisted instruction.

Two studies used a quasi-experimental analytic design to control for issues of student selection into courses and concluded that, compared to traditional courses, hybrid courses had a negative effect on the retention of information among first-year students in statistics courses at a four-year university (Kwak, Menezes, & Sherwood, 2015) and among university students enrolled in an introductory economics course (Cosgrove & Olitsky, 2015). In their study of students randomly assigned to either a hybrid learning or traditional research methods and statistics course, Goode et al. (2018) found that students who took the hybrid version of the course scored significantly lower on measures of quantitative mastery of statistical concepts than those who took the traditional version; however, the effect size was small. Many of the existing studies have reported small sample sizes and/or no equivalent comparison groups or were sponsored by an organization with an interest in the outcome (Dynarksi et al., 2007).

While these studies add to the literature on the effects of hybrid courses, they do not specifically examine the efficacy of an instructional model that relies nearly 100 percent on computer-based instruction, nor do they examine the context of students in need of developmental education. Of the studies that do focus on this population, some were authored with the relevant software provider, making the results subject to bias concerns (Perez & Foshay, 2002). Twigg (2013) descriptively reported on the outcomes of implementation at 32 institutions that redesigned 86 developmental math courses using common final exam scores, common exam items, and gains on pre- and posttests in the traditional and hybrid emporium formats of the courses to compare how much students learned in the two formats. She concluded that 71 of the redesigned hybrid emporium courses (83 percent) showed significant improvements over the traditional format. Vallade (2013) explored students' success in intermediate and college algebra after receiving developmental math instruction under the hybrid emporium model at two Tennessee community colleges and found that these students had higher passing rates and mean grades and lower failure and withdrawal rates than students who took traditional developmental math courses. And in their descriptive study comparing outcomes from online, blended, and traditional developmental math courses, Ashby, Sadera, and McNary (2011) concluded that there were significant differences between learning environments, with the students in the blended courses having the least success. None of these prior studies, however, controlled for issues of selection bias regarding the developmental math students who enroll in technology-based courses.

Two recent studies have attempted to address the issue of selection bias. An experimental study of a modularized, computer-assisted instructional format offered to developmental math students at one community college found no evidence that the technology-based course led to improvements in students' enrollment, progress, or completion of developmental math compared to the traditional math course (Weiss & Headlam, 2019). The computerized developmental math course helped students make progress toward completing the course in the first semester, but ultimately, they were slightly less likely to complete the full developmental math sequence of courses. A recent quasi-experimental study of the effects of the hybrid emporium model in Kentucky community colleges reported similarly discouraging findings. Exploiting differences in the adoption of technology-based instruction in certain courses over time, Kozakowski (2019) found that using the hybrid emporium model compared to traditional instruction in developmental math courses reduced course pass rates, retention, and degree attainment in the Kentucky community college system. The effects were similar for different levels of developmental courses. With the exception of rigorous studies such as these, there is limited evidence on the impacts of the hybrid emporium model on students' academic outcomes.

## Research on Online, Technology-Only Instruction

The most intensive use of technology as a teaching tool is found in online courses. There is now more rigorous research on the effects of online learning in higher education than ever (for a recent summary, see Xu & Xu, 2019). Studies on the impacts of online learning on math students generally report null or negative findings on performance in developmental and subsequent college-level math courses. In their study of online summer math courses at three universities, Chingos, Griffiths, and Mulhern (2017) found that students in the online courses were no more likely than students in traditional fall math courses to enroll in higher-level courses, earn more math credits, or improve their grades in other math courses during the first year of college. In their study of Virginia's community colleges, Xu and Jaggars (2011) reported a negative impact of enrolling in online introductory college-level math courses on grades in those courses. Additional work concluded that academically high-need students struggle in purely online courses (Xu & Jaggars, 2014).

In the high school setting, many online courses exist through credit recovery courses, where students who need to make up credits are allowed to take a course entirely online outside of the school day. Recent causal research at the high school level compared the academic outcomes for students taking online versus face-to-face credit recovery courses. Researchers found no statistically significant differences in the number of math credits earned in four years of high school and in on-time high school graduation rates between students in the online and face-to-face credit recovery courses (Rickles, Heppen, Allensworth, Sorensen, & Walters, 2018). Another study found that among high school students taking a course for the first time, virtual course-taking was associated with a lower likelihood of taking and passing a subsequent course in the same subject (Hart, Berger, Jacob, Loeb, & Hill, 2019). Similarly, Heinrich, Darling-Aduana, Good, and Cheng (2019) found mostly negative associations between online course-taking and districtwide standardized math scores, with students with the lowest academic performance prior to the course performing the worst. And in a randomized controlled trial of 1,224 ninth graders who failed algebra in Chicago public high schools, students in an online version of the same course reported that the course was more difficult and received lower scores on an algebra posttest compared to those in a face-to-face section of the repeated course (Heppen et al., 2017). This study found no statistically significant differences on the likelihood of passing subsequent math courses.

The prior literature on technology in high school and college math courses broadly suggests that the more technology is used to fully replace instruction, the more negative the impact on student grades in initial and subsequent math courses. For hybrid emporium courses, which rely on technology as the primary but not sole instructional tool, the results from prior research suggest null to negative impacts on student progress in developmental and college-level math courses. In the current study, I examine the effects of hybrid emporium courses in both community and four-year colleges in Tennessee. In addition to examining differences by sector, I also test whether the results differ by students' gender, age, and ACT score.

# 3. Policy Background and Descriptive Information

The percentage of students taking developmental math has declined across Tennessee community colleges over time, from 77 percent of community college students enrolled in a developmental course in 2011 to 65 percent in 2018 (Tennessee Higher Education Commission, 2019). This decline tracks with academic policies implemented in the state during this time. Beginning in the fall of 2012, Tennessee eliminated non-credit developmental education from four-year colleges, requiring that all non-college-credit-bearing courses be offered only at community colleges.[2] Four-year colleges were no longer allowed to offer non-credit-bearing, stand-alone courses, and as a result these institutions were required to reform their developmental courses to be deemed credit-bearing. The six four-year colleges continued to enroll students with academic weaknesses, but began offering corequisite courses in which students enrolled in a three-credit college-level math course alongside a one- to three-credit supplemental developmental math section. Thus, students were still enrolled in developmental math at four-year colleges, only now they were simultaneously enrolled in college-level math. Following this change in 2012, the state legislature required the adoption of corequisite remediation across community colleges in 2015–16. Similar to the four-year colleges, students completing corequisite courses received credit for both their college-level math course and its accompanying developmental math section.

In 2013–14, the state also implemented a developmental math high school transition course known as SAILS (Seamless Alignment in Learning Support), designed to reduce the number of students entering college underprepared for college-level math. The SAILS program scaled up over the following three years and is responsible for some of the decline in the number of recent high school graduates enrolling in developmental math in college (Kane et al., 2019). While not related to developmental education directly, in 2015–16, the first cohort of Tennessee Promise students graduated from high school and begin attending community colleges in the state tuition-free. All of these large-scale policy changes occurred primarily from 2012 onward and inform the developmental education context in Tennessee today.

As stated earlier, in 2012 TBR also voted in favor of increasing the adoption of "substantially technology-driven instruction" at all public institutions. Colleges had until

[2] Also in 2012, Tennessee colleges redesigned their developmental education competencies, providing more structure and specific content knowledge benchmarks for what students need to know before moving into college-level courses.

2013 to adopt a hybrid emporium model into their developmental math courses,[3] although several colleges had already done so. In a survey I sent to faculty and administrators across the 13 community colleges and six four-year colleges in 2016, respondents were asked to report on their timeline of adopting the hybrid emporium model. Table 1 was compiled from information available from TBR, The College Board, the Integrated Postsecondary Education Data System (IPEDS), and responses to the survey from each of the 19 TBR colleges. It is divided into two panels: community colleges and four-year colleges. This table compares the basic student population demographics of the colleges in the state, including the total number of students enrolled, percentage of non-White students, and percentage of students requiring math remediation. While there is diversity across the campuses on these dimensions, the difference-in-differences method of analysis described below is concerned with whether the institutions that adopted the hybrid emporium model in the earliest years (fall 2008 or earlier) are comparable to the institutions that adopted the model later. The institutions in Table 1 are used to construct the most observationally similar control groups of institutions for the "early adopter" and "late adopter" community and four-year colleges. Five community colleges and two four-year colleges reported adopting the hybrid emporium model at scale during or prior to fall 2008; these are early adopter colleges. The remaining institutions all adopted the model in spring 2011 or later; these are late adopter colleges.

The content of the hybrid emporium math courses is similar to the prior traditional developmental math courses. The hybrid emporium courses cover material in five math competency areas: (1) real number sense and operations, (2) operations with algebraic expressions, (3) analyzing graphs, (4) solving equations, and (5) modeling and critical thinking. While the traditional courses covered most of these same areas, they were not as explicitly defined or grouped as they were under the modules used in hybrid emporium courses.

In addition to surveying developmental math faculty and administrators at each of the 19 Tennessee public colleges, I also conducted follow-up phone interviews to gauge the extent to which campuses had fully implemented the model and to understand what instruction looked like in each of the colleges prior to the adoption of the hybrid emporium model. Faculty and administrators revealed that there was variation in the adoption of the model. For some, the adoption involved scaling up the model in different courses and sections over several semesters (thus leaving some courses and sections as

[3] The hybrid emporium model was thus used in developmental math when it was offered as a prerequisite stand-alone course and when it was offered as a corequisite section accompanying a college-level math course. While the full dataset used in this study includes both prerequisite and corequisite developmental courses, the cohorts used in the analysis (2006-07 to 2009-10) ensure that only prerequisite developmental math courses are used in the "control" condition and in the pre-2009 treatment condition.

the status quo for a period of time), while for others it involved the continued incorporation of some whole-class instruction into some sections permanently. Fortunately for the design of this study, the early adopter colleges reported a more consistent adoption of the hybrid emporium model, likely related to the leadership at these institutions and their desire to implement the model at scale. Further, only two late adopter colleges reported using technology in the classroom in other significant ways prior to their adoption of the hybrid emporium model. As a sensitivity check, I later drop these institutions from the analysis to check that they are not impacting the results.

The difference between the percentage of students enrolled in traditional developmental courses at early versus late adopter institutions is shown in Figures 1 and 2. These figures present the percentage of students enrolled in developmental math courses that use traditional instructional methods, averaged across the early and late adopter institutions, from summer 2006 to summer 2010. If all developmental math courses were taught using traditional instruction, both lines would be at 100 percent. Conversely, if all students were enrolled in hybrid emporium courses, both lines would be at zero percent. By definition, up until 2011, there were few sections of developmental math being taught using the hybrid emporium model at the late adopter colleges. However, at the early adopter colleges, an increasing number of developmental math students over this time period enrolled in hybrid emporium courses as the courses were scaled within their institutions.

**Table 1**
**Descriptive Information of Hybrid Emporium Model Scale-Up for the 19 Public Colleges of the Tennessee Board of Regents, Fall 2008**

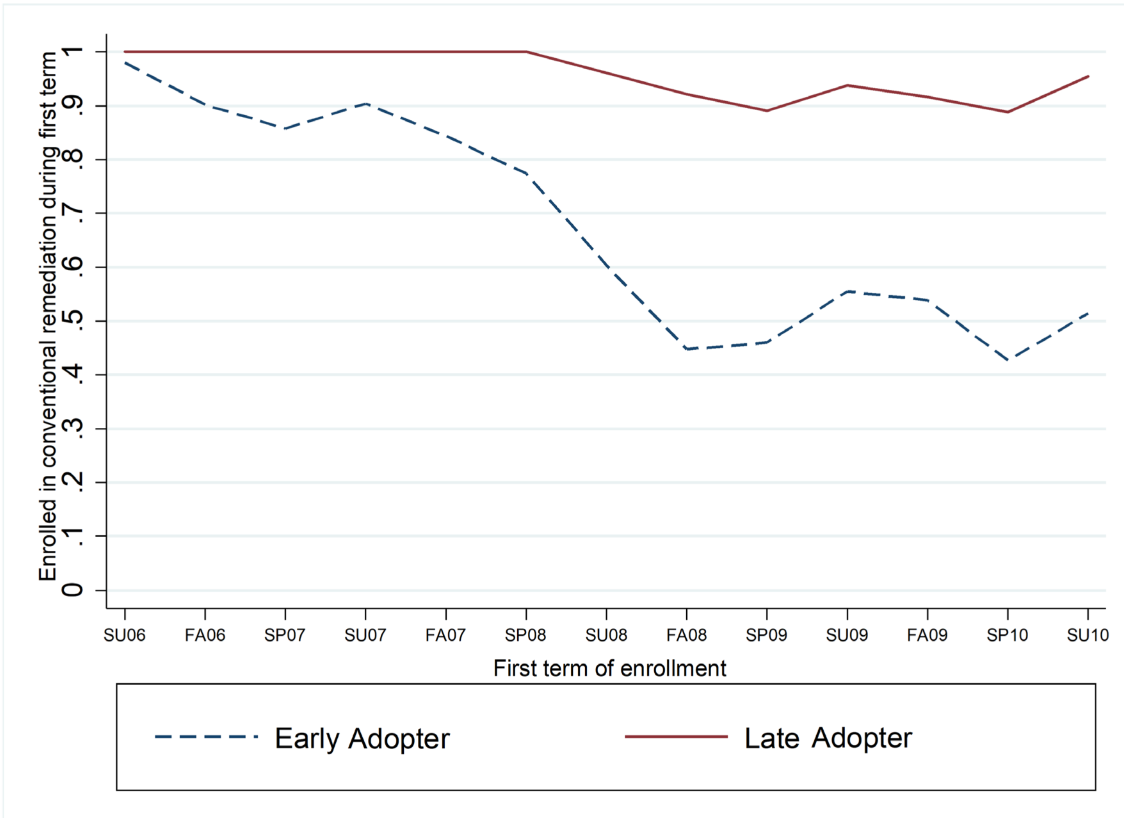
| Institution | Urban, Rural, or Suburban | Undergraduate Enrollment | % White | % Black | % Other Racial / Ethnic Minority | % Full-time | 3-Year Graduation Rate (%) | Approx. % Requiring Math Remediation | Term Adopted Hybrid Emporium Model |
|---|---|---|---|---|---|---|---|---|---|
| Community colleges | | | | | | | | | |
| 1 | suburban | 8,743 | 83 | 8 | 8 | 66 | 12 | 41–50 | *fall 2007* |
| 2 | suburban | 3,335 | 83 | 7 | 5 | 68 | 15 | 61–70 | *spring 2008* |
| 3 | suburban | 4,381 | 75 | 18 | 4 | 63 | 12 | 71–80 | *fall 2008* |
| 4 | urban | 8,485 | 74 | 16 | 5 | 65 | 7 | 51–60 | *fall 2008* |
| 5 | rural | 5,534 | 89 | 3 | 5 | 62 | 18 | 51–60 | *fall 2008* |
| 6 | urban | 7,716 | 58 | 30 | 9 | 58 | 6 | 71–80 | spring 2011 |
| 7 | suburban | 5,470 | 86 | 3 | 3 | 67 | 15 | 41–50 | fall 2011 |
| 8 | rural | 4,770 | 83 | 7 | 7 | 62 | 17 | 51–60 | fall 2011 |
| 9 | suburban | 7,241 | 81 | 9 | 6 | 62 | 13 | 61–70 | fall 2011 |
| 10 | rural | 4,394 | 81 | 9 | 8 | 61 | 15 | 61–70 | fall 2011 |
| 11 | rural | 2,749 | 75 | 21 | 3 | 62 | 8 | 61–70 | fall 2012 |
| 12 | suburban | 5,918 | 93 | 2 | 5 | 67 | 19 | 41–50 | fall 2012 |
| 13 | urban | 11,427 | 29 | 61 | 8 | 62 | 5 | 71–80 | spring 2012 |
| Four-year state universities | | | | | | | | | |
| 1 | urban | 8,573 | 66 | 19 | 10 | 80 | 36 | 31–40 | *fall 2008* |
| 2 | urban | 15,823 | 53 | 36 | 9 | 78 | 40 | 31–40 | *spring 2008* |
| 3 | urban | 6,431 | 23 | 68 | 5 | 78 | 35 | 31–40 | fall 2011 |
| 4 | rural | 8,438 | 86 | 4 | 7 | 83 | 52 | 11–20 | fall 2012[a] |
| 5 | rural | 11,028 | 84 | 6 | 6 | 84 | 41 | 21–30 | fall 2012[a] |
| 6 | urban | 21,252 | 69 | 18 | 9 | 81 | 45 | 31–40 | Did not adopt |

NOTES: Data collected from the Tennessee Board of Regents, The College Board, IPEDS, and surveys sent to institutional administrators. Italics in the Term Adopted column indicate "Early adopter" colleges, which adopted the hybrid emporium model prior to 2009. All colleges used Pearson software except for college number 4 under the four-year colleges, which reported using Hawkes.

[a] This college adopted the hybrid emporium model in its corequisite sections of developmental math, as stand-alone prerequisite courses were eliminated in 2012.

**Figure 1**

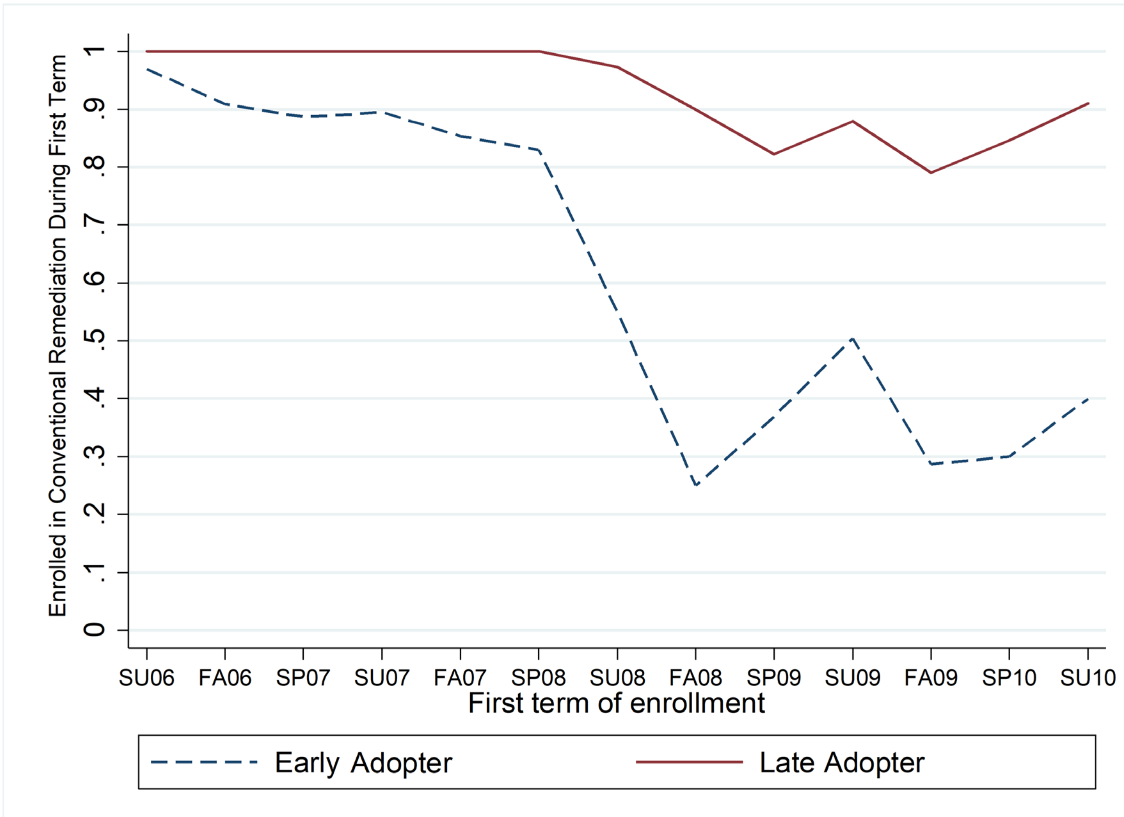
**Share of Developmental Math Students Taught Using Traditional Methods at Community Colleges, by Period of Hybrid Emporium Adoption**




NOTES: Among the 13 community colleges, five institutions adopted the hybrid emporium model prior to 2011 (the "early adopters"), and eight adopted in 2011 or later (the "late adopters"). Descriptive information on the early and late adopter colleges is found in Table 1.

**Figure 2**

**Share of Developmental Math Students Taught Using Traditional Methods at Four-Year Colleges, by Period of Hybrid Emporium Adoption**




NOTES: Among the six four-year public colleges, two institutions adopted the hybrid emporium model prior to 2011 (the "early adopters"), three in 2011 or later (the "late adopters"), and one did not adopt.

# 4. Empirical Strategy

## Data

This study uses survey data collected from the 19 two- and four-year TBR colleges, transcript data from the colleges and the TBR central office, and follow-up phone calls, short interviews, and site visits to confirm the survey responses. Information about the time frame of the hybrid emporium model scale-up and the basic details of the reform were collected from a survey sent to the developmental education faculty and administrators at each of the 19 TBR institutions. Transcript data from all 19 institutions from school years 2006–07 to 2015–16 were provided by TBR. The data include specific information on student course enrollment and performance and were available for the periods both before and after the adoption of the hybrid emporium model. These data are used to evaluate student outcomes resulting from the adoption of this new model.

## Methods

Research on the causal effects of participating in technology-based courses on subsequent educational outcomes has been notably absent. Much of the existing research compares the pass rates of students before and after the course redesigns were implemented, while failing to account for the selection of students into these courses and for any unobserved differences between them and their peers who did not take remedial courses. To address this issue, I adopt a difference-in-differences (DID) analytic strategy that involves exploiting variation in institutions' timelines for adopting the hybrid emporium model to obtain an estimate of the effect of being assigned to a hybrid emporium developmental math course on student outcomes.

A DID strategy has been used in other research estimating the effects of hybrid learning on course outcomes (Cosgrove & Olitsky, 2015; Deschacht & Goeman, 2015; Kwak, Menezes, & Sherwood, 2015). DID analyses do not require that researchers have access to all potential confounding variables. Rather, differences between the treatment and control groups are assumed to be fixed over time; hence, differences observed post-intervention can be attributed to the treatment (Zhou, Taber, Arcona, & Li, 2016).

I first compare the outcomes for all students assigned to a developmental math course at an early adopter institution before and after the adoption of the hybrid emporium model. This difference describes the general trend in student outcomes over the past 10 years. However, because student outcomes may have changed over time for reasons other than the adoption of the hybrid emporium model, I also utilize a second difference by including the outcomes for students from the late adopter two- and four-year institutions in Tennessee that were not using this model at the time. Subtracting these two differences provides the estimated effect of being assigned to a hybrid emporium math course on student outcomes. I use the following reduced form equation:

(1)
$$Y_{tj} = \beta_0 + \beta_1\left(POST_j * EMPORIUM_{tj}\right) + \beta_2\left(POST_j\right) + \beta_3\left(EMPORIUM_{tj}\right) + \beta_4\left(Z_{tj}\right) + \delta_{inst} + \varepsilon_{tj}$$

where $Y_{tj}$ refers to one of the outcomes at time $t$ for institution $j$. These outcomes include student performance on early college outcome variables, including the number of credit hours accumulated after the first and second year, the number of terms to completion of developmental math (a measure of progression through developmental math), persistence to the second and third year of college, passing a college-level math course,[4] and degree or certificate completion. I estimate the impact on completing an associate degree (for students attending two-year colleges); a bachelor's degree (for students attending four-year colleges); and any credential, including a certificate, an associate degree, or a bachelor's degree combined (for students attending both two-year and four-year colleges); all within six years. $POST_j$ is a dichotomous variable equal to one if a student is assigned to a developmental math course for the first time in the years after the adoption of the hybrid emporium model at her institution and zero otherwise. $EMPORIUM_{tj}$ is equal to one for students enrolled in an early adopter institution and zero for students attending any other two- or four-year public TBR institution in Tennessee. $Z_{tj}$ is a vector of student characteristics including gender, race/ethnicity, and prior academic performance (as measured by the junior-year ACT math and English scores and high school GPA). The DID model would be biased by unobserved college-level factors that differ between early and late adopter schools and influence student performance on any of the outcome variables. To address this concern, I add to the model an institution-level fixed effect to compare students' prior outcomes to average student outcomes in late adopter colleges. When early and late adopter colleges have a similar pretreatment trend, the DID model represents the counterfactual change of adopting a hybrid emporium model. Therefore, $\delta_{inst}$ represents individual dummy variables for each institution to capture institution-level fixed effects, and $\varepsilon_{tj}$ represents the residual.

Equation (1) is akin to the reduced-form model for an instrumental variables approach in which being assigned to a developmental math course is used as an instrument for whether a student ever enrolled in a developmental math course and

[4] Over 90 percent of students took one of three college-level math courses: Contemporary Math (beginning algebra), College Algebra, or Introductory Statistics.

whether the student attended a college that offered the hybrid emporium version during that year, using college and year fixed effects to account for temporal trends and institutional-level variation. This provides the policy-relevant intent-to-treat estimates of the effect of the hybrid emporium model on student outcomes. As is common for DID analyses, I also test for common trends and make other robustness checks, as described below.

Several issues and assumptions are relevant in DID studies. Serial correlation is one such issue (Bertrand, Duflo, & Mullainathan, 2004). When multiple time points of data are collected for the same person or unit of analysis, the error terms will be correlated. This leads the estimate of the standard error to be underestimated, leading to a higher Type I error rate. To adjust for serial correlation, I utilize a block bootstrap method to account for clustering at the time points for each person. A second common issue in DID studies is related to the stable unit treatment value assumption, which holds that whether Person A receives the treatment should not affect the outcome for Person B (Lechner, 2011). A third issue in DID analysis relates to the exogeneity assumption, which is violated when the covariates in the analysis are also affected by the treatment. In the context of this study, this could occur if students somehow knew they would be required to take a hybrid emporium developmental math course, which then changed their behavior such that measures of the control variables are actually endogenous. Finally, the common trend assumption in DID studies holds that the trend over time for the outcome variable of interest would be the same for the treatment and control groups if the intervention had not occurred. In Section 5, I describe the robustness checks I conducted to address these concerns.

In addition to the overall treatment effect, I examine several heterogeneous treatment effects, including gender, age, and incoming level of math preparedness, as measured by the ACT math exam. The hybrid emporium model may affect men and women differently for several reasons. Historically, more women enroll in developmental math than men, particularly at the lowest levels of developmental math (Hagedorn, Siadat, Fogel, Nora, & Pascarella, 1999). Prior research suggests that there is an important relationship between gender and math self-concept and math performance (Cadinu, Maass, Rosabianca, & Kiesner, 2005; Sax, 1994), which begins developing as early as elementary school (Cvencek, Meltzoff, & Greenwald, 2011). Among college students, Sax (1994) found statistically significant differences between the math self-concepts of male and female students, with women reporting lower self-concepts than men throughout college. Taking more math and science courses has a positive effect on both male and female students' math self-concepts. Math self-concept has been shown to be a positive predictor of math course grades and majoring in STEM (Sax, Kanny, Riggers-Piehl, Whang, & Paulson, 2015), and women are less likely than men to complete a

STEM major within six years of enrolling in college, even though women report higher grade point averages (Gayles & Ampaw, 2014). Female college students who do not need developmental math are more likely to graduate with a STEM major than those who do need to take developmental math courses (Gayles & Ampaw, 2014). Additionally, fifteen years ago it was generally the case that women had less computer experience than men (Margolis & Fisher, 2003).

Because the hybrid emporium model relies on technology-based instruction, there may be differential impacts of the intervention across age groups. Nationally, 62 percent of students 24 or older at public two-year institutions and 66 percent of students 24 or older at public four-year institutions enroll in a remedial course. For students 18 or younger, the numbers are 69 percent and 37 percent, respectively (U.S. Department of Education, n.d.). Students 24 or older are more likely to persist in online courses (Park & Choi, 2009), despite similar preparedness and attitudes toward computers across age groups (Broady, Chan, & Caputi, 2010; Wagner, Hassanein, & Head, 2010). Older students also perform better in online courses compared to their expected outcomes in comparable face-to-face courses, suggesting that younger students may need more support in a technology-based instructional environment (Wladis, Conway, & Hachey, 2015).

Finally, the hybrid emporium model may impact students with higher levels of academic need differently than students who are stronger academically. Prior research shows that interventions can result in differential outcomes when grouping students by their incoming test scores (Boatman & Long, 2018; Dadger, 2012; Hodara, 2015; Xu, 2016).

### Sample

The analytic sample includes cohorts from all TBR colleges from 2006–07 to 2009–10, prior to the adoption of the hybrid emporium model at the late adopter institutions. The outcomes for all cohorts are then tracked until 2015–16, offering six years of follow-up data.

Tables 2 and 3 describe the characteristics of students who began at early versus late adopter colleges, for community colleges and four-year colleges, respectively. Overall, the early and late adopter institutions look similar to one another, though there are a few small differences, such as average ACT scores and the share of students scoring below 19 on ACT math. These differences suggest the late adopter colleges may serve slightly lower achieving students, although these differences are substantively small.

## Table 2

**Community College Student Characteristics by Timing of Hybrid Emporium Adoption, Fall 2008**

| | All Students | | ACT Math Score < 19 | | Ever Enrolled in a Developmental Math Course | |
|---|---|---|---|---|---|---|
| | Early Adopter Institutions | Late Adopter Institutions | Early Adopter Institutions | Late Adopter Institutions | Early Adopter Institutions | Late Adopter Institutions |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Female | 0.550 | 0.597 | 0.593 | 0.619 | 0.613 | 0.666 |
| White | 0.707 | 0.674 | 0.633 | 0.618 | 0.631 | 0.623 |
| Black | 0.162 | 0.203 | 0.227 | 0.266 | 0.236 | 0.248 |
| Age at college entry | 23.38<br>(7.99) | 23.99<br>(8.41) | 18.95<br>(1.44) | 19.19<br>(2.22) | 23.57<br>(7.98) | 23.62<br>(6.99) |
| ACT math score | 19.38<br>(4.07)<br>[5,323] | 18.62<br>(4.00)<br>[11,452] | 16.11<br>(1.42)<br>--- | 15.87<br>(1.49)<br>--- | 16.07<br>(1.65)<br>[1,395] | 15.94<br>(1.68)<br>[3,559] |
| HS GPA/GED | 2.98<br>(0.740) | 2.93<br>(0.836) | 2.76<br>(0.638) | 2.71<br>(0.676) | 2.83<br>(0.832) | 2.80<br>(0.819) |
| Quintile of median ZIP code income (1=lowest) | 2.77<br>(1.35) | 2.64<br>(1.45) | 2.64<br>(1.35) | 2.58<br>(1.46) | 2.63<br>(1.33) | 2.43<br>(1.40) |
| Number of students | 7,935 | 17,859 | 2,681 | 6,730 | 2,007 | 5,191 |
| Number of colleges | 5 | 8 | 5 | 8 | 5 | 8 |

NOTES: The table displays means, with standard deviations in parentheses. The analytic sample includes data from all community colleges. ACT data is missing for some of the students in the sample. The number of observations for those with ACT math scores is in brackets.

**Table 3**

**Four-Year College Student Characteristics by Timing of Hybrid Emporium Adoption, Fall 2008**

| | All Students | | ACT Math Score < 19 | | Ever Enrolled in a Developmental Math Course | |
|---|---|---|---|---|---|---|
| | Early Adopter Institutions | Late Adopter Institutions | Early Adopter Institutions | Late Adopter Institutions | Early Adopter Institutions | Late Adopter Institutions |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Female | 0.598 | 0.546 | 0.710 | 0.610 | 0.732 | 0.603 |
| White | 0.571 | 0.605 | 0.519 | 0.501 | 0.514 | 0.478 |
| Black | 0.292 | 0.283 | 0.204 | 0.236 | 0.220 | 0.183 |
| Age at college entry | 22.60<br>(7.03) | 21.82<br>(7.51) | 18.96<br>(1.27) | 18.88<br>(1.76) | 20.70<br>(3.23) | 20.40<br>(4.29) |
| ACT math score | 20.43<br>(4.15)<br>[3,453] | 20.20<br>(4.48)<br>[3,730] | 16.47<br>(1.19)<br>--- | 16.19<br>(1.33)<br>--- | 16.17<br>(1.24)<br>[549] | 16.20<br>(1.50)<br>[917] |
| HS GPA/ GED | 3.15<br>(0.60) | 3.14<br>(0.58) | 3.03<br>(0.48) | 2.90<br>(0.50) | 2.99<br>(0.48) | 2.90<br>(0.51) |
| Quintile of median ZIP code income (1=lowest) | 3.39<br>(1.44) | 2.56<br>(1.40) | 3.00<br>(1.51) | 2.50<br>(1.40) | 2.82<br>(1.66) | 2.43<br>(1.37) |
| Number of students | 4,835 | 4,965 | 1,381 | 1,648 | 597 | 1,060 |
| Number of colleges | 2 | 3 | 2 | 3 | 2 | 3 |

NOTES: The table displays means, with standard deviations in parentheses. The analytic sample includes data from the five TBR four-year universities which eventually adopted the hybrid emporium model. ACT data is missing for some of the students in the sample. The number of observations for those with ACT math scores is in brackets.

# 5. Findings and Discussion

## Results

The main results for both the community colleges (column 1) and four-year colleges (column 3) are presented in Table 4, along with the comparison means for students attending late adopter institutions. Among community college students, hybrid emporium model developmental math courses did not result in statistically different pass rates for their developmental math course or statistically significant differences in the number of terms to completion of the developmental math course when compared to the traditional developmental course. However, under hybrid emporium courses students were 5.7 percentage points less likely to pass their first college-level math course; they also completed 1.6 fewer credits over six terms (from a comparison mean of 23.5 credits). Additionally, hybrid emporium students at community colleges were 3.5 percentage points less likely to complete an associate degree and 3.7 percentage points less likely to complete any credential within six years. When compared to a base credential completion rate of 20.8 percent, this is a sizable effect.

Among students beginning in four-year colleges, being assigned to a developmental math course taught using technology-based instruction led to higher rates of passing the developmental math course and completing the course in 0.5 fewer terms, compared to students assigned to traditional developmental math courses. However, similar to the results from community colleges, students assigned to hybrid emporium courses at the four-year colleges were 5.4 percentage points less likely to pass their first college-level math course and 5.0 percentage points less likely to persist from the second to the third year of college. There were no statistically significant differences in the number of credits completed over time or degree attainment. These findings suggest that students at four-year institutions benefit from the self-paced, technology-centered teaching when it comes to passing developmental math, but this positive impact does not carry through into college-level math.

Table 5 presents the impact estimates for instruction under the hybrid emporium model in community colleges by gender and age. While both female and male students who were assigned to hybrid emporium developmental math courses had lower pass rates in college-level math when compared to students assigned to the traditional developmental math course, these negative effects were slightly more pronounced for female students. However, male students assigned to hybrid emporium courses experienced reductions in number of credits earned over time and in earning an associate degree or any credential within six years, whereas there was no statistically significant effect for female students assigned to hybrid emporium courses on the number of credits completed or degree completion.

Columns 5–8 of Table 5 present the results for students beginning community college under age 23 compared to students 23 and older. Those 23 and older who were assigned to hybrid emporium developmental math courses spent 0.5 additional terms completing the developmental math course, but were no more or less likely to pass their first college-level math course compared to similarly aged students assigned to traditional developmental math courses. The effects observed at community colleges overall are largely driven by traditionally aged students, those under 23.

At the four-year colleges (Table 6), male and female students generally had similar outcomes as students at community colleges. Interestingly, older students who were assigned to hybrid emporium courses had higher pass rates in developmental math. They also spent fewer terms in developmental math compared to students under age 23.

Table 7 presents the results for those with ACT math scores 16 and below compared to those with ACT math scores above 16. At the community colleges, the negative student outcomes associated with the hybrid emporium model are largely concentrated among those with ACT math scores above 16. At the four-year colleges, there are fewer substantial differences by ACT score, although there are positive effects on credential completion among students with low ACT math scores. So, while the model may not be a significant improvement over traditional instruction, it is not harming students with the lowest math skills.

**Table 4**

**Coefficient Estimates of the Effect of a Hybrid Emporium Developmental Math Course on Course Pass Rates, Persistence, and Degree Attainment for Cohorts 2006–07 Through 2009–10**

| Dependent Variable | Two-Year College (1) | Two-Year College Comparison Mean (at Late Adopter Colleges) (2) | Four-Year College (3) | Four-Year College Comparison Mean (at Late Adopter Colleges) (4) |
|---|---|---|---|---|
| Passed developmental math | -0.010<br>(0.028) | 0.639 | 0.054**<br>(0.025) | 0.781 |
| Terms to completion of developmental math | -0.240<br>(0.212) | 2.01 | -0.502***<br>(0.093) | 1.42 |
| Passed first college-level math course | -0.057**<br>(0.022) | 0.412 | -0.054***<br>(0.015) | 0.425 |
| Cumulative credits within 3 semesters | -0.722*<br>(0.379) | 16.27 | 0.801<br>(0.497) | 23.05 |
| Cumulative credits within 6 semesters | -1.556***<br>(0.575) | 23.52 | -1.059<br>(0.940) | 40.76 |
| Retention from year 1 to year 2 | -0.065***<br>(0.015) | 0.450 | 0.006<br>(0.018) | 0.485 |
| Retention from year 2 to year 3 | -0.003<br>(0.014) | 0.265 | -0.050***<br>(0.015) | 0.447 |
| Earned associate degree within 3 years | -0.012<br>(0.011) | 0.056 | 0.003<br>(0.002) | 0.006 |
| Earned associate degree within 6 years | -0.035**<br>(0.014) | 0.132 | 0.001<br>(0.010) | 0.018 |
| Earned bachelor's degree within 6 years | -0.008<br>(0.005) | 0.047 | 0.056<br>(0.032) | 0.433 |
| Earned any credential within 6 years | -0.037**<br>(0.015) | 0.208 | 0.056<br>(0.032) | 0.463 |
| Number of observations | 18,743 | | 5,500 | |

NOTES: Standard errors in parentheses. The "any credential" outcome includes certificates, associate degrees, and bachelor's degrees.

* $p < .05$, ** $p < .01$, *** $p < .001$.

## Table 5

### Community College Coefficient Estimates of the Effect of a Hybrid Emporium Developmental Math Course on Course Pass Rates, Persistence, and Degree Attainment for Cohorts 2006–07 Through 2009–10, by Gender and Age

| | Gender | | | | Age | | | |
|---|---|---|---|---|---|---|---|---|
| | Women | Control Mean | Men | Control Mean | < 23 Years Old | Control Mean | 23 Years or Older | Control Mean |
| Dependent Variable | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| Passed developmental math | -0.003<br>(0.031) | 0.681 | -0.019<br>(0.047) | 0.565 | -0.008<br>(0.028) | 0.635 | -0.062<br>(0.146) | 0.763 |
| Terms to completion of developmental math | -0.135<br>(0.143) | 1.97 | -0.167<br>(0.174) | 2.11 | -0.243<br>(0.143) | 1.84 | 0.518**<br>(0.201) | 1.69 |
| Passed first college-level math course | -0.050*<br>(0.028) | 0.624 | -0.059<br>(0.055) | 0.577 | -0.055**<br>(0.021) | 0.606 | 0.142<br>(0.106) | 0.692 |
| Cumulative credits within 3 semesters | -0.600<br>(0.530) | 16.74 | -0.833*<br>(0.487) | 15.42 | -0.583<br>(0.381) | 16.21 | -5.536<br>(3.477) | 18.37 |
| Cumulative credits within 6 semesters | -1.354<br>(0.940) | 24.16 | -1.598*<br>(0.895) | 22.36 | -1.405**<br>(0.577) | 23.46 | -8.702<br>(6.267) | 25.15 |
| Retention from year 1 to year 2 | -0.063***<br>(0.014) | 0.451 | -0.060**<br>(0.026) | 0.440 | -0.066***<br>(0.015) | 0.462 | 0.310<br>(0.210) | 0.432 |
| Retention from year 2 to year 3 | 0.026<br>(0.019) | 0.284 | -0.052<br>(0.035) | 0.215 | -0.001<br>(0.015) | 0.266 | 0.348<br>(0.606) | 0.279 |
| Earned associate degree within 3 years | -0.009<br>(0.016) | 0.059 | -0.014<br>(0.011) | 0.053 | -0.012<br>(0.011) | 0.056 | 0.134<br>(0.112) | 0.068 |
| Earned associate degree within 6 years | -0.016<br>(0.017) | 0.138 | -0.056***<br>(0.018) | 0.122 | -0.035**<br>(0.014) | 0.132 | 0.088<br>(0.069) | 0.158 |
| Earned bachelor's degree within 6 years | 0.000<br>(0.007) | 0.047 | -0.021*<br>(0.00) | 0.047 | -0.008<br>(0.005) | 0.047 | 0.018<br>(0.035) | 0.029 |
| Earned any credential within 6 years | -0.010<br>(0.020) | 0.211 | -0.068***<br>(0.017) | 0.203 | -0.038**<br>(0.015) | 0.207 | 0.094<br>(0.073) | 0.229 |
| Number of observations | 11,921 | | 6,822 | | 11,269 | | 7,474 | |

NOTES: Standard errors in parentheses. The "any credential" outcome includes certificates, associate degrees, and bachelor's degrees.
* $p < .05$, ** $p < .01$, *** $p < .001$.

## Table 6

**Four-Year College Coefficient Estimates of the Effect of a Hybrid Emporium Developmental Math Course on Course Pass Rates, Persistence, and Degree Attainment for Cohorts 2006–07 Through 2009–10, by Gender and Age**

| | Gender | | | | Age | | | |
|---|---|---|---|---|---|---|---|---|
| | Women | Control Mean | Men | Control Mean | < 23 Years Old | Control Mean | 23 Years or Older | Control Mean |
| Dependent Variable | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| Passed developmental math | 0.042<br>(0.042) | 0.824 | 0.074<br>(0.044) | 0.709 | 0.050*<br>(0.025) | 0.781 | 0.271**<br>(0.114) | 0.848 |
| Terms to completion of developmental math | -0.517**<br>(0.239) | 1.13 | -0.219***<br>(0.078) | 1.45 | -0.296**<br>(0.130) | 2.024 | -1.189***<br>(0.106) | 1.70 |
| Passed first college math | -0.056**<br>(0.021) | 0.501 | -0.036<br>(0.029) | 0.453 | -0.053***<br>(0.014) | 0.486 | 0.581<br>(0.408) | 0.472 |
| Cumulative credits within 3 semesters | 0.955*<br>(0.481) | 23.87 | 0.091<br>(0.806) | 21.66 | 0.889*<br>(0.473) | 22.93 | -10.17<br>(8.45) | 34.59 |
| Cumulative credits within 6 semesters | -1.091<br>(1.044) | 42.48 | -1.844<br>(2.207) | 37.85 | -0.863<br>(0.869) | 40.613 | -15.54<br>(9.85) | 54.80 |
| Retention from year 1 to year 2 | 0.012<br>(0.018) | 0.541 | 0.000<br>(0.036) | 0.413 | 0.011<br>(0.017) | 0.499 | -0.386<br>(0.360) | 0.489 |
| Retention from year 2 to year 3 | -0.048**<br>(0.023) | 0.498 | -0.061**<br>(0.025) | 0.402 | -0.052***<br>(0.015) | 0.472 | 0.065*<br>(0.030) | 0.423 |
| Earned associate degree within 3 years | 0.002<br>(0.002) | 0.008 | 0.006*<br>(0.003) | 0.003 | 0.003<br>(0.002) | 0.006 | 0.003<br>(0.005) | 0.001 |
| Earned associate degree within 6 years | 0.004<br>(0.011) | 0.022 | -0.012<br>(0.013) | 0.011 | 0.000<br>(0.010) | 0.018 | 0.009<br>(0.006) | 0.008 |
| Earned bachelor’s degree within 6 years | 0.077<br>(0.129) | 0.473 | -0.027<br>(0.030) | 0.366 | 0.056*<br>(0.028) | 0.434 | 0.073<br>(0.354) | 0.409 |
| Earned any credential within 6 years | 0.085<br>(0.049) | 0.506 | -0.021<br>(0.034) | 0.390 | 0.056*<br>(0.028) | 0.464 | 0.073<br>(0.354) | 0.409 |
| Number of observations | 3,664 | | 1,836 | | 4,739 | | 761 | |

NOTES: Standard errors in parentheses. The “any credential” outcome includes certificates, associate degrees, and bachelor’s degrees.
* $p < .05$, ** $p < .01$, *** $p < .001$.

## Table 7

### Coefficient Estimates of the Effect of a Hybrid Emporium Developmental Math Course on Course Pass Rates, Persistence, and Degree Attainment for Cohorts 2006–07 Through 2009–10, by ACT Score

| | Two-Year Colleges | | | | Four-Year Colleges | | | |
|---|---|---|---|---|---|---|---|---|
| | ACT Math <= 16 | Control Mean | ACT Math > 16 | Control Mean | ACT Math <= 16 | Control Mean | ACT Math > 16 | Control Mean |
| Dependent Variable | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| Passed first developmental math | -0.018 (0.039) | 0.637 | 0.010 (0.017) | 0.644 | 0.062** (0.030) | 0.795 | 0.041 (0.036) | 0.761 |
| Terms to completion of developmental math | -0.216** (0.079) | 2.14 | -0.009 (0.109) | 1.52 | -0.399*** (0.111) | 1.76 | 0.004 (0.044) | 1.09 |
| Passed first college-level math course | -0.053 (0.036) | 0.401 | -0.064*** (0.020) | 0.461 | -0.050** (0.021) | 0.446 | -0.081** (0.035) | 0.521 |
| Cumulative credits within 3 semesters | -0.640 (0.490) | 15.94 | -0.818* (0.482) | 17.06 | 0.903 (0.717) | 22.84 | 0.562 (1.005) | 23.35 |
| Cumulative credits within 6 semesters | -1.170* (0.679) | 22.74 | -2.073** (0.920) | 25.33 | -1.877 (1.650) | 40.64 | 1.270 (1.358) | 40.93 |
| Retention from year 1 to year 2 | -0.065*** (0.018) | 0.401 | -0.065*** (0.017) | 0.474 | -0.023 (0.031) | 0.421 | 0.081*** (0.016) | 0.498 |
| Retention from year 2 to year 3 | 0.001 (0.021) | 0.247 | -0.007 (0.024) | 0.261 | -0.046*** (0.014) | 0.415 | -0.060* (0.031) | 0.466 |
| Earned associate degree within 3 years | 0.003 (0.011) | 0.042 | -0.040*** (0.010) | 0.090 | 0.001 (0.002) | 0.002 | 0.009 (0.005) | 0.011 |
| Earned associate degree within 6 years | -0.028 (0.018) | 0.112 | -0.046** (0.019) | 0.179 | -0.001 (0.007) | 0.014 | -0.008 (0.021) | 0.024 |
| Earned bachelor's degree within 6 years | -0.005 (0.005) | 0.036 | -0.011 (0.010) | 0.071 | 0.070* (0.031) | 0.420 | 0.022* (0.012) | 0.453 |
| Earned any credential within 6 years | -0.024 (0.018) | 0.181 | -0.062*** (0.022) | 0.271 | 0.072* (0.035) | 0.444 | 0.010 (0.028) | 0.491 |
| Number of observations | 12,990 | | 5,753 | | 3,523 | | 1,977 | |

NOTES: Standard errors in parentheses. The "any credential" outcome includes certificates, associate degrees, and bachelor's degrees.
* $p < .05$, ** $p < .01$, *** $p < .001$.

## Robustness Checks

Tables 8 and 9, along with Figures 3 and 4, present the results for three common robustness checks for the difference-in-difference analyses. Table 8 presents the results from a falsification test, in which I drop data from the actual first term of early hybrid emporium implementation and instead randomly assign a false term from the years prior to adoption. For example, if a college adopted the hybrid emporium model at scale in fall 2008, this school was randomly assigned a false adoption term of spring 2007 or fall 2007, etc. Since this test includes artificial adoption terms and excludes data from the post-hybrid emporium adoption terms, I would not expect to find significant results unless factors unrelated to the hybrid emporium model led to changes in the outcomes. As shown in Table 8, I do not observe any statistically significant effects for this falsification test, which improves confidence in the findings from the main analyses.

Table 9 presents a covariance balance check, in which I treat control variables as outcomes for the analysis. The goal of this covariate balance check is to estimate whether the observed effects may be driven, in part, by changes in the control variables over time. Examining gender, age at college entry, ACT math score, and high school GPA, I observe two statistically significant coefficients for gender and age at the community colleges. This suggests that the composition of the student body at the early adopter community colleges became more male and younger over time compared to the late adopter community colleges. This could be due to a statewide shift in the percentage of female students and the average age of students at all Tennessee colleges over time, with more female students enrolling at late adopter colleges, for example. Additionally, the magnitude of these differences is small relative to the mean values for late adopter schools.

In Figures 3 and 4, I test for the presence of time trends in the terms prior to and after hybrid emporium adoption at early adopter colleges. I display graphs for six of the 11 outcomes, although I observe similar trends for the outcomes not pictured. The vertical line represents the term of adoption of the hybrid emporium model at each of the institutions in the study. The coefficients to the left of the vertical line in Figures 3 and 4 capture the trend, by term, for each outcome prior to the adoption of the hybrid emporium model across two-year and four-year colleges, respectively. Detecting significant trends in the terms prior to adoption of the model would suggest that significant effects observed in the actual term of adoption could be driving the results, or could be due to chance variation or prior long-running trends. The gray lines above and below the center line represent the 95 percent confidence interval. Fortunately, for both community and four-year colleges, I observe that the estimates are stable in the pre-adoption terms. I observe only one statistically significant trend prior to the adoption of the hybrid emporium model, which is the completion of any credential within six years four terms prior to the adoption of the hybrid emporium model at four-year colleges. This is the only significant coefficient at the 5 percent level, which is reasonable to assume occurred due to chance.

The coefficients to the right of the vertical line allow for the effects of the hybrid emporium model to vary by term. For the early adopter colleges it may be the case that the direction and/or magnitude of the outcomes changes as the hybrid emporium model has been adopted for more terms. Generally, at the community colleges (Figure 3) I observe the outcomes to be fairly stable in the post-adoption terms. At the four-year colleges (Figure 4) I observe a decline in the terms to completion of developmental math in the post-adoption terms. I also observe a sharp drop in year two enrollment at four-year colleges in the second term after adoption and an increase in credits accumulated, which then return to the prior averages in subsequent terms. Overall, the event study analysis captured in Figures 3 and 4 reveals no substantive concerns with pre-treatment trends, and little evidence of changes in the outcomes in subsequent terms post-adoption.

**Table 8**

**Falsification Test (Random Offset Term) Coefficient Estimates of Hybrid Emporium Model, Entrants Through Summer 2007**

| | Two-Year Colleges | Four-Year Colleges |
|---|---|---|
| Dependent Variable | (1) | (2) |
| Passed first developmental math | -0.037<br>(0.027) | -0.159<br>(0.246) |
| Terms to completion of developmental math | -0.060<br>(0.088) | 0.041<br>(0.090) |
| Passed first college math | -0.002<br>(0.046) | -0.024<br>(0.061) |
| Cumulative credits within 3 semesters | -0.613<br>(0.425) | -1.046<br>(1.570) |
| Cumulative credits within 6 semesters | -0.065<br>(0.811) | -2.632<br>(1.484) |
| Retention from year 1 to year 2 | -0.005<br>(0.020) | 0.040<br>(0.079) |
| Retention from year 2 to year 3 | 0.032<br>(0.047) | -0.027<br>(0.048) |
| Earned associate degree within 3 years | 0.004<br>(0.012) | 0.002<br>(0.002) |
| Earned associate degree within 6 years | -0.014<br>(0.021) | 0.000<br>(0.005) |
| Earned bachelor's degree within 6 years | 0.015<br>(0.012) | 0.012<br>(0.042) |
| Earned any credential within 6 years | -0.004<br>(0.015) | -0.003<br>(0.037) |
| Number of observations | 3,821 | 1,440 |

NOTES: Standard errors in parentheses.
* $p < .05$, ** $p < .01$, *** $p < .001$.

**Table 9**

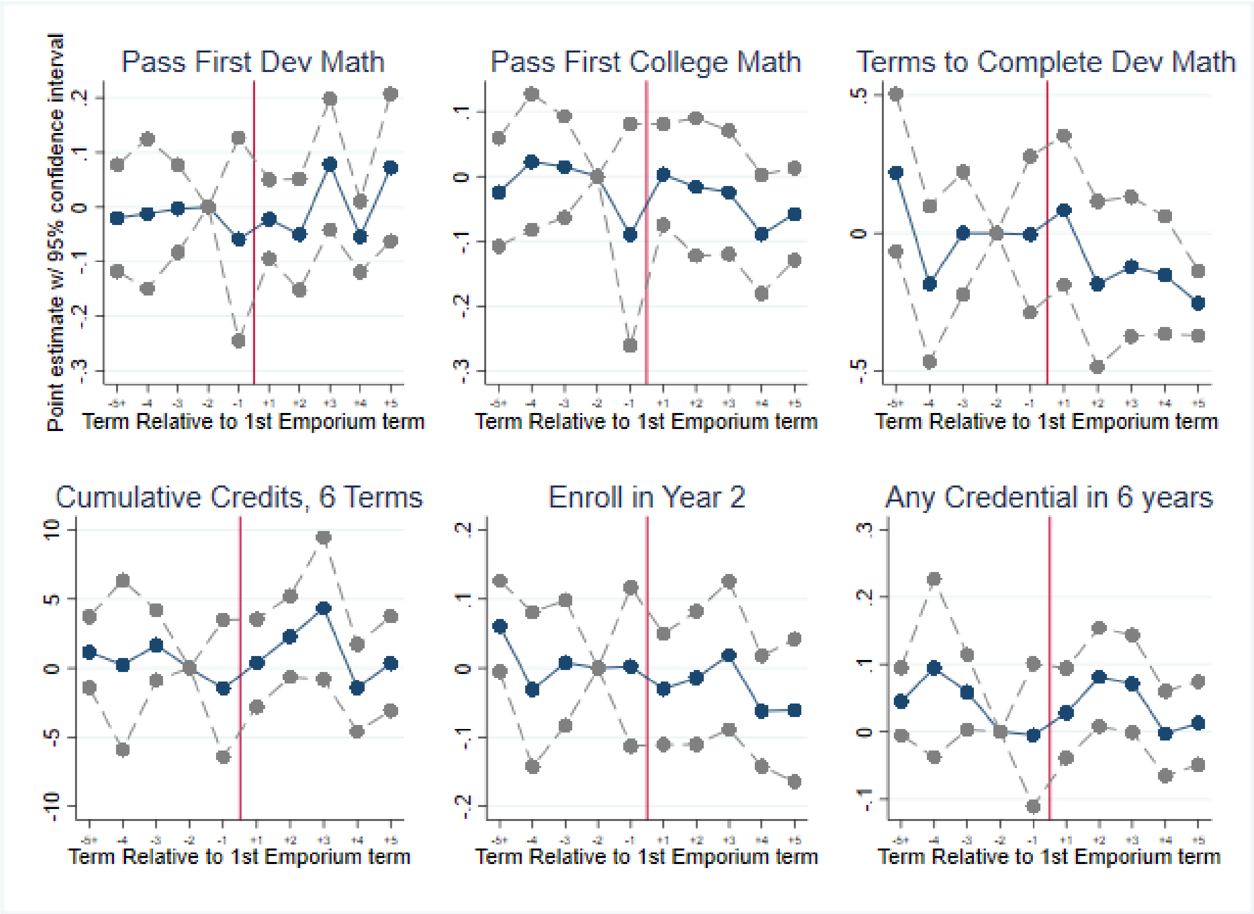
**Reduced-Form Estimates of Hybrid Emporium Model Participation on Covariate Balance**

| | Two-Year Colleges | | Four-Year Colleges | |
|---|---|---|---|---|
| Dependent Variable | Reduced-Form Estimate | Mean Values for Late Adopter Schools | Reduced-Form Estimate | Mean Values for Late Adopter Schools |
| Female | -0.039***<br>(0.010) | 0.644 | 0.013<br>(0.019) | 0.627 |
| Age at college entry | -0.072**<br>(0.030) | 19.12 | -0.056<br>(0.059) | 18.58 |
| ACT math score | -0.059<br>(0.039) | 15.73 | 0.094*<br>(0.051) | 16.13 |
| HS GPA | 0.059<br>(0.040) | 2.68 | 0.050<br>(0.046) | 2.90 |
| Number of observations | 18,875 | | 5,541 | |

NOTES: Race/ethnicity variables are represented as proportions. ACT math score is on a 1-36 scale.
* $p < .05$, ** $p < .01$, *** $p < .001$.

**Figure 3**

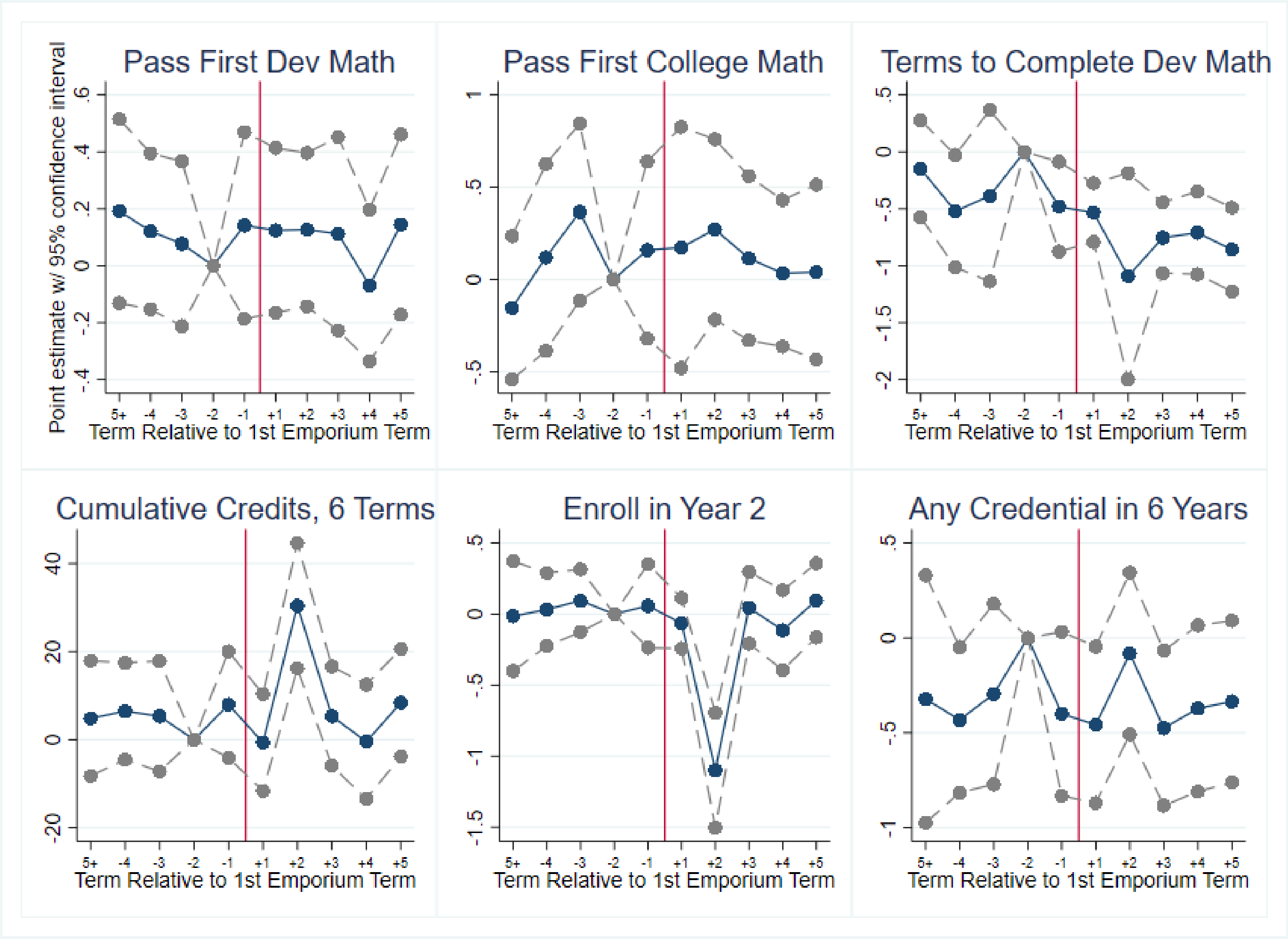
**Event Study Analysis for Community Colleges, Five Terms Pre- and Post- Hybrid Emporium Model Adoption**




NOTES: The vertical line represents the term of adoption of the hybrid emporium model. The coefficients to the left of the vertical line capture the trend, by term, for each outcome prior to the adoption of the hybrid emporium model across community colleges. Two terms before the adoption of the hybrid emporium model is omitted in the analysis.

**Figure 4**

**Event Study Analysis for Four-Year Colleges, Five Terms Pre- and Post- Hybrid Emporium Model Adoption**




NOTES: The vertical line represents the term of adoption of the hybrid emporium model. The coefficients to the left of the vertical line capture the trend, by term, for each outcome prior to the adoption of the hybrid emporium model across four-year colleges. Two terms before the adoption of the hybrid emporium model is omitted in the analysis.

## Discussion

In this study, I assess the impact of using the hybrid emporium model for developmental math courses on students' academic outcomes at both two-year and four-year public colleges in Tennessee.

### Community colleges

Among students attending community colleges, there appear to be no significant differences in the pass rates for developmental math courses or in the number of terms spent in developmental math between students who were assigned to a hybrid emporium developmental math course and those assigned to a traditional developmental math course. However, hybrid emporium students were 5.7 percentage points less likely to pass their first college-level math course and earned 1.6 fewer credits over six terms (from a comparison mean of 23.5 credits). Under a hybrid emporium model students were 3.5 percentage points less likely to complete an associate degree and 3.7 percentage points less likely to complete any credential within six years. These findings on passing college-level math and on associate degree attainment are similar in magnitude to what Kozakowski (2019) found in her study of the effects of technology-based instruction at Kentucky community colleges.

Among students attending community colleges, assignment to a hybrid emporium developmental math course reduced the likelihood that students would pass their first college-level math course (this was also the case among four-year college students—see below). For the main analysis, all three potential first college-level math courses (beginning algebra, college algebra, and introductory statistics) are combined, but the negative results are similar when isolating the first college-level math course to one of these three courses at both two-year and four-year colleges, suggesting that type of first college-level math course is not relevant to the results. Thus this negative finding is a puzzle, as it is not clear whether it is related to a negative effect of the technology or to the fact that in college-level math courses, students who had become accustomed to technology-based instruction in their developmental course then returned to a traditional format in the college-level course. One explanation for why students assigned to developmental math under the traditional model may perform better in their first college-level math course could simply be that the instructional methods of both courses are aligned. Future research examining the effects of technology-centered developmental math instruction should consider the effect of transitioning from one instructional mode to another between developmental and college-level courses.

In examining the effects of the hybrid emporium model for various subgroups of students at community colleges, I find that the lower overall pass rates in college-level math were largely driven by female rather than male students. Male students experienced greater reductions than female students in the likelihood of earning an associate degree or any credential within six years but were not more statistically likely to fail their first college-level math course. There were no statistically significant effects for female students in a technology-based developmental math course on the number of credits completed over time, or on credential completion.

I also find that the effects observed at community colleges were largely driven by younger rather than older students. These findings support earlier research that found that older students perform better in online courses compared to their expected outcomes in traditional courses (Wladis, Conway, & Hachey, 2015). I also observe that the negative student outcomes associated with the hybrid emporium model were largely concentrated among those with ACT math scores above 16. Community college faculty in Tennessee were initially concerned about the impact of this type of instructional model on students with very low ACT math scores, but results from this study suggest that students with lower ACT math scores were, broadly, not disadvantaged by exposure to the model. The negative findings for students close to the cutoff is consistent with other quasi-experimental research in developmental education that uses a regression discontinuity design, comparing the outcomes for students directly on either side of the placement cutoff (Boatman & Long 2018; Clotfelter, Ladd, Muschkin, & Vigdor 2015; Dadgar, 2012; Hodara, 2015; Martorell & McFarlin, 2011; Melguizo, Bos, Ngo, Mills, & Prather, 2016; Scott-Clayton & Rodriguez, 2015; Xu & Dadgar 2018). While these prior studies do not specifically examine the effects of the hybrid emporium model, they do align with these results, suggesting that developmental education students with placement test scores close to the cutoff experience null to negative outcomes.

### Four-Year Colleges

With respect to four-year college students, results from this study show that under a hybrid emporium model students had higher rates of passing developmental math, on average, and spent 0.5 fewer terms in developmental math compared to those assigned to a traditional course. Similar to the community college students, students at four-year colleges were 5.4 percentage points less likely to pass their first college-level math course, and they were 5.0 percentage points less likely to persist from the second to the third year. There were no statistically significant differences in the number of credits completed over time or on degree attainment at the four-year colleges. Further, there were no substantive differences by gender or by ACT math score. Older students reported higher pass rates in their developmental math courses under the hybrid emporium model, and also spent fewer terms in developmental math compared to students aged younger than 23 years of age.

## Limitations of the Study

While this study attempts to control for important differences in students who were assigned to and institutions that adopted technology-centered courses over time, several caveats should be acknowledged. First, this study examines the adoption of the hybrid emporium model of teaching developmental math in the earliest years of implementation in Tennessee. As is common in the adoption of new programs and technologies, much is learned and adjusted from the challenges in the early years. Qualitative interviews with faculty at six of these institutions revealed a consistent degree of skepticism about the success of this method of instruction in the early years of adoption. Student success and retention is based on a number of factors, but interactions with faculty are a critical component (Tinto, 1993). If faculty were demonstrating their own concerns and growing pains regarding this new style of teaching during this time, it is reasonable to assume that this may have influenced student success in the early years of adoption. As faculty and administrators become more facile with technology serving as the primary instructional tool, the impacts on student success may improve. With the difference-in-differences design, the impacts of the instructional method four or five years into implementation are, by definition, unknown.

This study also treats the hybrid emporium model as one common, overarching style of teaching and assumes that the primary change affecting all developmental math courses at these colleges from 2006–07 to 2010–11 was the adoption of the hybrid emporium model. While the pedagogy of this model is largely consistent, individual colleges and faculty members may have adopted additional technologies or offered other additional instruction. I was not able to observe, for example, whether faculty brought their class together at certain times during a class period to provide additional whole-class instruction, or supplemented the Pearson software (which all but one of the colleges used) with other technology-centered strategies. There may have been numerous small adjustments made to the technology-based course by instructors, and the effects of those adjustments on student outcomes are not distinguishable in this study.

## Cost Effectiveness of Technological Interventions

A primary reason many colleges cite for adopting technology in the classroom is lowering the cost of instruction. Computer-based instruction can allow for larger class sizes and potentially lower-cost faculty, either through higher faculty course loads or the hiring of adjunct faculty to facilitate the computer-based sections. Students may also save money through computer-based courses, potentially through the individualized pacing that allows them to complete their courses more quickly, or through saving money on textbooks (Twigg, 2013). However, simply reducing costs without improving student success will not result in net improvements in outcomes for either the institution or the student. Colleges need to evaluate both the benefits and the costs associated with remedial redesigns (Belfield, Jenkins, & Lahr, 2016), yet rigorous cost-effectiveness evaluations are generally rare in education (Levin & Belfield, 2015).

Several descriptive cost studies have found that computer-assisted instruction is more cost-effective than peer tutoring or traditional instructional formats (Buzhardt, & Semb, 2005; Niemiec, Sikorski, & Walberg, 1989). Twigg (2013) summarized the cost savings of moving to the adoption of the hybrid emporium model at 32 colleges across the country, comparing instructional costs prior to adopting the model to the costs after. Thirty-one of the 32 schools in the study reduced costs by an average of 20 percent after adopting computer-based instruction. However, the cost savings resulting from the adoption of the hybrid emporium model was not compared directly to the outcomes for students in this analysis.

Three technology-based and/or developmental math studies have specifically examined the costs of interventions compared to student outcomes. In the high school context, Barrow, Markman, and Rouse (2008) conducted a simulation to compare the cost-effectiveness of computer-based algebra instruction to a reduction in class size. They found that the cost-effectiveness of computer-assisted instruction was comparable to reducing class size from 30 to 14 students. Belfield, Jenkins, and Lahr (2016) conducted a cost-effectiveness study of corequisite remedial courses in Tennessee. In their analysis, they considered both the gain in college-level gateway course pass rates as a result of corequisite courses alongside the transition costs of corequisite remediation and the per-student costs of the courses. They concluded that the return on investment for corequisite courses is high, particularly when considering the impacts on college-level course pass rates and subsequent course completion. In a study of online courses across six different four-year universities, Bowen, Chingos, Lack, and Nygren (2014) found that there were no differences in the learning outcomes for students randomly assigned to a hybrid or traditional statistics course. Through simulations they estimated that the cost savings for institutions three to five years after launching the online courses were 36 to 57 percent. So while there were not positive gains in student outcomes as a result of online courses, these courses did reduce costs for the institution.

In the current study, I find that the adoption of the hybrid emporium model does not lead to improved outcomes for students in passing college-level math or in degree completion. Although college-level math completion (at both two- and four-year colleges) and degree attainment (at two-year colleges) were lower after the adoption of the hybrid emporium model, colleges might still be interested in continuing the model if it lowers costs for students or institutions. If the hybrid emporium model lowers the per-student cost of developmental math, then perhaps colleges are willing to accept declines in college-level math success, particularly if more students enroll in college-level math. However, the money colleges might save on instructional costs does not necessarily equal the longer term financial loss of not passing college-level math courses or of not earning a degree.

The field of higher education specifically needs more evidence of cost savings and cost benefits of interventions and reforms. To build this evidence for the use of the hybrid emporium model in developmental math offerings, the cost for each student in a hybrid emporium course must be calculated and compared to the per-student cost in a traditional course. Many specific elements go into these calculations, including equipment costs, faculty and staffing costs, software costs, and changes in class size, to name a few. While in some circumstances cost savings are immediately realized, in other cases, it might take a longer time for the cost savings to become apparent. The adoption of the hybrid emporium model has not yet been rigorously evaluated for cost savings to the institution, yet the fact that the results from this study suggest that it is not particularly efficacious implies that the return on investment would not be high. This is an important area for additional inquiry, as I do not observe gains in student success as a result of the hybrid emporium model, and the cost savings are not known.

# 6. Conclusion

As increasing numbers of colleges and state systems explore the use of technology-centered instruction in developmental education, it is important to understand the impacts of this shift on students' course performance and later academic progress. There are many reasons why technology could prove effective in teaching basic math skills and, conversely, many reasons why it could prove ineffective. Results from this study provide evidence that adopting technology-based instruction in developmental math courses does not lead to lower pass rates in developmental math itself for college students in Tennessee. In fact, at four-year colleges, students in this study passed their developmental math courses at higher rates under this model. At both two- and four-year institutions, however, students assigned to hybrid emporium developmental math courses had lower pass rates in their first college-level math course. While more students enrolled in college-level courses, more students also failed those courses. At the community colleges, there is evidence that this lower pass rate in college-level math courses may have repercussions for credential completion, as students who were assigned to a hybrid emporium developmental math course earned associate degrees at lower rates than their peers.

In the years since the adoption of the hybrid emporium model in Tennessee, the state has moved toward a credit-bearing, corequisite model for offering developmental courses. Since the fall of 2015, all developmental math courses (at both two- and four-year colleges) are still taken as a separate course, but now in the same semester as a college-level math course. As a result, the alignment in both the content and the instructional method has improved across the developmental and college-level course transition, with many of the introductory college-level math courses now also using the hybrid emporium model. Several colleges now also emphasize the importance of having the same instructor in both the developmental (corequisite) course and the college-level course. This degree of faculty alignment across developmental and college-level math was notably absent in the early years of the adoption of the hybrid emporium model and has the potential to reverse the negative impacts on college-level math performance observed in this study. For states and systems looking to adopt the technology-based instructional model for their developmental math courses, the results of this study speak to the importance of considerations regarding alignment in faculty and instructional methods across developmental and college-level courses.

# References


Allen, I. E., & Seaman, J. (2007). *Online nation: Five years of growth in online learning*. Needham, MA: The Sloan Consortium.

Allen, I. E., & Seaman, J. (2010). *Class differences: Online education in the United States, 2010*. Needham, MA: The Sloan Consortium.

Aker, J. C., Ksoll, C., Miller, D., Perez, K., & Smalley, S. L. (2015). *Learning without teachers? Evidence from a randomized experiment of a mobile phone-based adult education program in Los Angeles* (CDG Working Paper No. 368). Washington, DC: Center for Global Development.

Ashby, J., Sadera, W. A., & McNary, S. W. (2011). Comparing student success between developmental math courses offered online, blended, and face-to-face. *Journal of Interactive Online Learning*, *10*(3), 128–140.

Barrow, L., Markman, L., & Rouse, C. E. (2009). Technology's edge: The educational benefits of computer-aided instruction. *American Economic Journal: Economic Policy, 1*(1), 52–74.

Belfield, C., Jenkins, P. D., & Lahr, H. (2016). *Is corequisite remediation cost-effective? Early findings from Tennessee.* Community College Research Center, Teachers College, Columbia University.

Bertrand, M., Duflo, E., & Mullainathan, S. (2004). How much should we trust differences-in-differences estimates? *The Quarterly Journal of Economics, 119*(1), 249–275.

Boatman, A., & Kramer, J. W. (2019). *Content and connections: Students' responses to a hybrid emporium instructional model in developmental mathematics* (CAPR Working Paper). New York, NY: Center for the Analysis of Postsecondary Readiness

Boatman, A., & Long, B. T. (2018). Does remediation work for all students? How the effects of postsecondary remedial and developmental courses vary by level of academic preparation. *Educational Evaluation and Policy Analysis, 40*(1), 29–58.

Bowen, W. G., Chingos, M. M., Lack, K. A., & Nygren, T. I. (2014). Interactive learning online at public universities: Evidence from a six-campus randomized trial. *Journal of Policy Analysis and Management, 33*(1), 94–111.

Broady, T., Chan, A., & Caputi, P. (2010). Comparison of older and younger adults' attitudes towards and abilities with computers: Implications for training and learning. *British Journal of Educational Technology, 41*(3), 473–485.

Buzhardt, J., & Semb, G. (2005). Integrating online instruction in a college classroom to improve cost effectiveness. *Teaching of Psychology, 32*(1), 63–66.

Cadinu, M., Maass, A., Rosabianca, A., & Kiesner, J. (2005). Why do women underperform under stereotype threat? Evidence for the role of negative thinking. *Psychological Science, 16*(7), 572–578.

Cavalluzzo, L., Lowther, D., Mokher, C., & Fan, X. (2012). *Effects of the Kentucky Virtual Schools' hybrid program for algebra I on grade 9 student math achievement*. Washington, DC: Institute of Education Sciences, U.S. Department of Education, National Center for Education Evaluation and Regional Assistance.

Chen, B., & deNoyelles, A. (2013). Exploring students' mobile learning practices in higher education. *Educase Review Online*. Retrieved from https://er.educause.edu/articles/2013/10/exploring-students-mobile-learning-practices-in-higher-education

Chen, X. (2016). Remedial coursetaking at U.S. public 2- and 4-year institutions: Scope, experiences, and outcomes (NCES 2016-405).. Washington, DC: U.S. Department of Education, National Center for Education Statistics. Retrieved from http://nces.ed.gov/pubsearch

Chingos, M. M., Griffiths, R. J., & Mulhern, C. (2017). Can low-cost online summer math programs improve student preparation for college-level math? Evidence from randomized experiments at three universities. *Journal of Research on Educational Effectiveness, 10*(4), 794–816.

Clotfelter, C. T., Ladd, H. F., Muschkin, C., & Vigdor, J. L. (2015). Developmental education in North Carolina community colleges. *Educational Evaluation and Policy Analysis, 37*(3), 354–375.

Cosgrove, S. B., & Olitsky, N. H. (2015). Knowledge retention, student learning, and blended course work: Evidence from principles of economics courses. *Southern Economic Journal*, *82*(2), 556–579.

Crandall, J. R., & Soares, L. (2015). *The architecture of innovation: System-level course redesign in Tennessee*. Washington, DC: American Council on Education. Retrieved from http://www.acenet.edu/news-room/Documents/The-Architecture-of-Innovation-System-Level-Course-Redesign-in-Tennessee.pdf

Cvencek, D., Meltzoff, A. N., & Greenwald, A. G. (2011). Math–gender stereotypes in elementary school children. *Child Development, 82*(3), 766–779.

Dadgar, M. (2012). *Essays on the economics of community college students' academic and labor market success* (Unpublished doctoral dissertation). Teachers College, Columbia University, New York, NY.

Deschacht, N., & Goeman, K. (2015). The effect of blended learning on course persistence and performance of adult learners: A difference-in-differences analysis. *Computers & Education, 87*, 83–89.

Dynarski, M., Agodini, R., Heaviside, S., Novak, T., Carey, N., Campuzano, L., Means, B., Murphy, R., Penuel, W., Javitz, H., Emery, D., & Sussex, W. (2007). *Effectiveness of reading and mathematics software products: Findings from the first student cohort*. Washington, DC: Institute of Education Sciences, U.S. Department of Education, National Center for Education Evaluation and Regional Assistance.

Epper, R., & Baker, E. D. (2009). *Technology solutions for developmental math: An overview of current and emerging practices*. Seattle, WA: Bill & Melinda Gates Foundation. Retrieved from https://docs.gatesfoundation.org/documents/technology-solutions-for-developmental-math-jan-2009.pdf

Gayles, J. G., & Ampaw, F. (2014). The impact of college experiences on degree completion in STEM fields at four-year institutions: Does gender matter? *The Journal of Higher Education, 85*(4), 439–468.

Giani, M., & Martin, A. (2019, March). Mobilizing developmental education: The causal effect of mobile apps on developmental education student outcomes. *Council for the Study of Community Colleges 61st Annual Conference*. Presentation conducted for the Council for the Study of Community Colleges, San Diego, CA.

Goode, C. T., Lamoreaux, M., Atchison, K. J., Jeffress, E. C., Lynch, H. L., & Sheehan, E. (2018), Quantitative skills, critical thinking, and writing mechanics in blended versus face-to-face versions of a research methods and statistics course. *Teaching of Psychology*, *45*(2), 124–131.

Gray-Barnett, N. K. (2001). *An analysis of the academic success achieved by five freshman cohorts through a community college developmental education program* (Doctoral dissertation). Retrieved from ProQuest Dissertations and Theses database. (UMI No. ATT 3034561)

Hagedorn, L. S., Siadat, M. V., Fogel, S. F., Nora, A., & Pascarella, E. T. (1999). Success in college mathematics: Comparisons between remedial and nonremedial first-year college students. *Research in Higher Education, 40*(3), 261–284.

Hart, C. M. D., Berger, D., Jacob, B., Loeb, S., & Hill, M. (2019). Online learning, offline outcomes: Online course taking and high school student performance. *AERA Open, 5*(1).

Heinrich, C. J., Darling-Aduana, J., Good, A., & Cheng, H. (2019). A look inside online educational settings in high school: Promise and pitfalls for improving educational opportunities and outcomes. *American Educational Research Journal*.

Heppen, J. B., Sorensen, N., Allensworth, E., Walters, K., Rickles, J., Taylor, S. S., & Michelman, V. (2017). The struggle to pass algebra: Online vs. face-to-face credit recovery for at-risk urban students. *Journal of Research on Educational Effectiveness*, *10*(2), 272–296.

Herreid, C. F., & Schiller, N. A. (2013). Case studies and the flipped classroom. *Journal of College Science Teaching*, *42*(5), 62–66.

Hodara, M. (2015). The effects of English as a second language courses on language minority community college students. *Educational Evaluation and Policy Analysis*, *37*(2), 243–270.

Kane, T. J., Boatman, A., Kozakowski, W., Bennett, C., Hitch, R., & Weisenfeld, D. (2019). *College remediation goes back to high school: Evidence from a statewide program in Tennessee* (NBER Working Paper No. 26133). Cambridge, MA: National Bureau of Economic Research.

Kozakowski, W. (2019). Moving the classroom to the computer lab: Can online learning with in-person support improve outcomes in community colleges? *Economics of Education Review*, *70*, 159–172.

Kwak, D. W., Menezes, F. M., & Sherwood, C. (2015). Assessing the impact of blended learning on student performance. *Economic Record*, *91*(292), 91–106.

Le, C., Rogers, K. R., & Santos. J. (2011). *Innovations in developmental math: Community colleges enhance support for nontraditional students*. Boston, MA: Jobs for the Future. Retrieved from http://www.jff.org/sites/default/files/MetLife-DevMath-040711.pdf

Lechner, M. (2011). The estimation of causal effects by difference-in-difference methods. *Foundations and Trends® in Econometrics, 4*(3), 165–224.

Levin, H. M., & Belfield, C. (2015). Guiding the development and use of cost-effectiveness analysis in education. *Journal of Research on Educational Effectiveness, 8*(3), 400–418.

Margolis, J., & Fisher, A. (2003). *Unlocking the clubhouse: Women in computing*. Cambridge, MA: MIT press.

Martorell, P., & McFarlin, I., Jr. (2011). Help or hindrance? The effects of college remediation on academic and labor market outcomes. *The Review of Economics and Statistics*, *93*(2), 436–454.

Means, B., Bakia, M., & Murphy, R. (2014). *Learning online: What research tells us about whether, when and how*. London, UK: Routledge.

Melguizo, T., Bos, J. M., Ngo, F., Mills, N., & Prather, G. (2016). Using a regression discontinuity design to estimate the impact of placement decisions in developmental math. *Research in Higher Education, 57*(2), 123–151.

Means, B., Toyama, Y., Murphy, R., & Baki, M. (2013). The effectiveness of online and blended learning: A meta-analysis of the empirical literature. *Teachers College Record, 115*(3), 1–47.

Morgan, P., & Ritter, S. (2002). *An experimental study of the effects of Cognitive Tutor Algebra I on student knowledge and attitude*. Pittsburgh, PA: Carnegie Learning, Inc.

National Center for Academic Transformation. (2009). Project descriptions sorted by discipline. Saratoga Springs, NY: Author. Retrieved from http://thencat.org/PCR/Proj_Discipline_all.html

National Center for Academic Transformation. (2013). How to redesign a developmental math program by using the emporium model. Retrieved from http://thencat.org/Guides/Math/TOC.html

Niemiec, R. P., Sikorski, M. F., & Walberg, H. J. (1989). Comparing the cost-effectiveness of tutoring and computer-based instruction. *Journal of Educational Computing Research, 5*(4), 395–407.

Pane, J. F., Griffin, B. A., McCaffrey, D. F., & Karam, R. (2013). *Effectiveness of Cognitive Tutor Algebra I at scale* (RAND working paper WR-984-DEIES). Santa Monica, CA: RAND Corporation.

Pane, J. F., McCaffrey, D. F., Slaughter, M. E., Steele, J. L., & Ikemoto, G. S. (2010). An experiment to evaluate the efficacy of Cognitive Tutor Geometry. *Journal of Research on Educational Effectiveness*, *3*(3), 254–281.

Park, J. H., & Choi, H. J. (2009). Factors influencing adult learners' decision to drop out or persist in online learning. *Journal of Educational Technology & Society, 12(*4), 207–217.

Perez, S., & Foshay, R. (2002). Adding up the distance: Can developmental studies work in a distance learning environment? *T.H.E. Journal*, *29*(8), 16–24.

Powers, K. L., Brooks, P. J., Galazyn, M., & Donnelly, S. (2016). Testing the efficacy of MyPsychLab to replace traditional instruction in a hybrid course. *Psychology Learning & Teaching*, *15*(1), 6–30.

Rickles, J., Heppen, J. B., Allensworth, E., Sorensen, N., & Walters, K. (2018). Online credit recovery and the path to on-time high school graduation. *Educational Researcher, 47*(8), 481–491.

Ryan, S., Kaufman, J., Greenhouse, J., She, R., & Shi, J. (2016). The effectiveness of blended online learning courses at the community college level. *Community College Journal of Research and Practice*, *40*(4), 285–298.

Sax, L. J. (1994). Mathematical self-concept: How college reinforces the gender gap. *Research in Higher Education, 35*(2), 141–166.

Sax, L. J., Kanny, M. A., Riggers-Piehl, T. A., Whang, H., & Paulson, L. N. (2015). "But I'm not good at math": The changing salience of mathematical self-concept in shaping women's and men's STEM aspirations. *Research in Higher Education, 56*(8), 813–842.

Scott-Clayton, J., & Rodriguez, O. (2015). Development, discouragement, or diversion? New evidence on the effects of college remediation. *Education Finance and Policy*, *10*(1), 4–45.

Spradlin, K. D., & Ackerman, B. (2010). The effectiveness of computer-assisted instruction in developmental mathematics. *Journal of Developmental Education*, *34*(2), 12–42.

Tamin, R. M., Bernard, R. M., Borokhovski, E., Abrami, P. C., & Schmid, R. F. (2011). What forty years of research says about the impact of technology on learning a second-order meta-analysis and validation study. *Review of Educational Research, 81*(1), 4–28.

Tennessee Higher Education Commission. (2019). *Tennessee higher education fact book 2018–19*. Retrieved from https://www.tn.gov/thec/research/redirect-research/fact-book/fact-book.html

Tinto, V. (1993). *Leaving college: Rethinking the causes and cures of student attrition* (2nd ed.). Chicago, IL: University of Chicago Press.

Trenholm, S. (2006). A study on the efficacy of computer-mediated developmental math. *Research & Teaching in Developmental Education*, *22*(2), 51–62.

Twigg, C. A. (2011). The math emporium: A silver bullet for higher education. *Change: The Magazine of Higher Learning, 43*(3), 25–34.

Twigg, C. A. (2013). Improving learning and reducing costs: Outcomes from Changing the Equation. *Change: The Magazine of Higher Learning*, *45*(4), 6–14.

U.S. Department of Education, National Center for Education Statistics. (n.d.) *2003–04 beginning postsecondary students longitudinal study, second follow-up (BPS:04/09)*. Retrieved October 6, 2019, from PowerStats: https://nces.ed.gov/datalab/index.aspx

Vallade, J. K. (2013). *An evaluation of the emporium model as a tool for increasing student performance in developmental mathematics and college algebra* ((Unpublished doctoral dissertation). University of Toledo, Toledo, OH.

Wagner, N., Hassanein, K., & Head, M. (2010). Computer use by older adults: A multi-disciplinary review. *Computers in Human Behavior, 26*(5), 870–882.

Waxman, H. C., Lin, M-F., & Michko, G. M. (2003). *A meta-analysis of the effectiveness of teaching and learning with technology on student outcomes*. Naperville, IL: Learning Point Associates.

Weiss, M. J., & Headlam, C. (2019). A randomized controlled trial of a modularized, computer-assisted, self-paced approach to developmental math. *Journal of Research on Educational Effectiveness, 12*(3), 484–513.

Whinnery, E., & Pompelia, S. (2018). 50-state comparison: Developmental education policies. Denver, CO: Education Commission of the States.

Wladis, C., Conway, K. M., & Hachey, A. C. (2015). The online STEM classroom—Who succeeds? An exploration of the impact of ethnicity, gender, and non-traditional student characteristics in the community college context. *Community College Review, 43*(2), 142–164.

Xu, D. (2016). Assistance or obstacle? The impact of different levels of English developmental education on underprepared students in community colleges. *Educational Researcher*. 45(9).

Xu, D., & Dadgar, M. (2018). How effective are community college remedial math courses for students with the lowest math skills? *Community College Review*, *46*(1), 62–81.

Xu, D., & Jaggars, S. S. (2011). The effectiveness of distance education across Virginia's community colleges: Evidence from introductory college-level math and English courses. *Educational Evaluation and Policy Analysis, 33*(3), 360–377.

Xu, D., & Jaggars, S. S. (2014). Performance gaps between online and face-to-face courses: Differences across types of students and academic subject areas. *The Journal of Higher Education*, *85*(5), 633–659.

Xu, D., & Xu, Y. (2019). *The promises and limits of online higher education: Understanding how distance education affects access, cost, and quality*. Washington, DC: American Enterprise Institute.

Zhou, H., Taber, C., Arcona, S., & Li, Y. (2016). Difference-in-differences method in comparative effectiveness research: Utility with unbalanced groups. *Applied Health Economics and Health Policy, 14*(4), 419–429.