Undergraduate STEM Achievement and Retention: Cognitive, Motivational, and Institutional Factors and Solutions

Jennifer G. Cromley[1], Tony Perez[2], and Avi Kaplan[3]

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[1]University of Illinois at Urbana-Champaign

[2]Old Dominion University

[3]Temple University

Abstract

Student cognition and motivation, as well as institutional policies, determine student course grades and retention in science, technology, engineering, and mathematics (STEM) majors. Regarding cognition, study skills relate to course grades, and grades relate to retention in STEM. Several aspects of motivation are related to both grades and retention in STEM: self-efficacy (self-confidence for completing assignments), continuing interest in learning more about the subject, and effort control (remaining focused on classes and studying). Students' cognition and motivation are interdependent, and, furthermore, they play out in the context of multiple institutional policies, such as academic support centers, career counseling, financial aid policies, forced curving of course grades, course timing, and course registration policies. All of these interdependent factors can improve with targeted programs that complement each other. Some challenges for reform include instructor resistance to changing teaching and a lack of coordination, or even competing emphases, among university policies and resources, such as course scheduling, academic support, advising, career counseling, and financial aid.

Keywords

motivation, cognition, institutional barriers, STEM achievement, STEM retention

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Introduction

The need to increase the number of science, technology, engineering, and mathematics (STEM) graduates in the United States is well known. Although STEM degree earning is on the rise, so are the number of new jobs that require STEM knowledge and skills (National Science Board [NSF], 2015). Understanding the causes of undergraduates' STEM achievement, under-achievement, and dropout can point in the direction of policies to increase students' success and stem the tide of students who leave science majors, among whom females (of all races) and African American and Hispanic students (of both sexes) are over-represented. STEM achievement is important, as earning a low grade (e.g., below C) or failing even one STEM course can lead to as much as a 1-year delay in earning a college degree, and the prospect of an extra year of tuition and foregone earnings pushes many students out of STEM majors (Griffith, 2010; Maltese & Tai, 2011).

Predicting STEM Achievement

We review factors that contribute to or hinder students' STEM achievement, especially in introductory STEM courses. Most dropouts from STEM majors occur in the first 2 years of undergraduate study (Griffith, 2010) during which students are completing introductory courses in their discipline as well as a calculus sequence. We take this to suggest that policy initiatives to increase retention might best be targeted at students and courses during these first 2 years. We focus our review on three major types of predictors of STEM achievement, under-achievement, and dropout: cognitive predictors (e.g., reasoning skills), motivational predictors (e.g., perceived relevance of STEM course content), and institutional predictors (e.g., sequencing and course offerings). These three domains operate together to affect students' achievement, yet the research in each of these areas has largely been conducted independently from the others (Henderson, Beach, & Finkelstein, 2011). We consider the implications of this interdependence for institutional policy and instructional strategies. To be sure, our review does not include all factors that have been associated with STEM achievement (e.g., access to information about applying to college, who chooses STEM majors, high school teaching practices in STEM) and not even all cognitive, motivational, and institutional variables are found to have some relation to STEM achievement (e.g., stereotype threat in diverse student contexts [e.g., Massey & Fischer, 2005], beliefs that one's ability can grow [e.g., Dweck, 2000]). We focus on the processes that have the strongest research support and that have clear policy and instructional implications.

Cognitive Predictors: Science Knowledge, Reasoning Skills

One area of critical importance to students' STEM achievement is their prior STEM knowledge and cognitive skills. STEM courses are taught based on assumptions about students' background in STEM. Instructors have grounds to assume that students have some basic scientific knowledge, study strategies, and reasoning skills. Indeed, students' high school grade point average (GPA) is a known predictor of STEM achievement—STEM course grades (Hernandez, Schultz, Estrada, Woodcock, & Chance, 2013) and retention in STEM (Maltese & Tai, 2011)—as are standardized test scores such as the Scholastic Aptitude Test (SAT) or American College Testing (ACT; on grades: Ironsmith, Marva, Harju, & Eppler, 2003; Zusho, Pintrich, & Coppola, 2003; on retention: Nauta & Epperson, 2003; T. Perez, Cromley, & Kaplan, 2014). In addition, STEM undergraduates' grades and retention have been associated with prior STEM achievement: number of STEM Advanced Placement (AP) courses taken (on retention: Griffith, 2010), high school class rank (on grades: Martin, Montgomery, & Saphian, 2006; on retention: Brown, Lent, & Larkin, 1989), tests of deductive reasoning (on grades: Dai &

Cromley, 2014; Lawson, Banks, & Logvin, 2007), and spatial skills (on grades: Hegarty, Stieff, & Dixon, 2013; on retention: Wai, Lubinski, & Benbow, 2009).

However, research also suggests that prior achievement is a poorer predictor of engineering majors' GPA than of psychology majors' GPA (Jagacinski, 2013). This supports the often-quoted observation (Seymour & Hewitt, 1997) that many otherwise high-achieving students do not perform well in the sciences. Thus, background knowledge, study strategies, and reasoning skills may not be enough to secure high achievement in STEM for all students. Indeed, STEM course design and instruction are based not only on the reasonable assumption of students' prior knowledge, but also on the less reasonable assumption that students know how to be a student: what a syllabus is, and how to read and use it; how to navigate the rules of the complex college bureaucracy (including how to fill out forms, how to make requests politely, and what to do if the request is denied); and how to effectively seek help—what type of help and from whom—when they are struggling. These and other aspects of cultural capital (Collier & Morgan, 2008) are often missing for students who are the first in their family to attend college (about 20% of undergraduates at 4-year colleges, higher among under-represented minority [URM] students; Wang & Wickersham, 2014). Thus, although good high school students are likely to become good college STEM students, many good high school students still struggle with undergraduate STEM courses. This has led to increased interest in "non-cognitive," or motivational, predictors of achievement.

Motivational Predictors

Although the term motivation is used in everyday speech as if it were one thing (such as "being energized"), research in academic achievement motivation considers many different aspects of motivation. First, while motivation has a "quantity" dimension—that is, there can be more or less of it—it also has a "quality" dimension—there are different types of it, with some more conducive to achievement than others. Second, these types of motivation are made of different components or facets, each playing a role in energizing and directing the student's investment of effort. Whereas motivation research supports the role of numerous such components, only a handful shows large-enough effects on STEM achievement and retention. These are reviewed here.

Motivation research clearly demonstrates that motivation can be improved by changing instruction. Perhaps the most powerful predictor of STEM grades that has been shown to respond to intervention is STEM self-efficacy—having confidence that one can complete the tasks required in a course such as writing a lab report, studying for an exam, completing homework, and so on (on grades: Lent, Brown, & Hackett, 1994). Another key predictor of grades is interest—the persisting desire to engage with certain content (on grades: A. C. Perez, 2012; on retention: Crisp, Nora, & Taggart, 2009; A. C. Perez, 2012). A third key predictor is relevance of the STEM course material—the students' perception that the content is valuable to them, either now or for future goals, such as their degree or career. Relevance as perceived by students is related to both grades (Ironsmith et al., 2003; Obrentz, 2012; Zusho et al., 2003) and retention in STEM (Hurtado, Newman, Tran, & Chang, 2010; Jones, Paretti, Hein, & Knott, 2010). Unfortunately, research shows that many STEM undergraduates do not see the relevance of much of the content, such as calculus, and struggle in these required courses. A fourth predictor is maintaining one's effort in the face of distractions—for which different researchers have used different labels, and we will label effort control (Pintrich & De Groot, 1990). Clearly, undergraduates face numerous distractions and competing goals; staying focused on attending class and labs, completing assignments, and studying for exams are critical for maintaining academic achievement and remaining in a STEM major. Effort control is important for STEM grades (Obrentz, 2012).

Critically, all of these adaptive motivations—self-efficacy, interest, perceived relevance, and effort control—decline over the undergraduate years and simultaneously become more highly related to grades. For example, at the same time that interest is becoming more and more important for STEM grades, STEM students on average show lower and lower levels of interest. One possible reason for the decrease in students' confidence in their ability and interest in STEM is the increasing difficulty of course demands, assignments, and examinations. As students work harder than they ever have, but receive much worse grades than they did in high school, they seem to interpret this as a message that they are not able enough or that they are not welcome. Students interpret the effort they invest and the grades they receive as a strong message about whether they belong in a STEM major. However, these processes operate somewhat differently among URM students, whose lower retention in STEM is associated more with perceptions of a hostile racial climate on campus than with a general "sense of belonging" or being welcome at the college (Hurtado et al., 2010).

Institutional Predictors

Universities, colleges/schools, departments, and programs enact policies that can affect students' progress through STEM degrees, such as policies regarding math placement tests, course sequencing, grading practices, scholarships versus grants-in-aid, academic advising, career counseling, and academic support services. The effects of policies begin to be felt even before college has begun, for example, at student orientation, where many universities require students to take a math placement test that determines eligibility for math courses that are co-requisites for STEM courses. Students who might desire to complete a STEM major can be "weeded out" by poor scores on these tests before they even register for their first course.

Course timing and registration policies. Many universities offer courses only once in an annual sequence (e.g., a chemistry course offered only in the fall is a prerequisite for a biochemistry course offered only in the spring). An unintended consequence of this sequencing is that a poor grade in the prerequisite course sets the student back by an entire year (Sutton & Sankar, 2011). Another consequence is that courses may fill up within hours of registration opening (e.g., by 2:00 a.m. after registration opens at midnight), and only the most savvy students are able to register. Accurate and timely academic advising is crucial for students to navigate the course sequence for majors, to know what is offered when, and to know how to actually enroll in courses that tend to be over-subscribed; this is even more crucial for first-generation college students.

Career counseling. Career counseling is also a critical institutional resource for STEM students. Career counselors are a vital resource for licensing and credentialing requirements that may go beyond academic degree-program requirements. They can also help students better understand course requirements (e.g., why a biologist should know calculus), learn about the contributions to the common good that different careers can make, and reflect on the fit between the major and their interests and values (Hurtado et al., 2010).

Financial aid policies. Financial aid policies can affect persistence in STEM as well. Students from URM groups are known to be more borrowing-averse, and when aid changes from scholarships to loans, they are more likely to drop out of college (Wohlgemuth et al., 2006). Financial aid may be particularly influential for low-income students, as the achievement of students who work more than 16 to 20 hr, in addition to attending college, tends to suffer (Wolniak & Pascarella, 2007).

Academic support. Academic support centers, which can include course-specific tutoring by peers or professionals, workshops on time management and study strategies, testing and accommodation for learning disabilities, and other supports, are another university-level resource that can affect achievement and retention in STEM (see below).

Integration among services. Not only are these institutional policies important for student success, but integration among the various services also needs to be efficient (Kezar, Gehrke, & Elrod, 2015). For example, career counselors need to know where to send struggling (and potential dropout) STEM students for academic help. Would they receive the most appropriate support at the STEM-specific academic support center, the academic support center for National Collegiate Athletic Association (NCAA) student-athletes, or the university counseling center? Furthermore, many students will need more than one of these supports.

Forced curving of course grades. A final obstacle is forced curving of course grades in some STEM courses, when faculty are determined to give only a fixed percent of A or B grades (e.g., 10% of each), regardless of student mastery of content. STEM faculty engage in this almost twice as often as do non-STEM faculty (Hurtado, Eagan, Pryor, Whang, & Tran, 2012). Under such a grade-curving policy, many students are understandably discouraged by a poor grade, feel that they do not understand the material or are not as able as their peers, and may leave STEM despite high levels of mastery.

Summary of Student Processes and Institutional Obstacles

A multitude of personal cognitive, motivational, and institutional characteristics relate to students' achievement and retention. However, the research has treated these characteristics as distinct. Institutional fragmentation can play a larger role in STEM dropout for first-generation students because they and their families have less experience successfully navigating complex bureaucracies. However, in fact, these factors are interdependent and act together to influence students' achievement and retention, particularly for first-generation students. For example, knowledge can influence students' motivational beliefs, as do scheduling and grading practices. Instructional policies and motivation can enhance students' learning of reasoning skills. Evaluation of students' motivation and knowledge can influence instructors' and administrators' policy decisions. These interdependent factors that provide routes to high grades and retention are best considered as malleable processes rather than as stable events.

Policy Implications: Addressing Cognition, Motivation, and Institutional Obstacles

Much of the research reports on education initiatives that should become more widespread. However, an approach that focuses on a single component is unlikely to result in large increases in students' STEM success and retention. Rather, to be effective, decision-makers need to implement combinations of policy initiatives that simultaneously coordinate support for student cognition and motivation, with removal of institutional obstacles, all in a way that fits the characteristics of the institution, its faculty, and students.

Supporting Cognition

Recent literature reviews of undergraduate STEM teaching methods have clearly shown that certain teaching approaches can help college students learn better, and thereby persist in STEM. One major meta-analysis (a statistical analysis across 166 studies by Ruiz-Primo, Briggs, Iverson, Talbot, & Shepard, 2011) suggests that various combinations of conceptually oriented tasks, small-group learning, use of technology, and student-driven inquiry projects can effectively help students remember scientific facts, understand how the facts are connected, and apply what they have learned to new situations. However, the findings do not have simple and straightforward implications for those who train future STEM instructors: For example, whereas technology use by itself had large positive effects on student learning, technology with student-driven inquiry had small negative effects on learning. Thus, policy makers and educators seeking to implement best teaching practices must pay careful attention to the specifics of these findings.

Another meta-analysis of 225 published and unpublished studies on active teaching techniques for college students (Freeman et al., 2014) found that active learning techniques—such as clickers, think-pair-share, and "flipped" classrooms—increase exam grades and passing rates. The effect was similar across different STEM subjects. Active learning was more effective in smaller (£50 students) classes but was still effective in larger classes. Freeman et al. were not able to test whether all active learning approaches are equally effective due to lack of detail in many of the studies.

Our own research addressed a cognitive intervention involving videotaped demonstrations of biology problem solving (worked examples; see Booth, McGinn, Young, & Barbieri, 2015) that were released periodically over a semester; the intervention decreased students' sense that the course required too much effort to succeed (i.e., effort costs), which in turn was associated with higher course grades. In this case, our cognitive intervention affected students' motivation. This cognitive intervention provided students with detailed explanations of how to go through the process of remembering relevant information from earlier in the semester, carefully reading the problem, drawing appropriate conclusions (i.e., reasoning), and checking one's work. Feedback from students suggested that they often receive instruction about content-based questions and answers, but the reasoning process involved in figuring out an answer to a question is never demonstrated for them. This type of problem-solving demonstration could be used more widely in STEM education. Unfortunately, many STEM faculty are resistant to changing their teaching approaches (Brownell & Tanner, 2012). For this reason, many initiatives to improve STEM learning should be spearheaded at the department, college, or university level.

Supporting Motivation

Various motivation-boosting techniques—short-term (e.g., brief students writing about the relevance of the content; Hulleman & Harackiewicz, 2009) and longer term (e.g., semester-long exam feedback; Muis, Ranellucci, Franco, & Crippen, 2013)—have shown promise for increasing STEM student achievement or retention. For example, self-efficacy enhancing messages about the success of study strategies increased students' chemistry grades, presumably by helping students persist in studying (Muis et al., 2013). In our own research, similar messages have effects on students' achievement via biology reasoning, that is, increasing motivation affects cognition.

Both students' interest and perceived relevance can be increased by changing teaching. For example, a set of semester-long "connections" between basic chemistry content and various health topics increases students' perceptions of the relevance of introductory chemistry content, with positive effects on interest (Vogel Taylor, Mitchell, & Drennan, 2009). A different relevance-enhancing technique (Hulleman & Harackiewicz, 2009) asks students to write brief reflection papers on the relevance of an introductory biology course to their careers, with positive effects on students' interest in biology. In our own research, this relevance-writing task (delivered four times over a semester, and focusing on central concepts in the material) had effects on biology cognition, which in turn increased course grades. This relevance-writing task also provided a buffer against the commonly found decline in students' interest. Another motivational intervention (Kim & Bennekin, 2013) enhanced students' effort control and eventually their interest, using a computer program to teach community college students to set specific learning goals, anticipate interruptions to their learning, and plan how to stay on task. In summary, motivational predictors can be increased with brief student activities, which can also increase student achievement. However, as with increasing cognition, faculty resistance to changes in teaching is an obstacle for implementing motivation-boosting programs.

Self-Regulated Learning (SRL): Combining Cognitive and Motivational Interventions

One powerful but rarely implemented approach combines both cognitive and motivational interventions, using an approach called SRL. For example, a teaching method for technical college (high-minority, 2-year and 4-year) included demonstrations of how to check one's work, engage in and reflect on flexible problem-solving approaches, and consider frequent feedback from instructors, including feedback about errors, as learning opportunities (Zimmerman, Moylan, Hudesman, White, & Flugman, 2011). Across two courses, students improved their grades and passed the courses at a higher rate (68% vs. 49% and 76% vs. 62%). SRL-based interventions can also be delivered as for-credit courses, though these seem to work best when study strategies and motivational supports are taught via students' own real course assignments, not using a separate set of texts or problem sets (Wolters & Hoops, 2015). These more complex changes in teaching based on SRL hold great promise.

Institutional Approaches to Improving STEM Achievement and Retention

One major change in American universities over the last 20 years is the growth in academic support programs, including various types of tutoring and academic support centers. Research generally supports the effectiveness of academic support centers, and peer tutors appear to be as effective as other kinds of tutors. One advantage of using peer tutors is extra gains in understanding for the tutors themselves; that is, the process of explaining problem solving to a tutee consolidates the tutor's own knowledge and skills (Tsui, 2007). Learning centers also offer one-time workshops (e.g., on time management), and there is limited but positive evidence for their effectiveness (Wolters & Hoops, 2015). One consistent challenge for learning centers is that students who most need them are least likely to access them, either out of shame or because they do not realize that they are doing poorly (Sargent, Borthick, Lederberg, & Haardörfer, 2012-2013).

Academic enrichment specifically designed for URMs—such as pre-college Summer Bridge programs (Strayhorn, 2011) or ongoing academic support (e.g., through the federally funded TRIO Ronald E. McNair program or university-specific initiatives such as the Meyerhoff Scholars program at the University of Maryland, Baltimore County [UMBC])—show solid results (Hrabowski, 2011; McCoy, Wilkinson, & Jackson, 2008). However, these are complex, multi-component programs that combine several features such as mentoring, graduate school/career workshops, academic support, undergraduate research experiences, study and support groups, and counseling; it is not clear which components have the beneficial effects.

A second type of institutional initiative is providing students with more faculty contact via research experiences and mentoring. Although the mechanisms behind the effectiveness are not clear, formal programs where STEM students receive real research experiences as part of a formal program or formal mentoring show benefits for student achievement and retention, and this may be even more true for URMs (Hurtado et al., 2010). Furthermore, the benefits from same-race and different-race mentors for URMs appear to be similar, and benefits for female students appear to be similar for male and female mentors (Griffith, 2010), so administrators need not worry about the complications of matching mentors' and mentees' characteristics or about having a shortage of mentors.

Institutional obstacles to STEM achievement and retention are in some ways more difficult to address than supporting students' cognitive and motivational characteristics because the full effects of institutional policies are not immediately evident. For example, the effect on dropout of offering courses in a strict sequence or semester (e.g., only in the spring) or of not offering introductory courses during the summer is hidden from the administrators and staff who set the course schedules, register the students, and do the accounting of tuition revenue. Similarly, lack of coordination among academic advising, academic support, career counseling, and other resources may remain invisible to all three groups.

University-specific math placement tests may or may not keep talented students out of STEM, but universities should at least ensure that the tests meet the highest standards of quality (e.g., test reliability and validity: answer patterns show consistency within students, scores in fact do predict course success above and beyond already-collected information such as SAT scores because the test measures the most relevant skills and knowledge). Universities might consider a system to check whether math scores are consistent with already-submitted standardized test scores and high school grades, so that talented students who made careless errors on the placement test are not mistakenly prohibited from taking STEM courses. Finally, incoming students may need to be made aware of the consequences of the test for their future, regardless of how high their other test scores or grades are, and be encouraged to take their time answering and checking their answers, just as they would on any high-stakes exam. In addition, students could be allowed time to remediate and re-take the tests before fall classes begin.

A final challenge at the institutional level is forced curving, that is, the practice of limiting the percent of A and B grades, regardless of student mastery of the content. Although this may seem to be a matter of individual faculty choice, the practice has such negative effects on students' motivation that departments, schools, colleges, and universities should consider having policies that prohibit it. Forced curving of grades can counter the benefits of effective cognition and motivation supports, providing a prime example for the interdependence of these domains and the importance of coordination among them.

Conclusion

Our review suggests multiple challenges to STEM achievement and retention—stemming from students' cognitive skills and motivational orientations, as well as from institutional barriers. These factors are interdependent. Each of them can be effectively addressed, but each needs to be addressed in different ways and from different sources, such as instructors, departments, or university financial aid. In addition, each may need to be addressed differently for URMs and for over-represented students. Multi-component interventions show much promise, but in many cases it is unclear which components have added value. Taken together, the research suggests it is best to look at high achievement and retention in STEM as a process rather than as an event; one that unfolds over the course of the undergraduate years, but has an especially important impact on students' success and retention in the first 2 years. Institutions might benefit from evaluating these three types of factors and consider their interdependence in their particular context. This may allow informed decision-making about interventions for each factor that can enhance desirable change in the other factors as well. For example, faculty can demonstrate in detail how to complete the tasks required and actively engage students, students can receive motivational supports, and institutions can create more flexibility (e.g., in the timing of course offerings) and better integrated services, all of which can increase STEM achievement and retention.

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