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Insights from Two Decades of P-12 Engineering Education Research

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Keywords

engineering education, research review, instructional strategies, curriculum, girls in education, underrepresented students, robotics in education, interest and motivation, STEM education, outside of school

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Insights from Two Decades of P-12 Engineering Education Research

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Abstract

The 21st century has seen a growing movement in the United States towards the adoption of engineering and technology as a complement to science education. Motivated by this shift, this article offers insights into engineering education for grades P-12, based on a landscape review of 263 empirical research studies spanning the two decades from January 2000 to June 2021. These insights are organized around three core themes: (1) students' understandings, skills, and attitudes about engineering and technology; (2) effective methods of P-12 engineering education; and (3) benefits of P-12 engineering education. The insights are captured in the form of evidence-based claims summarized as a set of ten findings. The findings start with the recognition that students at all age levels in the United States—though not in many other countries—have narrow conceptions of technology and engineering. A key finding is that for students to pursue science, technology, engineering, and mathematics (STEM) fields, it is important to develop their interest at an early age. Several findings address effective strategies for engaging students in engineering, both in schools and in afterschool and summer programs. These include generalizable teaching methods suitable across a wide range of educators and students, as well as topical approaches around specific themes such as the design of robots, or biomedical devices. One of the most encouraging findings is that multiple methods have successfully addressed a major social inequity: improving the attitudes, STEM skills, and career aspirations of girls, students of color, and students from low-income families. The last group of findings addresses the benefits of engineering education including not only increased knowledge and skills, but also lifelong skills such as teamwork, communication, and creativity, as well as persistence, motivation, self-confidence, and STEM identity. We hope that these insights may be of value to researchers, educators, administrators, and policy leaders.

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1.0 Introduction

A quiet revolution is working its way through elementary and secondary public education in the United States. Science education of the 20th century was almost entirely confined to the "pure science" disciplines, but over the past two decades the focus of the school curriculum has gradually shifted from purely science and mathematics towards inclusion of engineering and technology. This movement has been facilitated by a series of new education frameworks and guidelines relevant to society's 21st-century needs, with the result that engineering is gradually being integrated with the teaching of science for *all* students from preschool through grade 12 (P-12).

As part of this growing adoption of P-12 engineering education, we have had the privilege to work with a growing cadre of educators deeply committed to supporting the new vision. Our work over the last decade has involved collaborating with

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a wide range of teachers, district leaders, government agencies, teacher organizations, foundations, and non-profits to support integrating engineering education into school environments and afterschool and summer programs. Over the course of these collaborations with our teaching and research colleagues, three questions continually arose:

> What are students' understandings, skills, and attitudes about engineering and technology?
> What are effective methods of P-12 engineering education?
> What are the benefits of P-12 engineering education?

To guide our work based on the findings of educational research, we have conducted regular searches of the literature. As we organized this information for a new resource to support primary and secondary teaching of engineering and technology (Keeley et al., 2020), we realized that the information may be useful to a wider audience of science, technology, engineering, and mathematics (STEM) educators and researchers. For this article, we used an inductive process to formalize our insights as evidence-based claims and summarized these as a set of ten findings. The result is this landscape study of 263 empirical research studies that provide data on students' knowledge, capabilities, and attitudes, as well as effective teaching methods, and beneficial outcomes of P-12 engineering education.

2.0 Context

To establish a context for the current review, this section briefly describes the educational standards documents that are driving change and summarizes the findings from previous research reviews.

Science standards that include engineering

Although engineering had entered various science standards documents in the USA by the end of the 20th century (e.g., American Association for the Advancement of Science, 1993; National Research Council [NRC], 1996; Rutherford & Ahlgren, 1991), it was not integrated as an equal partner to science until publication of *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC, 2012). The *Framework* served as a blueprint for the *Next Generation Science Standards* (NGSS Lead States, 2013) which includes standards for engineering design processes, standards that integrate engineering with the traditional sciences, and a prominent role for such crosscutting concepts as the interdependence of science and engineering, and the influence of science, technology, and engineering on society and the natural environment. As of this writing, 44 states have adopted or adapted either the *Framework* or the *NGSS* as standards for all P-12 students.

Engineering standards that include science

Two new documents are now available that provide learning goals in technology and engineering that are more extensive than those in the NGSS. The *Framework for P-12 Engineering Learning* (FPEL) (American Society for Engineering Educators [ASEE], 2020) specifies the knowledge, practices, and habits of mind that students should acquire by 12th grade. It was developed by a collaborative team of educators and researchers who conducted a Delphi study involving teachers, university professors, and other stakeholders to establish a consensus of what students should learn about engineering (Strimel et al., 2020). The document is aligned with the NGSS, but also goes beyond it: "As described in this framework, elementary engineering learning should integrate concepts from the NGSS, middle school engineering learning should enhance NGSS concepts, and high school engineering learning should extend beyond NGSS" (ASEE, 2020, p. 20).

Another initiative, the *Standards for Technology and Engineering Literacy* (STEL) (International Technology and Engineering Education Association [ITEEA], 2020), is a substantial revision of an earlier document that specifies standards and benchmarks, developed by a team of 30 educators including teachers, supervisors, college professors, industry representatives, and colleagues from affiliated professional organizations (Loveland et al., 2020). It is more similar to the NGSS in structure than the FPEL, since each benchmark begins with a verb to describe what students should be able to do to demonstrate their knowledge and capabilities, facilitating its use in curriculum development and assessment (Han et al., 2020). The STEL also includes several core ideas like those in the NGSS, such as engineering design, the wise use of natural resources, and the interdependence of science and engineering.

Although the NGSS fully integrates engineering, it is weighted largely towards science, whereas the other two documents are weighted towards engineering while acknowledging the importance of science. Although all three standards documents provide excellent guidelines for what students should learn about technology and engineering, they do not describe empirical research findings about what instructional methods and materials work for whom and in what situations. Providing that perspective is the purpose of the current landscape study.

Prior reviews of engineering education research

We identified five prior reviews of the broad field of engineering education research. Diaz and Cox (2012) conducted a systematic review of P-12 studies published between 2000 and 2011, with the aim of developing a "big picture" of the field. The authors selected, classified, and synthesized research studies and summarized the results. Jones et al. (2013) reviewed the broad field of technology education research over the previous two decades to establish directions for future research. Hynes et al. (2017) conducted a systematic international review of P-12 engineering education research spanning 2000 to 2015 to trace the historical development of the field, describe the current state of knowledge and practice, and support the development of theory, as well as identify new areas for exploration. The National Research Council [NRC] conducted two research reviews as elements of larger reports on engineering education. The first review (NRC, 2009) was conducted to examine the evidence for claimed benefits of engineering education, and concluded that "Overall, the review turned up limited evidence for many of the benefits predicted or claimed for K-12 engineering education. This does not mean that the benefits do not exist, but it does confirm that relatively few well designed, carefully executed studies have been conducted on this subject" (NRC, 2009, pp. 50–51). The second review (NRC, 2014), conducted to investigate the value of integrated STEM, found that "Research on the impact of integrated experiences on students' achievement, disciplinary knowledge, problem-solving ability, and ability to make connections between domains is not extensive, and concerns related to both the design of studies and the reporting of results hamper the ability to make strong claims about the effectiveness of integrated approaches" (NRC, 2014, p. 52). Since both NRC studies questioned the quality of study designs, it is reasonable to suppose that many research studies were not included due to a preference for some study designs over others.

The present landscape study goes beyond prior reviews by:

1) Including many additional studies.
2) Allowing for a wide range of study designs, including qualitative, quantitative, and mixed designs.
3) Including the following research reviews of subareas of engineering education: communicative literacies (Silvestri et al., 2021), argumentation (Wilson-Lopez et al., 2020), robotics (Anwar et al., 2019), flipped classrooms (Lo & Hew, 2019), engineering in the middle grades (Ganesh & Schnittka, 2014), engineering design processes (Crismond & Adams, 2012), systems and optimization (Silk & Schunn, 2008a), engineering skills (Petrosino et al., 2007), and use of Arduino microcomputers (Lee, 2020).
4) Focusing on questions that are of greatest interest to practitioners.

3.0 Methodology

Collecting studies

We conducted a series of literature searches using the EBSCO version of ERIC (Education Resources Information Center) database, using the search terms: "engineering education," "research," and "K-12 or primary school or elementary school or middle school or high school or secondary school," from January 2000 to June 2021. To facilitate easy access for a wide range of educators, we limited the search to documents that were in English and available in full via online access. All the studies we included were either available free online or via the Portland State University Library or interlibrary loan. We also examined reference sections of the papers in our growing collection for other potentially relevant studies. We reviewed all the papers whose titles suggested they might have useful empirical data.

Criterion for inclusion

Our criterion for selection for this review was that the studies provide data on what students know, can do, and/or can learn about engineering. Although we came across many interesting and valuable studies about teacher professional development, new curricula, and other topics, we did not include them if they did not provide evidence—derived from data on students—on which to base instructional decisions.

Research designs

Regarding research methods used by the studies we selected, we cast a wide net, accepting studies that ranged from randomized controlled experiments to quasi-experimental research designs to qualitative case studies. This approach is consistent with Grant and Booth's (2009) discussion of review typologies, which noted that "restricting studies for inclusion to a single study design such as randomized controlled trials…can limit the application of this methodology to providing insights about effectiveness rather than seeking answers to more complex search questions, for example, why a particular intervention is effective… In recent years, there has been a noticeable shift towards the inclusion of a wider range of study designs incorporating quantitative, qualitative and mixed methods studies" (p. 102).

Landscape approach

Although we initially intended to include all studies that fit our criteria, we soon realized that the number of studies was highly skewed to studies of robotics, with nearly as many papers in robotics as all other areas of P-12 engineering education combined. Since our purpose was a broad overview of the field of P-12 engineering education research, we decided on a selective rather than comprehensive approach. We included a review of 147 studies of robotics education (Anwar et al., 2019), but not each study on robotics, so it would not dominate our view of the field. We use the term "landscape" as a descriptive metaphor for this report, since our overview of the research is comparable to looking at a broad vista and noting the peaks, valleys, and obstacles navigated by travelers, rather than emphasizing the most heavily trafficked paths. The selected set of 263 studies ranges from the research reviews mentioned above, to quantitative investigations involving tens of thousands of students, to qualitative in-depth case studies of just a few participants. The studies included in the present landscape review are represented by publication year in Figure 1, which also illustrates the period of time covered by each of the prior reviews mentioned above.

Many of these studies have been developed with support from government agencies, while others have had support from private philanthropy. As shown in Figure 2, most of the research studies have taken place in schools, but a significant number have been conducted in out-of-school time (OST) learning environments. Most studies have focused on students at the middle and high school levels, but there is a rapidly growing body of work at elementary grades.

Sorting studies into categories

Once we determined that a study met our criterion, we summarized its purpose, method, and results, and assigned codes along five dimensions: (1) research methods, (2) venue (school versus out of school time), (3) student characteristics,

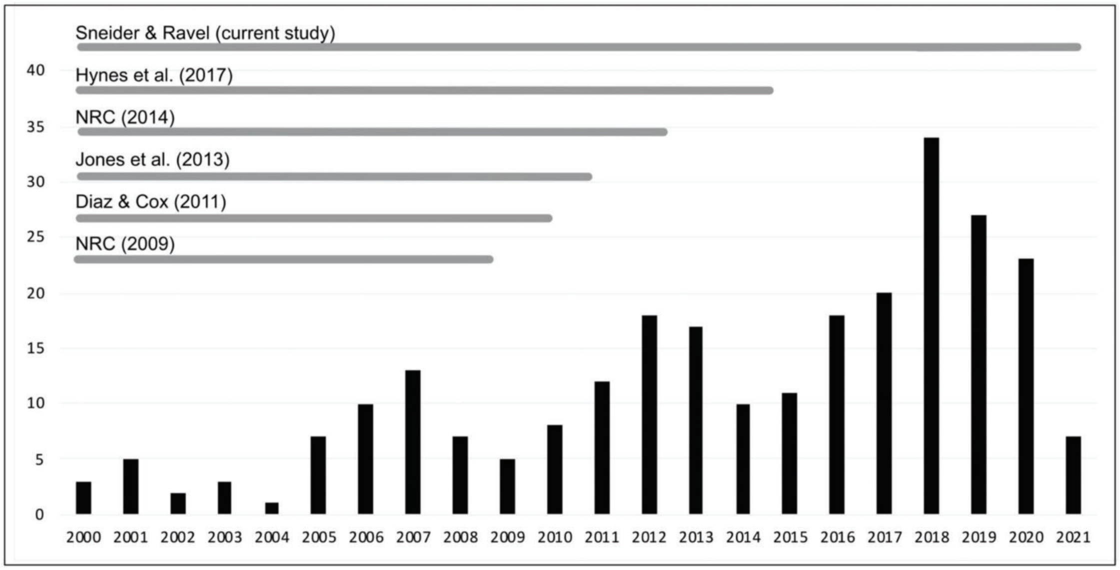

Figure 1. Black bars represent the number of studies included in the current review by year of publication. Gray bars indicate the span of years searched by prior engineering education reviewers.

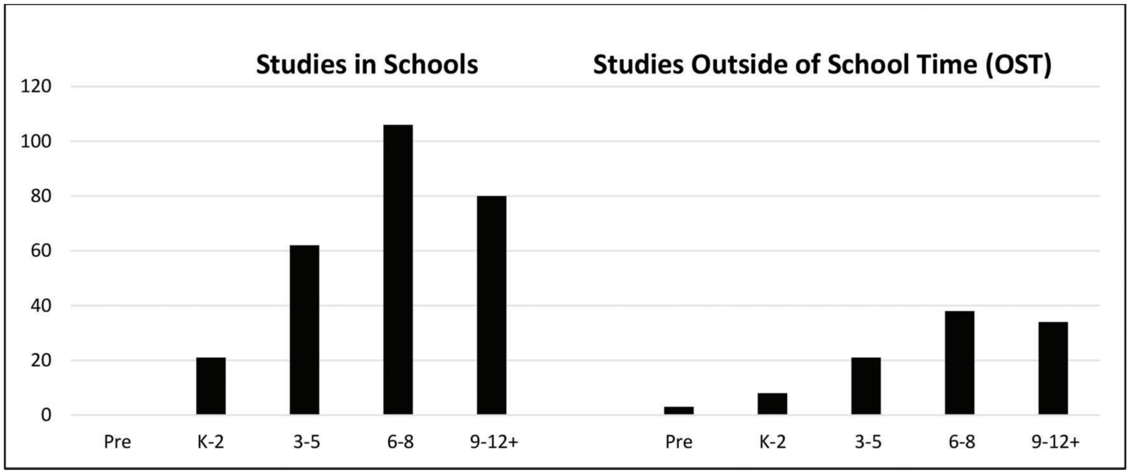

Figure 2. Number of studies included in the current review that took place in schools and outside of school time by grade level.

(4) purpose, and (5) student outcomes. The codes are listed in Table 1. Based on these codes we considered several ways to categorize the studies, keeping in mind our audiences. We decided on a set of ten categories that would provide a set of findings and claims having balanced usefulness across an audience of teachers, curriculum developers, and researchers.

Synthesizing findings

Our next task was to use an inductive approach to draw claims and findings from each category. Although many studies were quantitative, the descriptions of their purposes, methods, and results constituted qualitative data. The method we selected for analyzing those data in an authentic manner was grounded theory (Glaser & Strauss, 1967), in which "the researcher does not formulate any hypothesis in advance and tries to approach the research area with as few preconceptions as possible" (Hallberg, 2006, p. 141). The method has been modified many times since it was first proposed but remains "a useful research approach with capacity to manage the complex and continuously changing social world" (p. 148). Using this inductive method, we formulated a series of claims that we believed to be supported by the evidence from the studies in each category, and then summarized the claims in a single statement, which we refer to as a "finding." Following this inductive approach led to the development of ten findings organized by our research questions.

Limitations of this study

- This study is not a meta-analysis intended to draw definitive conclusions by pooling data from a large body of research. Rather, its purpose is to organize and summarize the accumulated evidence of students' current knowledge, capabilities and attitudes, effective instructional methods, and valuable outcomes that are of topical importance to both researchers and practitioners.
- This is not a comprehensive list of all research studies on P-12 engineering education. We emphasized the broad landscape of research rather than focusing on a few areas (such as robotics) where disproportionately large numbers of studies exist.
- As we collected and categorized studies, we came across investigations that our database searches had missed and added them to our review. Although we expect there are additional studies that would be useful to add, we believe that this set has sufficient breadth for sketching the broad outlines of the field of P-12 engineering education research at the present time.
- Findings and claims represent our *interpretation* of the body of literature. The *evidence* that supports the findings is the actual studies themselves.

Table 1 Codes for classifying research studies.

DIMENSIONS
Dimension 1: research design
Dimension 2: setting
Dimension 3: student characteristics
Dimension 4: purpose of study
Dimension 5: outcomes

D1 RESEARCH DESIGN
Review of research
Analysis of large datasets
Quantitative study
Qualitative study
Mixed methods

D2 SETTING
School
Outside of School Time (OST)

D3 STUDENT CHARACTERISTICS

Grade levels
Primary (P–2)
Elementary (3–5)
Middle (6–8)
Secondary/HS (9–12)

Gender
Gender gap
Preference by boys/girls
Support programs for girls

Race/Ethnicity
Black/African American
Hispanic/Latinx
Other minorities
Lower income
Special needs students

Location
Urban
Rural
Suburban

D4 PURPOSE OF STUDY

To gather information
Behaviors while designing
Compare beginners versus experts
Factors that influence interest
Technology and engineering literacy
Identify learning needs
Perceptions of engineers
Reviews of research studies
Understanding of materials

To test generalizable methods
Analyze engineering challenges
Argument-driven design
Assessment tool
Authentic tasks
Co-create curriculum with students
Cohesion (meaning making)
Community service
Engineering notebooks
Enrichment OST programs
Fail forward mindset training
Family programs
Fiction to inspire design
Flipped classroom
Girl-friendly materials
Hands-on activities
Making/tinkering
Mathematical modeling
Mentors
Role models
Mobile devices
Multigenerational workshop
Short workshops
Social justice
Structures and materials
Troubleshooting
Videos about engineers

To compare different methods
Abstract versus concrete
Competition versus cooperation
Design versus inquiry
Engineering versus traditional
High versus low ability
Placement of engineering activity
Sequence of activities
Short versus long treatment
Single sex versus co-ed

To test topical approaches
CAD/drawing
Environment/sustainability
Food technologies
Mathematical modeling
Medical/biomedical tech
Mobile devices
Robotics
Wearable/e-textiles

To test engineering units and curricula
DESIGNS
Engineering Is Elementary
Engineer Your World
Engineering courses
Engineering the Future
Project Lead the Way
SLIDER
STEM units and courses
Technovation
Visualizing Technology
WISE
Other extended treatments

D5 STUDENT OUTCOMES

Knowledge
Different engineering careers
Engineering concepts
Science and math concepts
Perceptions of engineers
Perceptions of learning
Perceptions of technology
Requirements to become an engineer
Knowledge of technology
Knowledge of the EDP
Knowledge of STEM integration

Abilities
Address real-world problems
Computational thinking
Computer programming
Create high-quality designs/products
Design abilities
Design portfolios
Design thinking
Feedback and iteration
Iterate and optimize
Math/data analysis abilities
Mechanistic reasoning
Science practice capabilities
Simulation skills
Social skills
Technical abilities

21st-century skills
Higher-level thinking
Reasoning with evidence
Creativity/idea fluency
Confidence/identity
Innovative
Resilient
Persistent
Self-directed learning
Teamwork/leadership
Empathy/mutual caring

Attitudes
Aspire to a STEM career
Appreciate the value of STEM
Confidence/self-efficacy
Environmental/sustainable views
Identity/agency as STEM learner
Technology and engineering interest
Motivation/identity

Behaviors
Attendance and retention
Engagement in engineering/STEM
Take elective STEM courses

4.0 Findings

We have identified the following ten findings in response to our research questions:

A. What are students' understandings, skills, and attitudes about engineering and technology?

FINDING 1. Students in the USA have narrow conceptions of technology and engineering.
FINDING 2. Developing interest in engineering at an early age is essential for later engagement.
FINDING 3. Girls and students from low-income families are less likely to pursue engineering.

B. What are effective methods of P-12 engineering education?

FINDING 4. Many generalizable methods of engineering education can be effective.
FINDING 5. Topical approaches focused on specific technological systems can be effective.
FINDING 6. Several engineering curricula have been found to be effective.
FINDING 7. Engineering education outside of school time [OST] has also been found to be effective.

C. What are the benefits of P-12 engineering education?

FINDING 8. Engineering supports learning of science concepts and abilities.
FINDING 9. Engineering builds 21st-century skills.
FINDING 10. Engineering increases STEM motivation and identity.

Each of the ten findings are supported by claims, which are justified by the evidence. Claims are denoted by numbers and letters (e.g., claims 1a, 1b, 1c, etc. support Finding 1). Table 2 lists all the studies, organized by the findings that they support. Studies that support more than one finding are listed under each one. This section provides brief summaries of one or more studies as examples of the kind of evidence that is provided by the research literature in support of the claim. The examples represent only a fraction of the studies listed in Table 2. Given the length of Table 2, we have included at the end of the narrative.

RESEARCH QUESTION A. What are students' understandings, skills, and attitudes about engineering and technology?

FINDING 1. Students in the USA have narrow conceptions of technology and engineering

Several studies based on large datasets, with support from qualitative studies that have examined students' ideas in greater depth, have converged on this finding. Achieving the twin goals of engineering and technology literacy for all and a stronger engineering workforce requires helping our students understand that they live in a world surrounded by technology that is shaped by engineers. Thirty-one studies contribute to the claims that support this finding.

1a. Limited conceptions of technology are widespread among children and adults

Figure 3 combines the results of several studies, based on pre–post tests of almost two thousand elementary students. The data support the conclusion that before instruction in one or more of the EIE units, 90% or more have a narrow view of technology, whereas after instruction, the majority of students are able to apply the broader definition that technology includes all of the ways that people have modified the natural world to meet their needs (Cunningham, 2018).

Telephone surveys of 1,000 adults conducted by the Gallup organization (Rose & Dugger, 2002) concluded that "Many Americans view technology narrowly as mostly being computers and the Internet" (p. 1). A subsequent study of 800 adults (Rose et al., 2004) confirmed the earlier findings, leading to the conclusion that narrow conceptions about the nature of technology held by elementary school children change little over time without instruction.

1b. Students in the United States have limited understanding of what engineers do

Cunningham (2018) reported on a series of studies using a questionnaire called "What Is Engineering?" A summary of results from more than 30,000 elementary school children revealed that before instruction children tended to focus on things having to do with electronics, cars, or buildings, such as "install wiring," or "repair cars." Open-ended responses included statements such as, "An engineer is a person who works on different things like engines and electronics" (p. 13). After instruction in a unit of the EIE curriculum, "Students were more likely to focus on the type of work…such as 'improve bandages,' 'think of ways to clean air,' and 'figure out how to package bottles so they don't break'" (p. 128).

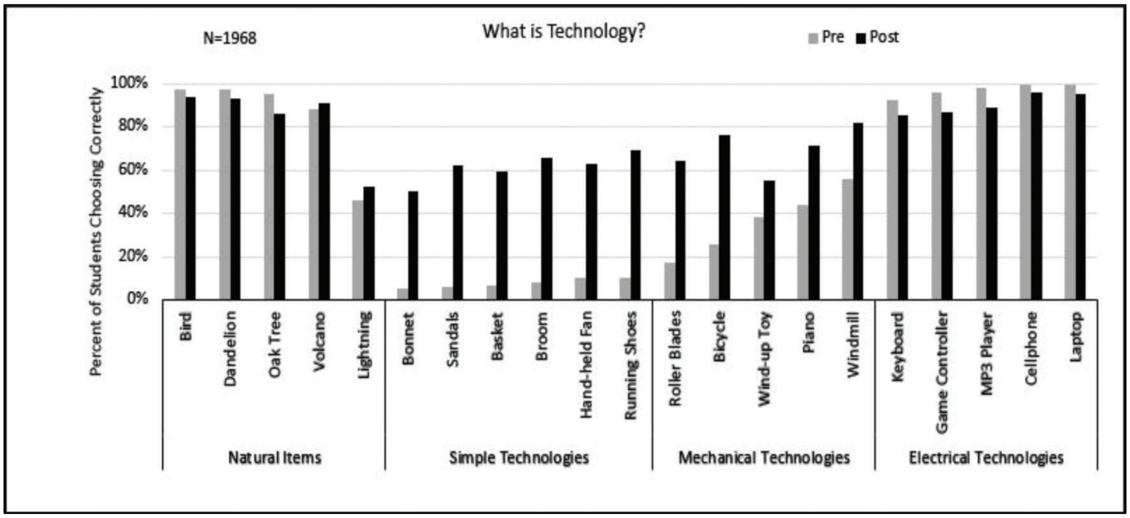

Figure 3. Students' conceptions of technology (adapted with permission from Cunningham, 2018, p. 127).

Ganesh (2011) reported a study of 116 middle school students, primarily Latinx girls, who participated in an afterschool engineering program. The students took the Draw an Engineer Test at the beginning and end of the year. Prior to the program, students primarily thought of engineers as males who build and work with engines. Only two students drew engineers as female, one of whom fixed cars. At the end of the year, students drew pictures that represented engineers as people who can be female or male, design products that people need, and go to college. Studies of high school students have also revealed a narrow conception of engineering (e.g., Anderson & Gilbride, 2003a,b; Anderson et al., 2006; Verdín et al., 2018), similar to the findings of elementary and middle school students cited above.

Narrow views of engineering are not shared by students in all countries. Köycü and de Vrie (2016) asked a sample of 7,591 students, aged 15–18 from 39 countries, to draw concept maps of what they thought engineering was about and respond to 32 concept items about engineering. A factor analysis revealed that most students' views were accurate, invoking an active process in which engineers researched and developed new products and materials, and were also involved in marketing. When the students were asked whether engineering is a "male profession," 74% of the males and 81% of the female students clearly indicated that women are just as good as men were in engineering. The survey also included attitudinal items revealing that most students in the study had a positive view of engineering.

These and other studies show that although the great majority of students in the United States initially have a narrow understanding of technology and engineering, they can deepen their understanding with instruction.

1c. Fewer than half of students in the USA are proficient in engineering and technology literacy

The National Assessment of Educational Progress in Technology and Engineering Literacy (NAEP TEL) is a computer-administered assessment that measures problem-solving abilities related to design and systems, the use of digital tools for collecting and communicating information, and students' understanding of issues related to technology and society. These capabilities are assessed through a variety of means, including online scenarios in which students develop solutions to real-world problems (NCES, 2019). The NAEP TEL was administered to a nationally representative sample of 20,500 eighth-grade students in 2014 and again to 15,400 eighth-grade students in 2018. In 2018, 46% of students scored at or above the proficient level on the NAEP TEL, up from 43% in 2014.

Similar results were obtained for 15-year-olds on an assessment of collaborative problem solving by the Programme for International Student Assessment (OECD, 2017). Administered to about 540,000 students in 35 OECD countries and 37 partner countries, students interact with computerized simulations to solve a problem. Students in the highest two (of four) proficiency levels can perform multistep tasks that require integrating multiple pieces of information. Some 43.5% of students in the USA scored in the top two proficiency levels, which is below Japan (58.4%), Korea (52.0%), Finland (49.6%), Canada (49.5%), Estonia (49.4%), New Zealand (49.0%), Australia (48.9%), and Germany (45.1%) and above 27 other countries.

1d. Students are limited in their understanding of design processes

Crismond and Adams (2012) searched more than 170 peer-reviewed design journals and identified several hundred articles that compared beginning designers with informed designers. For example, they found agreement among several studies that beginning designers expect the design challenge to be a straightforward, well-structured problem, which can be solved immediately. In contrast, informed designers start by exploring the design challenge as fully as possible to be sure they are solving the right problem.

Crismond (2013a) published an accessible overview of the findings from the above study for a teacher audience, organized by the eight practices of science and engineering from the NGSS with tips for helping students overcome their difficulties. For example: "Beginning designers sometimes resist requests to generate multiple solutions to a challenge… This habit, known as idea fixation, involves the inability of designers to see new ways of using objects they are exposed to and a premature commitment to a particular design solution. Brainstorming can help designers avoid such fixation. If students can think of three or more viable solutions, then it is harder (although not impossible) for them to fixate on any single plan" (p. 53).

To gain insight into the factors that influence students' design capabilities, Bartholomew et al. (2018) developed a tool for judging students' reasoning processes as they were involved in an open-ended design task. The tool enabled separate scores for prototype designs and design portfolios in which students documented their design process. Bartholomew and Strimel (2018) reported on use of the tool with 706 middle school students, who worked in small groups over five class periods. The researchers found that students were familiar and comfortable with and receptive to open-ended design problems and enjoyed working through them. Of the variables tested, the only significant correlations with design capabilities were maturity ($p < 0.05$), self-reported experience working with digital technologies ($p < 0.01$), and how often students indicated they solved open-ended problems in school ($p < 0.01$). An interesting result is that younger students designed better products, but older students produced better portfolios.

Implications of Finding 1

Finding 1 is essentially a snapshot of the status of engineering education in the United States. Engineering is at the heart of the objects, processes, and technological systems that we interact with daily. Yet, the vast majority of students in the USA have a narrow conception of technology as limited to electronic systems, such as televisions, cell phones, and computers, and of engineers as the people who work primarily with machinery, such as repairing cars and constructing buildings. These conceptions are unlikely to change without instruction. Also, a national assessment shows that most students in the United States are not proficient in engineering and technology literacy—capabilities needed for citizens and workers in modern society. The implication of these findings is that curriculum and instruction at all levels needs to be intentional about helping students become aware of the technologies that surround them, the purpose of engineering in creating and improving the technological world, and the methods that engineers use to solve problems and meet people's needs. While with structured exposure students can readily learn and value the purpose and practices of engineering, implementation is progressing slowly. In a national sample of about 10,000 teachers, the percentage who reported emphasizing engineering was 8% of elementary teachers, 10% of middle school science teachers, and 5% of high school science teachers (Banilower et al., 2018, p. 109).

FINDING 2. Developing interest in engineering at an early age is essential for later engagement

This finding is based on 15 studies that have investigated STEM interest to determine how it changes over time, and the extent to which early interest leads to STEM careers.

2a. Early interest is a strong predictor of future career

Tai et al. (2006) analyzed data from the National Education Longitudinal Study (NELS), which collected data from 24,599 eighth-graders in 1988 and followed up with the same individuals in 1990, 1992, 1994, and 2000. At the end of the study 3,359 participants, then age 25, remained in the sample. NELS data include mathematics and science achievement tests that were administered in the first three surveys of data collection, when students were mostly enrolled in the 8th, 10th, and 12th grades, as well as school transcripts and self-report surveys of activities, interests, and aspirations. The researchers found that students who expressed interest in STEM careers in eighth grade were 3.4 times more likely to complete a four-year baccalaureate degree in physical sciences or engineering than those who did not express STEM interest in middle school. Mathematics achievement was also an important predictor. However, an average mathematics achiever with a science-related career expectation in eighth grade had a higher probability of earning a four-year degree in physical science or engineering than a high mathematics achiever with a nonscience career expectation (i.e., 34% versus 19%).

The finding that eighth-grade interest in STEM has long-term effects was confirmed by Sadler et al. (2012) who conducted a retrospective study of 6,860 undergraduates in a nationally representative sample from 34 two- and four-year colleges. The survey asked students about their career interests at various points in their lives. They found that at the end of high school the single most important factor (in aspiring to a STEM career) was interest at the start of high school.

2b. Most students maintain their interests in technology and engineering through middle school

The great majority of studies on students' attitudes and interests have generally asked students how much they "like science." A different approach was taken by Falk et al. (2016a, b) who surveyed 106 students in a low-income urban community, starting when they were in fifth grade and following them over four years. Questions on the survey were not about "science" in general, but rather about specific science- and engineering-related activities. Although the researchers found the expected decline in science interest, it was only attributable to about 25% of the sample. For about a third of the students, science and math interest remained high and interest in technology/engineering *increased*. Significant predictors of STEM interest turned out to be parental attitudes ($p < 0.001$), science activities ($p < 0.01$), and opportunities to engage in technology/engineering activities ($p < 0.001$).

Implications of Finding 2

To increase the number of students who pursue engineering as a career goal, increasing their interest no later than middle school is essential. The implication of this finding is that prior to high school, instruction should prioritize engagement and encourage positive attitudes about engineering, even above conceptual and cognitive skills. It is encouraging that many studies have found that engineering activities are inherently motivating, and one study (Falk, 2016a,b) has even shown that unlike students' interest in science, which tends to decline over the middle school years, interest in technology and engineering increases.

One of the most important takeaways from this landscape study is that *interest* is the critical factor, not aptitude. This is very encouraging as an actionable direction for improving engineering education.

FINDING 3. Girls and students from low-income families are less likely to pursue engineering

While the rationale for integrating engineering into science education emphasizes its value for *all youth* to be able to understand and apply the structured problem-solving process of engineering, inequities persist. As documented in the most recent *Science and Engineering Indicators* report (National Science Board & National Science Foundation, 2020), reaching girls and students from low-income communities with effective programs so that they can come to recognize themselves as a person who can engineer solutions to problems continues to be an urgent need. Sixteen studies contribute to the claims that support this finding.

3a. Far fewer girls than boys express interest in engineering and those who do face obstacles to pursuing their interests*

As mentioned previously, fewer than half of students in the USA are proficient in engineering and technology literacy as measured on the NAEP TEL. However, on both the 2014 and 2018 assessments girls performed significantly higher than boys (NCES, 2019). Nonetheless, most are far less interested in engineering as a potential career than boys.

Sadler et al. (2012) collected self-report surveys about STEM interests from 6,860 college students from a nationally representative sample of colleges. The survey asked students about their career interests at various points in their lives. At the start of high school, 39.5% of males and 15.7% of females reported career interests in STEM. During the high school years, the percentage of males interested in a STEM career remained stable (from 39.5% to 39.7%), whereas for females it declined (from 15.7% to 12.7%). Males interested in STEM careers were mostly drawn to engineering whereas females interested in STEM careers were more attracted to medicine and health.

Moote et al. (2020) reported similar findings in a large survey of students in England, including 9,319 students aged 10–11, and 13,421 students aged 15–16. The researchers found that the most important factor related to career aspirations in engineering is gender, and the widespread belief that engineering is for men only starts early. "The association of engineering with masculinity is evident in aspirations from age 10" (p. 34).

Several researchers have attempted to determine why girls and students of color are less likely to express an interest in engineering than boys. Maltese and Cooper (2017) used self-report surveys from 7,970 college students to examine gender differences in STEM pursuits. They found that self-driven interest was especially important for males, while females relied more heavily on support from others. Parental attitudes were especially important. They found that "a significantly greater percentage of females reported that their parents were not supportive of their STEM interests" (p. 8).

3b. Students of color and from low-income families face numerous obstacles in pursuing engineering

On the 2018 NAEP TEL, the percentage of students who scored at or above the proficient level was much lower for students from schools with a higher percentage of eighth-graders receiving support from the National Student Lunch Program (29%) than students from wealthier communities (61%). Since a much higher percentage of Black and Latinx students (44% and 45% respectively) come from communities of poverty, compared with white students (8%) (McFarland et al., 2019, p. xxxii), the needs are especially great for students of color who may aspire to a career in engineering. Even if

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*Readers are asked to interpret references to "boys and girls" as including non-binary students.

these students manage to maintain good grades and obtain scholarships, they still face social difficulties of coping in large classes with few students of color at colleges and universities with an even smaller percentage of Black and Latinx professors (Bonner, 2019, pp. 14–15).

The obstacles are especially great for female students of color from low-income families. Bystydzienski et al. (2015) reported on a three-year afterschool program for 131 high-achieving female students beginning in tenth grade and following them through college. Two-thirds were from low-income families. Although 82% of the participants reported that they knew little or nothing about engineering before the program, by the second year of the study more than half were seriously considering an engineering career. However, interest in engineering was not sufficient for lower-income minority women to pursue engineering in college. Their decision not to pursue an engineering career was not due to their lack of academic preparation or interest, but to a lack of financial resources and social support for engineering, as well as fears of failure. The percentage who enrolled in engineering in college was just 21%.

Implications of Finding 3

The barriers faced by girls, students of color, and all students from low-income families are well known, as evidenced by the large number of studies we examined that focused on these groups. The challenge to the field of engineering educators is to develop insights into the root causes of these barriers and address those that can be addressed though engineering education. Fortunately, many of the studies we reviewed have succeeded in helping girls, students of color, and students from low-income families develop interest, knowledge, skills, and career aspirations related to engineering. Seventy-five of the studies in our sample focused on gender issues and 48 studies involved primarily students of color and from low-income families. These studies are identified with footnote markers "*" and "†" in Table 2. We provide examples of some of these studies throughout this landscape review and synthesize relevant findings in Claim 10c.

RESEARCH QUESTION B. What are effective methods of P-12 engineering education?

FINDING 4. Many generalizable methods of engineering education can be effective

Finding 4 is based on studies of potentially transferrable methods that lend themselves to a variety of engineering units on various technologies. Findings from these studies contribute valuable information for curriculum development. Ninety-eight studies contribute to the claims that support this finding.

4a. Certain broad guidelines can help increase students' engineering motivation, knowledge, and skills

Sadler et al. (2000) developed several engineering and science middle school units that were tested in schools nationwide with 457 students. The researchers used a variety of tools to monitor student learning, including classroom observations, student interviews, and two types of pre–post tests: selected-response subject matter tests with common preconceptions as distractors, and open-ended pre–post tests of students' abilities to identify variables and generate hypotheses, create and troubleshoot experiments, and interpret data graphically. This study is one of the first to identify the value of what Dasgupta (2019) refers to as a "sub-optimal design," which is a simple construction to engage students' interest and develop skills, but that performs at a basic level from which students can improve significantly. Student teams are then able to use a variety of creative ideas to dramatically improve the performance of the device. However, to ensure that students develop positive attitudes, several other criteria are necessary. Students must clearly understand the goal of the activity—what specific measurable test will reveal improvement. Moreover, they must be able to utilize feedback that results from tests in which students can observe how well each other's designs perform. Also, opportunities for teams to test their designs and share results, then redesign based on the best ideas, was found to be an especially productive approach to increasing STEM motivation and identity.

Crotty et al. (2017) worked with 48 grade 4–9 teachers from three school districts who developed their own units in which engineering was integrated with science or mathematics. They tested their units during summer camps and then taught the unit during the following academic year. The teachers kept daily logs of their teaching. The logs were coded to identify different ways that the 48 teachers integrated engineering into their science units. Different approaches to integration served as the independent variable of the study. The dependent variable was student scores on pre–post achievement tests of engineering content. A total of 2,530 students completed the pre–post tests. Based on their significant findings ($p < 0.001$) the researchers concluded that "when engineering is introduced at the beginning of the unit to provide context for the learning…student achievement gains with engineering assessment items are greater than when engineering is incorporated only at the end of the unit" (p. 1).

4b. A number of specific methods have been found to increase students' engineering design capabilities

To help students learn to define problems, Watkins et al. (2014) used fiction to engage fourth-graders in formulating and solving problems encountered by characters in a fictional story. The researchers recorded videos and analyzed students' conversations. They found that rather than treating problems as straightforward, as expected based on prior research studies, students demonstrated promising beginnings of developing a better definition of the problem. A similar study was conducted by Portsmore et al. (2012), also with fourth-graders, noting that the students were capable of reasoning and decision-making about their design.

To aid in developing design solutions, MacDonald et al. (2007) conducted a study in a grade 3–4 classroom with 13 girls and 9 boys to examine the effects of explicitly teaching drawing. About four hours of instruction per week were provided over ten weeks. Students studied simple machines and drew and built vehicles and devices that moved. Data were collected through observations and field notes as well as audio recordings with small groups of children. Two main types of interventions were found to be helpful: teaching drawing separately through an art unit and explicitly integrating drawing into the design technology task. The researchers concluded that it is important to have the students make design drawings before, during, and after they build, just as professionals do.

Xie et al. (2018) reported on two pilot studies of a computer-aided design (CAD) unit to help students make science-based design decisions. The first study involved 27 ninth-grade students in an urban high school. After a year of development, the improved CAD program was tested again with 37 high school students enrolled in an online summer course. Data included pre–post assessments of science and engineering, process data from the software, students' designs, and an exit survey. The improved intervention resulted in significant pre–post learning gains for students who used the CAD treatment ($p < 0.00015$), with a very high effect size (Cohen's $d = 0.954$).

Implications of Finding 4

One of the most important findings of this landscape study is that there are many *generalizable* methods of engineering instruction that increase the likelihood of successful outcomes and can be applied in various contexts. These include starting a science unit with an engaging challenge rather than using engineering as a capstone at the end of a unit. An especially helpful approach is to provide students with a simple suboptimal design, which provides lots of room for improvement, coupled with clear measurable goals and several opportunities to test and iterate their designs. Other useful approaches include drawing, sketching with paper and pencil, sketching with CAD, and using fictional stories to engage students in designing solutions to problems encountered by the protagonists. Several methods have also been found to help students increase specific design capabilities. Those mentioned in this section include problem definition, generation of design solutions, and science-based design decisions; however, there are many others.

FINDING 5. Topical approaches focused on specific technological systems can be effective

Similar to science pedagogy where a focus on *natural phenomena* is used to spark interest and engage students in the inquiry process, a focus on real-world *technological systems* can be used to engage students in the world of engineering and the design process. Forty-two studies contribute to the claims that support this finding.

5a. Instruction on technological systems has been found to increase interest and engagement

Robotics is the most frequent technological system in P-12 engineering education research literature. Anwar et al. (2019) conducted a rigorous systematic review of 147 studies on the educational effects of P-12 robotics programs in both formal and informal settings. The analysis revealed that educational robotics can "help students in a variety of ways, including the understanding of abstract concepts, providing them with a feedback-oriented learning environment, giving them a collaborative working environment, and opportunities to work and explore solutions to real-world problems" (p. 29). The researchers identified an especially interesting group of educational robotics studies that responded to the needs in Finding 3 above: "Acknowledging the lack of ethnic, socioeconomic, and gender diversity in STEM, 16 studies focused on increasing the proportion of women and minorities in STEM professions. Many underrepresented students are also disposed to having a strong aversion to STEM (due to misconceptions regarding the nature and relevance of the fields). So, researchers and educators are finding it beneficial to incorporate certain cultural, social, and aesthetic elements into their designed studies" (pp. 29–30).

Although not as common as robotics, several studies investigated bioengineering systems, such as prosthetic arms (High et al., 2010), model lungs (Hmelo et al., 2000), and artificial hearts (Foster & Ganesh, 2013). Monterastelli et al. (2008) conducted a study in which 86 high school juniors were challenged to design, build, and test a device to remove impurities from simulated blood, while using a minimum amount of dialysate and minimum cost. A pre–post test showed significant gains ($p < 0.05$) in conceptual understanding of biological concepts (e.g., dialysis, diffusion, concentration). Attitude surveys showed that about half of the students increased their interest, attitudes, and confidence levels in science and engineering.

One of the studies we reviewed demonstrated that *within* a given technological system, the specific examples selected for instruction make a difference in student engagement. Hutchinson et al. (2011) presented four manipulative tasks—all on nanoscale science and engineering—to 164 rural and 96 urban middle and high school students. The students were given self-report surveys and 40 students received interviews. The students were most interested in topics and phenomena that related to their everyday lives, were novel, and involved manipulatives. Conversely, they were least interested in topics and phenomena they viewed as irrelevant to their lives, they believed they had learned previously, and in which they were not actively involved.

5b. Girls and boys have both different and common interests in specific technological systems

Kelly et al. (2007) reported on Techtronics, a 40-hour afterschool program consisting of four modules taught by university students to sixth- and seventh-graders with strong participation by girls and students of color. Thirty-nine students were given post-surveys at the end of each module. Boys preferred programming, while girls preferred biomedical engineering. The researchers concluded that "these findings suggest the importance for both genders of having activities that allow students to work directly with tools to construct their own projects and inclusion of medical/human applications as important features for engaging both male and female middle school students" (p. 12.285.17).

Jackson et al. (2021) involved seven ninth-grade teachers and their students ($N = 361$) in a study that compared students' responses to engineering robotics using traditional rigid robots versus soft robots made from materials such as silicone and fabrics. Twenty-two classes were randomly assigned to one of the two conditions. Measures were self-report retrospective pre-tests with several subscales. A main effect showed positive gains ($p < 0.001$) for interest, general self-efficacy, experimental self-efficacy, tinkering self-efficacy, and design self-efficacy. The only significant gender difference was on tinkering self-efficacy, which is interpreted as comfort with the manual aspects of engineering, such as assembly, disassembly, manipulating devices, and similar tasks. Boys performed significantly higher than girls ($p < 0.05$) in the rigid robotics condition, but not in the soft robotics condition. A significant interaction effect ($p < 0.05$) provided evidence that "engagement with the soft robotics experience led to an increase in tinkering self-efficacy for girls, which relieved gender differences in that element of engineering perception" (p. 153).

Buchholz et al. (2014) reported on an ethnographic study of middle school students engaging in engineering challenges to design electric circuits using e-textiles, involving the use of conductive thread, fabric, and needles. Given their comfort level with the materials, girls quickly assumed leadership in co-ed teams. The researchers concluded that "The results from our work highlight the importance of attending to the socially constructed and gendered histories of materials. We found that the girls took up sewing and crafting practices more often and for longer periods than the male members, and mediated actions that enabled the girls to lead and determine the project's next steps" (p. 17).

Güdel et al. (2019) conducted a self-report survey with 480 middle school students. The researchers found that there were marked gender differences in interest and self-efficacy, especially regarding *using and repairing technical tools* and *understanding technological processes*. However, there were no gender differences in *designing in the context of sustainability.*

Implications of Finding 5

Unlike studies in the previous section, which focused on generalizable methods, studies in this section are too closely tied to specific technologies to generalize to other topics. However, they are generative of ideas for expanding the variety of technological systems typically used in engineering education. For example, although robotics is by far the most researched topic, other topics, such as biomedical systems, energy generation, environmental engineering, and sustainability, are also motivational, and provide natural linkages to science and societal issues. Especially valuable have been studies of technologies that are of equal interest to boys and girls. An important and actionable observation is that choice of a technological system with direct relevance to students' lives will have higher student interest.

FINDING 6. Several engineering curricula have been found to be effective

For this landscape study, we define "engineering curriculum" as a set of instructional methods and materials for teaching engineering, usually involving several different technological systems and several units spanning school quarters, semesters, or an entire year. Sneider's (2015) three-volume compendium provides overviews of 40 engineering curricula, some of which have been the target of many research studies, and others that have not been studied at all, except during initial development. Forty-eight of the studies in our sample measure the impact of specific curricula. Nearly all these studies show that students succeed in learning concepts and skills in engineering, and often in science and mathematics as well.

6a. At the elementary level, engineering activities help to improve science outcomes

EIE is a series of more than 20 units for grades K-5 that engage students in hands-on engineering challenges that complement common topics in the science curriculum. The findings of more than 100 studies of EIE have been summarized in a book (Cunningham, 2018) chronicling EIE's development and wide dissemination. According to the research summary in Chapter 7, students engaged in one or more units of EIE: (a) learned about technology and engineering; (b) learned basic engineering concepts; (c) improved their understanding of key science concepts; and (d) became more interested in engineering. Also, students from groups underrepresented in STEM showed increased interest and achievement. In one of the studies, Cunningham and Lachapelle (2007) compared the results of pre–post tests of 5,139 students who participated in two of the EIE units with 1,827 elementary students who did not participate in the units. Analysis of the data showed that students participating in EIE performed significantly better ($p < 0.0001$) than control students on nearly all science questions in the post-assessments. The researchers concluded that engineering education is worth the extra time because it results in equivalent or increased science learning, in addition to learning about engineering.

Wendell and Rogers (2013) studied the impact of Science Through LEGO™, which integrates engineering design activities into the science curriculum. In the first year of the efficacy study, 12 elementary teachers taught science with their school's or district's status quo curriculum. In the second year, they taught the same science content with a new engineering design-based curriculum that incorporated LEGO™ design challenges. In both years, students completed pre- and post-tests on science content and attitudinal surveys. Students using the LEGO™ engineering curriculum achieved significantly greater gains ($p < 0.0001$) on science content tests than did their peers using the status quo curricula.

6b. At the middle school level, studies show that STEM integration has had beneficial effects

Puntambekar and Kolodner (2005) conducted two studies to improve aspects of a middle school curriculum called Learning by Design. In Study 1 the researchers tested the effectiveness of design diaries to scaffold eighth-graders in a design activity. They scored diaries from 109 students and observed classes. In Study 2 researchers refined the design diaries by adding prompts, and sequenced activities to provide more interactions. Data from the second study showed significant improvements (at the $p < 0.001$ level) in students' abilities to justify their designs and explain the science.

Siverling et al. (2019) reported on the impact of a seven-unit curriculum on students' abilities to argue from evidence in engineering. The curriculum was developed by a team of upper elementary and middle school teachers and researchers. While the science content differed for each unit, they all included motivating and engaging engineering challenges to which students could apply concepts from state science and mathematics standards, as well as data analysis and measurement. They were designed to help students develop teamwork and communication skills, and to learn from failure. The researchers collected data from seven upper elementary and middle school classrooms in three school districts using audio recordings of student teams to examine how students used evidence-based reasoning to justify their designs. The results of their qualitative study demonstrated that "students integrated content from all four STEM disciplines when justifying engineering design ideas and solutions, thus supporting engineering design-based STEM integration as a curricular model" (p. 457).

Kanter (2009) evaluated the impact of a middle school science curriculum (called "I, Bio") of about 10 weeks' duration, designed to engage students in learning life science concepts through engineering design activities. The researcher tested the curriculum with the assistance of 12 middle school teachers, who taught the curriculum in 37 classrooms ($N = 652$), including a high percentage of students of color and from low-income families. Students significantly improved their meaningful understanding of science from pre- to post-tests ($p < 0.001$).

Engineering by Design is a PreK-12 series of curriculum materials, ranging from flexible introductory units that span 1–6 weeks at the elementary level, to 18-week courses at the middle school level, to a series of full-year (36-week) courses at the high school level, intended to provide a solid precollege foundation in engineering design and applications. Jackson et al. (2016) conducted a study of one 16-week course at the middle school level to measure the impact of the course on middle school students' perceptions of their design abilities and creative thinking. Participants were 1,570 students enrolled in the course in several middle schools across the United States. Students responded to self-report surveys online before and after engaging in the unit. Analysis of the data revealed statistically significant gains ($p < 0.001$) on both measures of design abilities and creative thinking.

6c. At the high school level, several engineering curricula have been shown to be effective

PLTW is a multiyear sequence of high school engineering courses. Tai (2012) reviewed 30 studies of PLTW with data on student achievement. The review concluded that "Our findings from this review show the strong, positive impact of PLTW on mathematics and science achievement as well as other important factors. …PLTW offers a pathway to prepare and motivate students to enter careers in science and engineering, which are both stable and high paying" (Tai, 2012, p. 6).

Several studies also examined the effects of UTeach Engineer Your World (EYW), a full-year high school course developed by the UTeachEngineering program at the University of Texas-Austin, in which students apply science and math to solving problems. A series of studies reported on the integration of engineering with math and science content, beginning with Farmer et al. (2012) who reported the results of a pilot study with 230 high school students. The researchers found that there is a need to explicitly teach data analysis methods and to start the project with hands-on activities, so it is more engaging. Studying the impact of the updated course, Berland et al. (2014) administered questionnaires on the engineering design process to 179 EYW students and interviewed 16. The study found that students better understood and valued those aspects of engineering design that were more qualitative (e.g., interviewing users, generating multiple solutions) than the more quantitative aspects of design in which students apply math and science to their designs. Berland and Steingut (2016) analyzed self-report surveys from 113 students who had taken EYW and concluded that it is important to help students recognize the value of each of the STEM domains by explicitly discussing the ways in which math and science are necessary.

Engineering the Future (ETF): Science, Technology and the Design Process, is a full-year course that was developed by the Museum of Science Boston in the early 2000s for high schools in Massachusetts, which was one of the first states to adopt a strong engineering strand in its science standards. The course was later modified to support NGSS and is now used nationally. During an early pilot study, Wainwright (2007) administered assessments of students' understanding of electrical circuitry to 54 students and interviewed seven. The researcher found that many of the students retained misconceptions and recommended improvements. Yao (2006) evaluated two units of the improved course that spanned one semester of ETF with the assistance of 11 teachers and 498 high school students. Pre–post tests revealed that students significantly improved their ability to answer engineering design questions from both units ($p < 0.001$). Also, students significantly improved their ability to explain electrical phenomena and improved their level of confidence in explaining electric circuits.

Implications of Finding 6

As described in the Context section of this landscape review, new science education standards include engineering at the same level as science. Consequently, many curricula have been developed with a primary aim of teaching science (and in some cases math as well) through design challenges. Other curricula have engineering as the primary goal, with science playing a supporting role. Still others provide a balance across the STEM fields. The great majority of these studies have found positive impacts with respect to students' increased knowledge and skills in both science and engineering, as well their understanding of technology and engineering, their attitudes about the value of engineering to society, and, in some cases, a willingness to consider engineering as a potential career.

FINDING 7. Engineering education Out of School Time (OST) has also been found to be effective

The studies that we reviewed took place in afterschool or summer programs in a wide range of venues, from school buildings after 3 PM, to museums, libraries, and summer engineering camps. Although attendance in OST programs is voluntary, and they are often taught by facilitators with lesser experience in teaching or formal STEM education, these venues are conducive to extended design projects since facilitators do not have to worry about covering required topics or giving tests. While in many cases availability, cost, and transportation are barriers for students from low-income families, public support made it possible for 3.3 million children from low-income families to attend a summer program in 2019, an increase from 33% in 2013 to 38% in 2019 (Afterschool Alliance, 2020). Sixty studies contribute to the claims that support this finding.

7a. Role models and mentoring can be very effective

Campo et al. (2009) reported on an outreach program in which volunteer undergraduates from Rice University went to local high schools at least once per week to mentor students in engineering after school over 5–7 weeks. More than 90% of the mentees were Latinx and 3% African American. A total of four cohorts had participated at the time of the study. The number of participants in each cohort ranged from 23 to 34. A large proportion of the volunteer mentors were themselves members of underrepresented minority groups, enrolled in engineering. Data from attitude surveys and pre–post physics tests showed that the mentorship program was very successful in improving students' understanding of physics, knowledge of what engineers do, and knowledge of what it takes to prepare for and survive in college.

Ilumoka et al. (2017) reported on STEM UP, a program designed to attract more girls and women to engage in engineering through four components: (1) an industry-based mentoring program featuring practicing female and minority STEM professionals as mentors; (2) afterschool, classroom-based, hands-on STEM workshops involving construction and testing of real-life engineering subsystems; (3) a five-week summer day camp involving exposure to hands-on STEM projects; and (4) parent/guardian workshops designed to inform and empower parents in their efforts to support their children's success in STEM. The program served primarily Hispanic and African American middle and high school students and their caregivers. Results show that students who participate in industry-based mentoring are 55% more likely to demonstrate interest and confidence in STEM subjects and 25% more likely to show greater interest in pursuing STEM careers.

7b. OST programs can have long-term impacts

Godwin et al. (2016) analyzed data from 15,847 college students who participated in the Science, Technology, Engineering, and Mathematics Talent Expansion Program and took a survey about their career intentions and prior experiences. The findings indicated that out-of-school experiences increased the odds of students choosing engineering disciplines. Experiences traditionally stereotyped as masculine and more often reported by men, such as tinkering, increased the odds of choosing engineering disciplines with higher representation of men. However, some experiences equally reported by men and women, such as mixing chemicals or engaging with chemistry in the kitchen or talking with friends or family about science, predicted higher odds of choosing engineering disciplines with higher representation of women (i.e., chemical, biomedical, and environmental engineering.)

Vega (2006) reported on Technovation, an afterschool program "designed to reduce the gender gap in computer science degrees and related professions by providing young women with an accessible, entry-level coding experience, scaffolded by peer and mentor support, and training in entrepreneurship and business leadership. The program centers on an annual challenge to design an app that addresses a local community problem." Vega conducted a pilot study ($N = 117$) and main study ($N = 653$) of the program in which students completed self-report surveys at least four months and up to five years after the end of the program. Participants were primarily high school students, although some middle school students were included. Findings were that the Technovation experience increased girls' interest in computer science, entrepreneurship, and business leadership. Among prior participants who were now in college, 26% were majoring in computer science, a rate 65 times higher than the national average. Some 33% who were not in computer science were in some other STEM major with engineering most common—a rate more than twice as high as the national average.

Ancheta (2008a) conducted a self-report survey of 362 girls from predominantly underrepresented groups who had participated in Techbridge, an afterschool engineering curriculum with female role models and activities designed to interest girls. The study found that 67.7% plan to take or have already taken advanced or honors mathematics and/or science classes in high school and 97.5% either plan to attend college or are already attending college. The most important aspect of the program that increased their interest in STEM, identified by 72.5% of the survey respondents, was participating in hands-on projects. Some 16% of the girls identified field trips and role models as the part that got them most interested in STEM.

7c. Summer camps allow more time for STEM, which in turn leads to deeper impact

In their study of the long-term impact of a two-week middle school engineering summer camp for girls, Hubelbank et al. (2007) conducted telephone interviews of 88 students who had attended the camp as sixth-graders 4–7 years previously, and 41 students who had applied for the camp but did not attend. Camp Reach was taught by female role models focused on hands-on learning, building self-efficacy, collaboration, and teamwork, and emphasized how engineers make the world a better place. The results were that camp participants were significantly more likely to enroll in elective computer science classes ($p < 0.02$) and other science/engineering classes ($p < 0.05$) in high school than the control group.

Anderson and Gilbride (2003b) reported on a week-long hands-on summer engineering camp for 10th-grade girls. The impact of the camp was measured by exit surveys right after the camp, and by follow-up phone surveys. The researchers reported that "On average, 80% of the interviewed camp alumni went on to study at a university. There, over half enrolled in engineering programs, and of those, almost three-quarters said that the summer camp experience greatly or moderately influenced their decision" (p. 89).

Nugent and Barker (2010) compared the impact of a week-long robotics/geospatial technologies summer camp for middle school youth with a three-hour robotics intervention. The camp participants ($N = 147$) were given a content test on computer programming, mathematics, geospatial technologies (GPS/GIS), engineering, and attitudes, before and after the camp. The control group ($N = 141$) were given the same test before and after a three-hour robotics intervention. The week-long summer camp led to significant pre–post test learning gains for males and females ($p < 0.001$), but males scored higher than females on both tests. The short-term intervention did not result in cognitive learning gains but did positively impact the students' attitudes towards the value of science, mathematics, robotics, and GPS/GIS.

7d. Making and tinkering can increase engagement and support engineering practices

While there are no universally agreed on definitions of making, tinkering, and engineering, there are similar elements of creative construction among the three types of activities. In examining the literature, *making* tends to be used very broadly, as any process of production, ranging from the use of hand tools to create a simple object to the use of 3D printers or other advanced tools. *Tinkering* usually refers to a particular kind of making, in which participants apply their own ideas to creatively change a basic design, whereas *engineering* is a systematic process of developing a solution to solve a problem or meet a need.

Quan and Gupta (2020) studied tinkering as a means for teaching engineering design and to contribute to a more refined understanding of what tinkering is. The research setting was a summer camp for high school girls using a design-based Arduino microcomputer. Each camp had about 25 girls, who used Arduinos one or two hours per day for two weeks. The researchers' conclusion was that tinkering can help participants make progress toward some instructional goals, such as supporting the engagement of students in engineering design practices, but the method can also hinder progress toward other goals, such as developing a robust solution to a design problem.

Worsley and Blickstein (2016) conducted a qualitative ethnographic study of ten high school students and three engineering graduate students assigned to design a tower using popsicle sticks, tape, and a paper plate to support a mass above a table. All participants worked individually. Their work was recorded on video, and they were interviewed about their reasoning strategies. Because no written instructions were provided to the participants, they largely perceived this to be a making/tinkering task rather than an engineering task. Four strategies emerged from the analysis: unexplained reasoning; materials-based reasoning; example-based reasoning; and principle-based reasoning. Although the set of strategies suggests a continuum from beginner to expert strategies, the researchers noted that "we observed 9th grade students who used principle-based reasoning, and a PhD student who used materials-based reasoning" (p. 70).

7e. Competitions allow for individuals or teams to participate, with or without guidance

There are a great many engineering competitions that provide opportunities for students to tackle engineering design challenges, either on their own or as part of a team. Many of these allow for individuals to participate at no cost, while others require adults to help organize and fund opportunities for participation. One website (University of Maryland, 2012) lists 65 engineering competitions. Following are three examples of research studies selected to illustrate the range of competitions and their effects on students of different ages and genders.

Perhaps the best-known engineering competition is FIRST Robotics. Although elementary and middle school versions exist, the high school competition, which requires several thousand dollars to fund a single team and an adult with significant engineering skills to supervise, is the most widely researched. Burack et al. (2019) conducted a five-year longitudinal study of FIRST participants. Using a self-report survey, the researchers found that in comparison with 162 controls, the program had a statistically significant positive impact on 289 FIRST participants on five STEM-related attitudes and interests, including life and workplace skills, STEM career interests, and postsecondary aspirations.

Witherspoon et al. (2016) collected self-report surveys from 502 elementary, middle, and high school students who had participated in various robotics competitions, to determine how the experience shaped their interests in programming. The researchers found that students who were more involved wanted to learn more programming. In the youngest groups (entry-level competitions) girls were heavily involved in programming, but in more advanced competitions fewer girls were involved, even after controlling for prior programming experience.

ExploraVision is a useful and easily accessible alternative approach that requires no equipment and no cost to participate. Students write essays describing inventions that they think would solve current problems. Students research the history of a given technology and use creative thinking to imagine future technological breakthroughs. Eisenkraft (2011) conducted a retrospective study of a representative sample from more than 15,000 submissions over 18 years and found that students most frequently recommended changes in communications and medical technologies, and a great many students were concerned with negative impacts of changes in technology, such as the loss of jobs.

Implications of Finding 7

In contrast to in-school engineering teaching, which usually emphasizes the development of knowledge and skills, the aim of most afterschool and summer programs is primarily to spark interest in engineering, and to clearly illustrate that engineering is open to all regardless of background. Many of the programs reported in these studies have focused on girls and students of color, providing them with engaging hands-on activities presented by college mentors matched with participants in gender, racial, and ethnic characteristics. Other approaches include using engineering as a means for solving problems that students identify in their own lives, or that help them tackle problems within their communities. Competitions are a different strategy that can form the focus of a club or even be undertaken by individuals with little or no adult guidance. These studies support the overall findings of a NRC study (Fenichel & Scheingruber, 2010) intended to provide guidelines for OST programs—that the most effective OST programs are intellectually, academically, socially, and emotionally engaging to youth; are responsive to youths' interests, experiences, and cultural practices; and make connections between formal and informal educational experiences.

RESEARCH QUESTION C. What are the benefits of P-12 engineering education?

FINDING 8. Engineering supports learning of science concepts and abilities

Historically, the primary reason for including engineering in the science curriculum was to motivate students to learn science concepts and skills, or to demonstrate the value of science applied towards meeting human needs. Although new science education standards also identify knowledge and capabilities of engineering as important in their own right, engineering activities retain their importance as a complement to science. Eighty-five of the studies we reviewed provide evidence of engineering in support of science learning.

8a. Comparative studies have shown that integrating engineering into science teaching is more effective than traditional science teaching methods

Alemdar et al. (2018) conducted a study to investigate the impact of a middle school engineering curriculum on students' academic achievement in science and mathematics and non-cognitive skills such as engagement and self-efficacy in academics. The Engineering Design Process conceptual model was used as a framework to integrate science and mathematics into problem-based learning. Participants included sixth- through eighth-grade students at four public middle schools in Georgia with 67% receiving free and reduced lunch (N in the engineering condition = 1,153; N in the control condition= 976). Results showed that students who have taken at least two 18-week engineering courses had statistically significantly greater gains on state-level standardized tests of science ($p < 0.001$) and mathematics ($p < 0.001$) compared with students who were not enrolled in these courses. Pre–post self-report surveys also revealed a statistically significant increase in cognitive and behavioral engagement in STEM and science interest.

Mehalik et al., (2008) compared pre–post test scores of 585 eighth-grade students who studied electricity by designing an alarm system with scores of 466 students who learned the same electrical concepts using a scripted inquiry method. Students who learned with the design approach had significantly higher gains ($p < 0.001$) on electrical concepts. African American students benefitted the most; their gains were six times higher than those of the control group.

Because researchers usually need to work with existing classes of students, fully randomized experimental studies are rare in education. However, two such studies have demonstrated the value of integrated science and engineering instruction. Uswatun (2020) conducted a fully randomized control group study with 192 high school students during a four-week electronics unit in which the students designed and fabricated an apparatus, and then used it to conduct experiments. Students in the STEM condition were compared with a control group who learned the same material using traditional teaching methods. Understanding was measured using selected response items with the addition of a space for open-ended explanations. Although some misconceptions remained in all conditions, the fewest misconceptions remained in the experimental treatment group ($p < 001$).

Yaki et al. (2019) randomly assigned 49 of 100 high school students to an eight-week integrated STEM genetics curriculum and 51 students to a control group who learned the same conceptual material via traditional methods. All students received pre–post tests adapted from the national (Nigerian) high-stakes examination. Findings revealed a significant main effect in favor of the STEM approach ($p < 0.05$), with no interaction effects for academic ability level. Students with low academic abilities had the highest mean gain.

8b. Success in learning science through engineering depends on a number of factors

Some of the most helpful research studies of the impact of engineering education are those that failed to achieve the desired results, since they shed light on critical aspects of instruction.

To investigate how instructional practices correlated with student outcomes in a multiyear project entitled Science Learning through Engineering Design involving more than 200 teachers and 5,000 students, Capobianco and Lehman (2018) focused their study on 4 teachers and 93 fourth-grade students. Quantitative data included an observational rubric to characterize instruction, and pre–post tests of students' science knowledge. Qualitative data included classroom observations and interviews with the teachers. Averaging across all four teachers, students scored about 50% on the pre-test and 80% on the post-test, a statistically significant difference ($p < 0.0001$). Students of teachers who implemented the engineering design approach with high fidelity by fostering collaboration and engaging the students in developing models scored higher than students of teachers who implemented the program with low or moderate fidelity.

Chu et al. (2019) investigated an instructional model, called argument-driven engineering, intended to give students opportunities to design and critique solutions to meaningful problems using the core ideas and practices of science and engineering. One hundred eighth-grade students completed three design tasks during the school year that were created using the argument-driven engineering instructional model, and completed a survey designed to measure engineering identity (recognition and interest) at three time points. The results of a hierarchical linear modeling analysis suggested that students' engineering identity and interest decreased from one survey to the next. The researchers speculated that the disappointing results were due to the difficulty of the design tasks and their observations that teachers left out key activities.

Schnittka (2012) conducted a case study of a middle school teacher who presented engineering activities using the National Science Foundation-funded unit *Save the Penguins* with two classes. Each class had 23 students with similar gender and ethnicity characteristics. One of the classes included several special needs students, and the class's average score on the state math assessment was lower than that of the other class. The teacher's expectations and treatment of the two classes differed to such a degree that students in the lower-level class were not given the same opportunities to discuss their designs and explore the science content through demonstrations and discussion. Consequently, while students in both classes made gains in knowledge about the science content of the unit, students in the lower-level class did not attain the same conceptual level. Despite the differences in instruction, students in the lower-level class were very creative engineers.

Implications of Finding 8

Educators who prioritize the learning of science concepts and practices will find in these studies sufficient evidence to show that engineering activities can help students develop a deeper understanding of science by applying scientific ideas and capabilities to meeting engineering challenges. However, adding engineering to the science curriculum does not always produce better outcomes. Like all educational activities, success depends not only on methods and materials, but also on the design of the curriculum and quality of instruction.

FINDING 9. Engineering builds 21st-century skills

Thirty-six studies measured gains in students' 21st-century skills, such as creativity, teamwork, and communication, which have long been recognized as important not only in science, but also in everyday life (Trilling & Fadel, 2009).

9a. Engineering activities can increase creativity

The Anwar et al. (2019) review identified 53 K-12 robotics studies that focused on creativity as an outcome. In one example, Nemiro et al. (2017) studied fourth–fifth grade students over three years ($N = 163$) as they worked in teams to meet robotics challenges. Work on a challenge began with an initial period of idea generation, planning, and creative building, which was then followed by an iterative period of testing and adjusting the robot's design and computer program to meet the challenge. Each class was observed by two researchers who took field notes, which were coded and analyzed. These data were supplemented by weekly design journals from 25 of the students. Creativity was judged by novel robot designs and ways in which the students personalized their robots. Although all teams were told to first plan their robots, some teams spent little time in planning and started building right away, while others brainstormed and developed detailed plans before building. Four techniques for improving creativity emerged from the observations: analogues, probing questions, examples of robots provided by teachers, and robotic journals.

9b. Engineering activities can increase idea fluency

Dasgupta et al. (2019) collaborated in developing a middle school unit in which students learned to use CAD to plan an energy-efficient house. Participants were 408 middle school students in grades 6, 7, and 8. Among other outcomes, the researchers measured *idea fluency*—the number of unique design ideas that students could generate, one aspect of creativity—by examining the automatic software logs from students' designs. They found that the students "generated new ideas until the last day of the design activity; indicating that they saw value in generating multiple ideas and were not fixated on any one idea" (p. 137).

9c. Engineering activities can help students develop communication and teamwork skills

Tuttle et al. (2016) reported on the use of three teacher-developed units that integrated engineering and physical science: hot air balloons (density), bumper cars (motion), and bridges (forces at equilibrium). Participants were 28 first-grade students, including six with special needs. The teacher worked from the beginning of the year to model good teamwork skills, such as taking turns. Data illustrative of students' teamwork capabilities are reported in the form of verbatim discussions among the students.

Kelly et al. (2017) described an ethnographic study in which 28 second-grade students and 24 fourth-grade students were videotaped when engaged in EIE units. The researchers concluded from their video records that the students learned how one needs to act to be a member of a team, and thus came to view themselves as successful.

At the high school level, Melchior et al. (2005) found that among 173 high school students who completed a self-report survey about their experiences in FIRST robotics competitions, 91% reported that they felt they "really belonged" on the team, and 95% reported an increased understanding of the value of teamwork. Some 89% claimed increased understanding of the role of science and technology in everyday life, 86% reported increased interest in science and technology generally, and 69% said the experience increased their interest in science and technology careers.

9d. Engineering solutions to authentic problems can help students develop self-efficacy and resilience

Ruth et al. (2019) worked with students from 15 socioeconomically diverse high schools who enrolled in the EPICS service-learning program, in which they applied engineering to problems in their communities. Students were given pre–

post self-report surveys of attitudes about engineering, new ways of doing things, the value of feedback, growth mindset, social responsibility, and the importance of multiple perspectives in solving problems. A comparison of pre-surveys completed by 578 students and post-surveys completed by 386 of the students revealed statistically significant improvement in engineering-related concepts and attitudes, even though the average pre-survey scores were quite high. Qualitative data, collected via interviews and class observations, revealed increases in engineering self-efficacy and skills, community embeddedness, and increases in resiliency and a positive response to failure.

Implications of Finding 9

There is strong evidence from many studies that engineering activities help students develop 21st-century skills such as creativity, idea fluency, reasoning, communication and collaboration skills, divergent thinking, teamwork, and persistence in the face of challenges. Implications of these findings are that curriculum developers, teachers, and teacher educators should address engineering challenges with these outcomes in mind, provide scaffolding that students may need to develop these capabilities, and methods for assessing students' accomplishment of 21st-century skills.

FINDING 10. Engineering increases STEM motivation and identity

Fifty-six studies that we reviewed reported that engineering activities led to increases in STEM motivation and STEM identity. On balance, these studies have demonstrated that students are strongly motivated when asked to design solutions to real problems, particularly when they are given the opportunity to carry the engineering process all the way through prototyping, testing, and communicating their designs.

10a. Engineering challenges shift initiative from the teacher to the students

Barnett (2005) conducted a study in an urban school characterized by very poor attendance. The study compared 25 students who designed remotely operated vehicles (ROVs) with 32 students who studied the same physics topics in traditional classes. As shown in Figure 4, attendance increased for students engaged in designing remotely operated vehicles. The engineering students learned physics and saw connections to their other coursework. The author also noticed a difference in teacher behavior. The engineering unit teachers "adopted an *organized chaos* posture and shifted their role from one of discipline keeper and content gatekeeper to one of coach and facilitator" (p. 87).

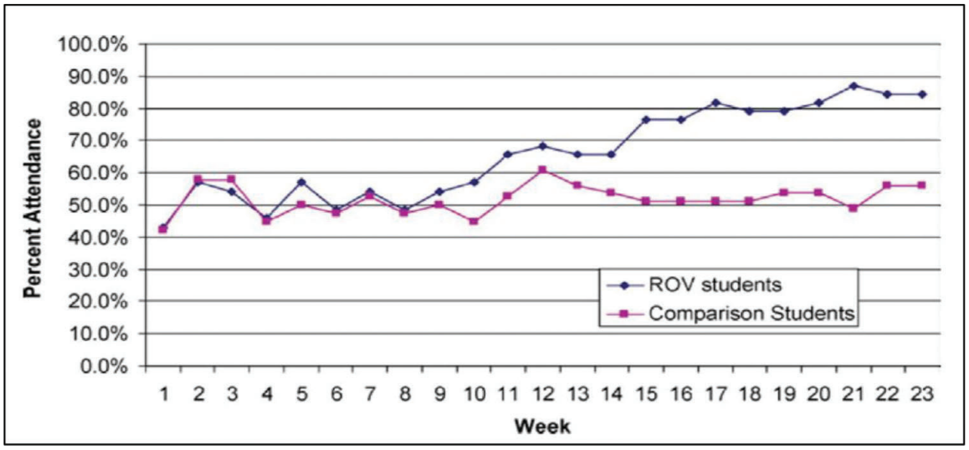

Figure 4. Attendance of ROV group versus comparison group. (Reprinted by permission from Springer/Nature: Barnett, M. (2005). Engaging inner city students in learning through designing remote operated vehicles. *Journal of Science Education and Technology*, *14*(1), 87–100, p. 91.)

10b. Using engineering to help solve community problems can increase STEM confidence and identity

Penuel (2016) described two ethnographic research studies, using classroom field notes and interviews. Study 1 documented an effort to engage African American students in developing ideas (bike lanes) to expand their mobility within and across their neighborhood, observing how they became more engaged as their voices were heard. Study 2 described a study of an urban farming nonprofit organization aimed at empowering students by helping them learn to grow and sell nutritious food. The author concluded that "in each study, young people gained access to science and engineering knowledge and practice through their participation in design activities in a network of social practice. And in each case, young people's participation in design activities was integral to collective efforts to organize new, more just social futures" (p. 101).

Barton and Tan (2010, 2018, 2019) and Tan et al. (2013, 2019) produced a series of papers that documented efforts to meet the needs of high-poverty urban students by helping them define and solve problems they encounter in their schools and community. As an example, Barton and Tan (2018) described a longitudinal ethnographic study of 41 team maker projects in two community-centered programs. The researchers explained how the middle school students' practices were grounded in their own lived experiences, growing up in historically marginalized communities but with broad cultural wealth and a hope for using their making work to advance their communities. The resonance with students' daily lives was clear from the nature of the projects such as a heated sweatshirt, more accessible library resources, an anti-bully app, and a rape alarm jacket.

10c. Engineering education can inspire girls and students of color to pursue engineering as a career

Seventy-five of the studies in this review provided data relevant to gender or explicitly addressed means for encouraging more girls and young women to engage in engineering. Although in some cases a study simply reported results by gender, other studies used methods such as girls-only engineering camps, or female mentors and role models to encourage girls to consider an engineering career. High et al. (2010) demonstrated several different approaches in a single study. Middle school girls participated in a curriculum unit called Get a Grip in which students designed a prosthetic arm. Many of these students also participated in an afterschool mentoring program by female college students majoring in engineering, and a hands-on co-ed summer program focused on the differences between science and engineering. Based on a pre–post self-report survey, students who participated in Get a Grip ($N = 850$) outperformed controls ($N = 550$) in math confidence, science confidence, effort towards math and science, awareness of engineering and interest in engineering as a potential career. Girls' confidence and belief in their own abilities and potential in science and math was significantly more positive than the boys' beliefs in the girls' abilities to do science and math. Also, the girls who participated in the summer camp demonstrated significantly more knowledge of what an engineer does and interest in pursuing an engineering career than girls who did not attend the camp.

Forty-eight of the studies that we examined provided data on studies that involved primarily students of color and from low-income families, including many that tested specific ways to better serve these audiences. For example, Denson (2017) investigated the MESA program, which was started in California during the 1970s to provide pathways to STEM careers for students from populations underrepresented in STEM fields. MESA activities take place primarily after school and during summers. Many MESA participants begin their involvement in middle school and continue to participate through high school and into college, where they may serve as mentors for younger participants. Data were collected from focus group interviews with a total of 19 females and 11 males, and a self-report survey given to 484 underrepresented students who had participated in MESA. Results showed a positive influence of MESA activities on students' self-efficacy, interests, and perceptions related to engineering ($p < 0.001$). The most influential factors were hands-on activities, followed by meeting with professionals (i.e., role models), student advisors (mentors), and field trips. A surprising theme that emerged from the focus-group interviews was that participants talked more about their roles as mentors in informal mentoring settings, as opposed to the informal mentoring that they received from MESA teachers and advisors. Participants spoke about mentoring not only their fellow underclassmen but also volunteering with local middle and elementary school students.

Recognizing the immense influence of parents to either support or discourage their children's interest in engineering and other STEM fields, Rozek et al. (2017) evaluated the long-term effects of a brief intervention that involved communicating with parents about the important role that they play in their teenagers' confidence and decisions about enrolling in mathematics and science courses. The intervention consisted of a website and two brochures, as well as advice about how to communicate the information to their children. Control parents received no treatment. The researchers found that the intervention increased high school course taking in STEM fields, and improved mathematics and science standardized test scores on a college preparatory examination (ACT) by 12 percentage points. Students' increased interests in pursuing a STEM career were evident five years after the intervention. Pattison et al. (2020) described a different intervention involving 15 English- and Spanish-speaking preschool age children and their families, conducted through a Head Start program. The study documented how both children and parents developed engineering-related interests through the program.

Implications of Finding 10

Looking across these studies, it is not surprising that engineering activities increase STEM motivation and identity. Engineering is highly interactive. If the design challenge is sufficiently compelling and the goals are clear, initial engagement rapidly deepens into commitment to meeting the challenge. Over the long term, as students come to expand their initially narrow views and recognize that technology pervades their daily lives, they begin to value STEM as far more meaningful than just a set of school subjects. By solving authentic problems, students gain a sense of agency, and as they learn about the wide diversity of engineering fields, they encounter opportunities to develop an intense interest that has personal meaning and offers potential career goals. Consequently, building engineering into the curriculum has high potential to enable students to see the value of STEM learning in their lives now, and in the future. However, engineering activities alone are not sufficient to support students whose interest in engineering has been awakened. Long-term support by their parents and others through programs providing STEM access and mentoring is also essential.

5.0 Discussion

At the start of this century, science education was largely separated into the traditional science disciplines focused on understanding the natural world, with significantly less attention focused on the human-made world. Although there were calls for making science more relevant and highlighting the pro and con impacts of technology on society and the environment, the patchwork of state standards made it very difficult to implement systemic change.

Over the past two decades, the focus of the school curriculum has gradually shifted from purely science and math to a more balanced coverage of integrated STEM. The shift towards inclusion of engineering and technology has been facilitated by a series of new education frameworks and guidelines such as *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC, 2012), *Next Generation Science Standards* (NGSS Lead States, 2013), and, more recently, a *Framework for P-12 Engineering Learning* (ASEE, 2020) and *Standards for Technology and Engineering Literacy* (ITEEA, 2020). These developments have been in response to society's growing recognition of the needs for STEM literacy and have energized the field of P-12 engineering education research. This landscape study illustrates that we now have a better handle on the benefits and challenges of including engineering and technology in P-12 education, and a range of effective solutions to meet the challenges is emerging. Following is a brief overview of our findings.

A. What are students' understandings, skills, and attitudes about engineering and technology?

This question led us to identify the challenges faced by engineering educators. It has been well-documented that the great majority of children in the USA have a narrow conception of technology as electronics and mechanics, and of engineers as the people who work primarily with computers or machinery, such as repairing cars and constructing buildings. Evidence that students in many other countries have a better understanding of technology and engineering can be interpreted as good news, since it implies that instruction can be effective in developing a more accurate understanding. A more difficult problem to solve may be that most students in the United States are not proficient in engineering and technology literacy—problem-solving capabilities needed for citizens and workers in modern society. A complementary challenge is to inspire more students to consider engineering as a profession. The research literature converges on the finding that to do so, students need to develop interests in the field by the time they reach middle school, and then to maintain that interest throughout their high school years. The barriers to maintaining interest and pursuing engineering as a career are especially high for girls, students of color, and all students from low-income families.

B. What are effective methods of P-12 engineering education?

Our findings offer considerable hope that the challenges of introducing engineering into P-12 education can be successfully met. A wide range of effective strategies for engaging students in engineering have been developed and tested with various audiences, both in schools and in afterschool and summer programs. The diversity of designs in the studies we have reviewed have illustrated how different strategies, teaching methods, and materials can help students build skills and develop interest in the field of engineering.

The research shows that a variety of generalizable methods can be effective across content, ages, and demographics. For example, comparative studies have shown that fully integrating engineering into science lessons is more effective than traditional lessons alone, and more effective than using engineering activities as a capstone at the end of a science unit. Fictional stories have been successfully used to engage students in problem scoping—defining problems faced by the protagonist as a launching point for engineering design. Drawing has also been found to be helpful, including paper-and-pencil sketching as well as CAD. Action research studies have led to instructional principles, such as the use of a suboptimal design as a starting point, allowing students the opportunity to creatively redesign and improve performance through frequent testing and iteration.

Our findings also reference a variety of effective topical approaches focused on specific themes, which allow educators to select areas of personal interest or that are especially relevant to their students' lives. Topical approaches that have been widely successful include the design of robots and various biomedical devices such as an artificial heart, artificial lung, prosthetic limb, or dialysis machine. Other successful units have involved the design of technological systems that are purposeful and familiar to students, including electrical alarm systems, food hydrators, and solar power arrays. Such units involve a wide variety of materials, ranging from cardboard and tape to computer simulations, Arduino microcomputers, and 3D printers.

There is also evidence that formal, systematic engineering curricula covering various topics and instructional approaches can be effective at the elementary, middle, and high school levels. The relatively small number of engineering curricula that have been subject to research studies have shown them to yield valuable results, not only improving engineering knowledge and skills, but in many cases mathematics and science capabilities and STEM attitudes and interests as well.

Perhaps the most encouraging finding is that many engineering methods and materials have been found to be successful in addressing a major social inequity: improving the attitudes, STEM skills, and career aspirations of girls, students of color, and students from low-income families. Achieving gender equity can be as simple as choosing design challenges that use materials of equal interest to boys and girls. For reaching students from non-dominant ethnic and cultural groups an effective approach has been to provide purposeful engineering design challenges directly relevant to the students' lived experiences, with the assistance of mentors, role models, and programs for parents to help them understand their important role in encouraging their children's STEM interests. Studies relevant to these issues are designated by footnote markers "*" and "†" in Table 2.

C. What are the benefits of P-12 engineering education?

Much has been accomplished since the NRC conducted its last comprehensive study in 2014. There is now a robust collection of studies demonstrating that the integration of engineering into the teaching of science can support deeper learning of science and mathematics concepts and capabilities; that engineering helps students develop 21st-century skills that are essential for daily life and a wide range of jobs; and that learning engineering can increase student motivation and help students develop an identity as STEM learners.

6.0 Conclusion

Taken together, these findings support the rationale for including engineering as a fundamental part of the P-12 learning experience for all students. With this recognition as impetus, research on the best ways to integrate engineering into the school curriculum, and into afterschool and summer programs is gaining momentum, and we hope this landscape study will play a supportive role in nurturing that bold initiative. Bringing engineering knowledge, capabilities, and habits of mind to *all students* is an empowering vision that will require the best ideas and actions of researchers and educators to realize.

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Table 2 Studies that provide evidence in support of findings.
*Data are relevant to gender differences.
†Data are relevant to youths of color and/or from low-income families.

FINDING 1. Students in the USA have narrow conceptions of technology and engineering

- Anderson & Gilbride, 2003a*
- Barton et al., 2005†
- Chan et al., 2019*
- Coalition, 2005*
- Crismond & Adams, 2012
- Crismond, 2013a
- Cunningham, 2018*†
- Dika, 2016*†
- English et al., 2011
- Ergun & Balcin, 2019
- Fralick et al., 2009
- Ganesh, 2011*
- Jocz & Lachapelle, 2012
- Köycü & DeVries, 2016*
- Lachapelle & Brennan, 2018*
- Lachapelle et al., 2013a, 2012
- Lind et al., 2019
- Naukkarinen & Bairoh, 2020*
- National Center for Education Statistics (NCES), 2019*†
- Organisation for Economic Cooperation and Development (OECD), 2017*†
- Oware, 2007
- Ozogul et al., 2017*†
- Pekmez, 2018
- Penuel, 2016†
- Svenningsson, 2020
- Verdín et al., 2018
- Vossen et al., 2020
- Weber et al., 2011
- Weinberg, 2017, 2018

FINDING 2. Developing interest in engineering at an early age is essential for later engagement

- Ancheta, 2008a,b*
- Anderson & Gilbride, 2003a*
- Falk et.al., 2016a,b
- Ing et al., 2014
- Maksimovic et al., 2020
- Maltese & Cooper, 2017*
- Maltese & Tai, 2011
- Matusovich et al., 2020*†
- Miller et al., 2020*†
- Montfort et al., 2013†
- Moore, 2006†
- Sadler et al., 2012*
- Tai et al., 2006

FINDING 3. Girls and students from low-income families are less likely to pursue engineering

- Bystydzienski et al., 2015*†
- Chan et al., 2019*
- Coalition, 2005*
- Ing et al., 2014
- Lachapelle & Brennan, 2018*
- Maksimovic et al., 2020
- Michael & Alsup, 2016*
- Montfort et al., 2013†
- Moote et al., 2020*
- Naukkarinen & Bairoh, 2020*
- NCES, 2019*†
- Ozogul et al., 2017*†
- Reynolds et al., 2009*†
- Sadler et al., 2012*
- Tan et al., 2013, 2019*†
- Wang et al., 2013a*

FINDING 4. Many generalizable methods of engineering education can be effective

- Akins & Burghardt, 2006
- Anderson & Gilbride, 2003a,b*
- Anderson et al., 2006*
- Aranda et al., 2020a,b
- Bartholomew et al., 2017, 2018
- Bartholomew & Strimel, 2018
- Barton & Tan, 2010, 2018, 2019†
- Barton et al., 2021†
- Bers, 2007
- Beyer & Auster, 2014
- Bowen & DeLuca, 2015
- Bowen & Peterson, 2019
- Cantrell et al., 2006*†
- Capobianco & Lehman, 2018
- Carlone et al., 2021
- Ching et al., 2016
- Chiu & Linn, 2011
- Chu et al., 2019*
- Crismond, 2013b
- Crotty et al., 2017
- Dasgupta, 2019
- English et al., 2013
- Glancy et al., 2017
- Godwin et al., 2016*
- Güdel et al., 2019*
- Guzey & Aranda, 2017
- Guzey et al., 2019
- Hegedus et al., 2014
- Hertel et al., 2017
- Hirsch et al., 2007
- Holly, 2021
- Hudson et al., 2015*
- Hynes & Swenson, 2013†
- Ilumoka et al., 2017*†
- Jackson et al., 2021*
- Johnson, 2016
- Kapucu, 2019
- Kelly et al., 2007*
- Klahr et al., 2007*
- Klein-Gardner et al., 2012
- Koskey et al., 2020
- Koul et al., 2018*
- Lachapelle & Cunningham, 2016*
- Lind et al., 2020
- Lo & Hew, 2019
- Long et al., 2020
- Lottero-Perdue & Settlage, 2021
- Lyons & Thompson, 2006
- MacDonald et al., 2007
- Malkiewich & Chase, 2019
- Marks & Chase, 2019
- Mathis et al., 2018
- McCormick & Hammer, 2016
- McFadden & Roehrig, 2019
- Mentzer & Forsmire, 2015
- Moreno et al., 2011
- Nathan et al., 2013
- Nemiro et al., 2017
- Oliver & Hannafin, 2001
- Pallis & McNitt-Gray, 2013*
- Pattison et al., 2018, 2020
- Penuel, 2016†
- Petrosino et al., 2007
- Phelps et al., 2018
- Portsmore et al., 2012
- Purzer et al., 2012
- Quan & Gupta, 2020*
- Reynolds et al., 2009*†
- Rivale et al., 2011*
- Rozek et al., 2017
- Ruth et al., 2019*†
- Sadler et al., 2000
- Sarican & Akgunduz, 2018
- Schnittka, 2012
- Schnittka & Bell, 2011
- Schnittka & Schnittka, 2016*
- Schut et al., 2019, 2020
- Seiler et al., 2001†
- Silk & Schunn, 2008a
- Sinervo et al., 2020
- Skorinko et al., 2012*
- Starling et al., 2015
- Sung & Kelley, 2019
- Tuttle et al., 2016
- Watkins et al., 2014
- Welch & Lim, 2000*
- Wilson-Lopez et al., 2016
- Worsley & Blikstein, 2016
- Wright, 2018
- Zarske et al., 2012*†
- Zubrowski, 2002

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Table 2
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FINDING 5. Topical approaches focused on specific technological systems can be effective

Anwar et al., 2019*†
Apedoe et al., 2008, 2012
Ardito et al., 2020*
Barnett, 2005†
Blikstein, 2013
Buchholz et al., 2014
Burack et al., 2019*
Burghardt et al., 2010
Carberry & Hynes, 2007
Dasgupta et al., 2019
Dubriwny et al., 2016
Foster & Ganesh, 2013
Gale et al., 2018
Hansen et al., 2018
Hernandez et al., 2014
High et al., 2010*
Hmelo et al., 2000
Hutchinson et al., 2011
Klein & Sherwood, 2005
McGrath et al., 2009*†
Mehalik et al., 2008†
Melchior et al., 2005
Monterastelli et al., 2008*
Nemiro et al., 2017
Rahman et al., 2017*, 2018
Sadler et al., 2012*
Schnittka et al., 2010
Silk & Schunn, 2008b
Silk et al., 2009
Smith & Talley, 2018
Sullivan & Bers, 2019*
Suratno, 2014
Svarovsky & Shaffer, 2007
Tan et al., 2019*†
Uswatun, 2020
Wendell & Rogers, 2013
Whitehead, 2010
Witherspoon et al., 2017
Wyss et al., 2012*
Xie et al., 2018

FINDING 6. A wide range of engineering curricula have been found to be effective

Alemdar et al., 2018
Anderson et al., 2006*
Apedoe & Schunn, 2013
Berland et al., 2013, 2014
Berland & Steingut, 2016
Bottoms & Uhn, 2007
Carlone et al., 2021
Ernst & Clark, 2006
Cunningham, 2018*†
Cunningham & Kelly, 2017
Cunningham & Lachapelle, 2007
Diefes-Dux, 2015
Farmer et al., 2012
Fortus et al., 2004
Hegedus et al., 2014
Hertel et al., 2017
Hsu & Cardella, 2012
Hsu et al., 2012
Jackson et al., 2016
Jocz & Lachapelle, 2012
Kanter, 2009
Kelly et al., 2017
Klein & Sherwood, 2005
Kolodner et al., 2003
Lachapelle & Cunningham, 2016*, 2017*†
Lachapelle et al., 2011, 2013a,b, 2017†
Lamb et al., 2018
Mamlok et al., 2001
Pekmez, 2018
Phelps et al., 2018
Puntambekar & Kolodner, 2005
Robinson et al., 2018†
Ruth et al., 2019*†
Tai, 2012*†
Tran & Nathan, 2010
Utley et al., 2019*†
Valtorta& Berland, 2015
Wainwright, 2007
Wells et al., 2016
Witherspoon et al., 2017
Wright et al., 2018†
Yaki et al., 2019
Yao, 2006

FINDING 7. Engineering OST has also been found to be effective

Ancheta, 2008a,b*
Anderson & Gilbride, 2003a*
Barton & Tan, 2018†
Bers, 2007
Beyer & Auster, 2014
Blanchard et al., 2015†
Blikstein, 2013
Bricker & Bell, 2014
Burack et al., 2019*
Bystydzienski et al., 2015*†
Campo et al., 2009†
Carberry & Hynes, 2007
Cloutier et al., 2018*
Cunningham, 2018*†
Denson, 2017*†
Ehsan & Cardella, 2020
Eisenkraft, 2011
Falk, et.al., 2016a,b
Frey & Powers., 2012
Ganesh, 2011*
Ganesh & Schnittka, 2014
Godwin et al., 2016*
Hammack et al., 2015
High et al., 2010*
Hubelbank et al., 2007*
Ilumoka et al., 2017*†
Johansson, 2020
Jones et al., 2015
Kelly et al., 2007*
Kittur et al., 2017
Lam et al., 2014*†
Madihally & Maase, 2006
Matson et al., 2007*
McLean et al., 2020*
Melchior et al., 2005
Moore, 2006†
Mueller et al., 2018
Nugent & Barker, 2010*
Ortiz et al., 2018†
Ozis et al., 2018*†
Pallis & McNitt-Gray, 2013*
Parekh & Gee, 2018
Pattison et al., 2020
Pinnell et al., 2018
Rorrer et al., 2005†
Schilling & Pinnell, 2019*
Schnittka & Schnittka, 2016*
Skorinko et al., 2012*
Songerath & Meadows, 2018*
Sullivan & Bers, 2019*
Svarovsky, 2011*
Svarovsky et al., 2018*
Vega, 2006*
Verdín et al., 2021†
Wang et al., 2013b
Wilson-Lopez et al., 2018, 2021†
Witherspoon et al., 2016*

(Continued)

Table 2
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FINDING 8. Engineering supports learning of science concepts and abilities

Akins & Burghardt, 2006
Alemdar et al., 2017, 2018
Apedoe & Schunn, 2013
Apedoe et al., 2008, 2012
Barnett, 2005[†]
Berland & Steingut, 2016
Berland et al., 2013
Bottoms & Uhn, 2007
Bowen & DeLuca, 2015
Bowen & Peterson, 2019
Buchholz et al., 2014
Burghardt et al., 2010
Campo et al., 2009[†]
Cantrell et al., 2006*[†]
Capobianco & Lehman, 2018
Carberry & Hynes, 2007
Ching et al., 2016
Chiu & Linn, 2011
Chu et al., 2019*
Crismond, 2001, 2013a,b
Cunningham & Lachapelle, 2007
Dasgupta, 2019
Dasgupta et al., 2019
Davis et al., 2002
Egbue et al., 2015*
English et al., 2013
Fortus et al., 2004
Foster & Ganesh, 2013
Gale et al., 2018
Glancy et al., 2017
Guzey & Aranda, 2017
Guzey et al., 2019
Hansen et al., 2018
Hernandez et al., 2014
Hmelo et al., 2000
Hsu et al., 2012
Hudson et al., 2015*
Hutchinson et al., 2011
Hynes & Swenson, 2013[†]
Ilumoka et al., 2017*[†]
Kanter, 2009
Klein & Sherwood, 2005
Kolodner et al., 2003
Koul et al., 2018*
Lachapelle et al., 2011, 2013b, 2017[†]
Langman et al., 2018
Lind et al., 2020
Long et al., 2020
Malkiewich & Chase, 2019
Mamlok et al., 2001
Marks & Chase, 2019
Mathis et al., 2018
McFadden & Roehrig, 2019
McGrath et al., 2009*[†]
Mehalik et al., 2008[†]
Monterastelli et al., 2008*
Nathan et al., 2013
Nugent & Barker, 2010*
Oliver & Hannafin, 2001
Puntambekar & Kolodner, 2005
Roth, 2001
Sadler et al., 2000
Schnittka & Bell, 2011
Seiler et al., 2001[†]
Silk et al., 2009
Siverling et al., 2019
Svarovsky & Shaffer, 2007
Tai, 2012*[†]
Tran & Nathan, 2010
Uswatun, 2020
Valtorta & Berland, 2015
Wainwright, 2007
Wendell & Rogers, 2013
Wilson-Lopez et al., 2020
Witherspoon et al., 2017
Wyss et al., 2012*
Xie et al., 2018
Yaki et al., 2019
Yao, 2006

FINDING 9. Engineering builds 21st-century skills

Aranda et al., 2020a,b
Barton & Tan, 2010, 2018, 2019[†]
Blikstein, 2013
Buchholz et al., 2014
Capobianco & Lehman, 2018
Carberry & Hynes, 2007
Carlone et al., 2021
Ching et al., 2016
Cloutier et al., 2018*
Dasgupta et al., 2019
Ganesh & Schnittka, 2014
Guzey & Aranda, 2017
Guzey et al., 2019
Hansen et al., 2018
Hegedus et al., 2014
Hertel et al., 2017
Holly, 2021
Hynes & Swenson, 2013[†]
Johnson, 2016
Kelly et al., 2017
Klein-Gardner et al., 2012
Kolodner et al., 2003
Koul et al., 2018*
Lind et al., 2020
Lottero-Perdue & Settlage, 2021
Nemiro et al., 2017
Schut et al., 2019
Sinervo, et al., 2020
Sontgerath & Meadows, 2018*
Tan et al., 2019*[†]
Tuttle et al., 2016
Wilson-Lopez et al., 2021[†]
Zarske et al., 2012*[†]

FINDING 10. Engineering increases STEM motivation and identity

Alemdar et al., 2018
Ancheta, 2008a,b*
Anderson & Gilbride, 2003a,b*
Anderson et al., 2006*
Barnett, 2005[†]
Barton & Tan, 2010, 2018[†]
Barton et al., 2021[†]
Blikstein, 2013
Bottoms & Uhn, 2007
Bricker & Bell, 2014
Burack et al., 2019*
Bystydzienski et al., 2015*[†]
Campo et al., 2009[†]
Capobianco et al.,2012
Carlone et al., 2021
Chu et al,, 2019*
Ernst & Clark, 2006
Cunningham, 2018*[†]
Denson, 2017*[†]
Diefes-Dux, 2015
Dubriwny et al., 2016
English et al., 2013
Ganesh & Schnittka, 2014
Güdel et al., 2019*
Hansen et al., 2018
Hegedus et al., 2014
High et al., 2010*
Holly, 2021
Hudson et al., 2015*
Hutchinson et al., 2011
Hynes & Swenson, 2013[†]
Ilumoka et al., 2017*[†]
Jackson et al., 2016, 2021
Jones et al., 2015
Kapucu, 2019
Kelly et al., 2007*
Kelly et al., 2017
Klahr et al., 2007*
Kittur et al., 2017
Long et al., 2020
Mueller et al., 2018
Rorrer et al., 2005[†]
Rozek et al., 2017
Ruth et al., 2019*[†]
Schnittka et al., 2010
Sontgerath & Meadows, 2018*
Sullivan & Bers, 2019*
Suratno, 2014
Svarovsky, 2011*
Tai, 2012*[†]
Vega, 2006*
Witherspoon et al., 2016*

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