Progress toward Lofty Goals: A Meta-synthesis of the State of Research on K-12 Engineering Education (Fundamental)

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Abstract

This paper synthesizes literature on formal and informal engineering education in K-12 settings. We focus on outcomes related to (1) developing interest and/or identities in engineering, including in (2) engineering careers, (3) recruitment of increased numbers of students, (4) learning and achievement of science, technology, and mathematics content/practices, (5) learning and achievement of engineering content/practices, (6) understanding the nature of engineering, and (7) broadening participation of diverse learners.

Employing the methodology of previous reviews [1-4], we reviewed papers published between 2008-2016 (n = 131 papers). We used Google Scholar and a set of search terms including synonyms for K-12 settings, informal settings, and engineering education, to identify relevant peer reviewed journal articles. We coded each paper based on goals, data, analysis, and outcomes achieved. We then synthesized findings and gaps from previous reviews and the 2008-2016 time period.

We find that in the past eight years the field has developed increasingly rigorous research methods, but many publications still report studies that have not adopted this higher level of rigor. There are still opportunities for growth tied to qualitative methods in particular. Further, there are still few published studies that contribute in meaningful ways to our understanding of how to recruit and retain learners from diverse groups. We close by setting research agendas and avenues needed to understand and impact concerns over diversity and inclusion in engineering.

Introduction and background

Despite myriad calls for and programs aiming to bring engineering into K-12 settings, progress has been hampered by an already crowded curricular scope, comparatively limited resources for teacher professional development on teaching engineering practices, and a relatively sparse adoption of state standards that include engineering. In this metasynthesis, we reflect on past findings and contrast this with more recent publications about the state of K-12 engineering education.

We ground our analysis by considering various motivations for bringing engineering into K-12 settings (figure 1). Many have argued persuasively about the critical importance of K-12 engineering education, but we find a range of reasons in these arguments. Specifically, we find some arguments focused on high-level concerns, such as maintaining global competiveness [6] or solving grand challenges [7, 8]. Stemming from the high level motivations, we see common arguments for increasing the total number of engineers, sometimes motivated with a sense of urgency [9-11] citing decreases in the number of students completing engineering degrees between 1985 and 2000 [12]. Others argue for the need to diversify the profession, situating diversity as a resource [13]. However, there are many noted barriers to increasing the number and diversity of engineers, and many of these have been attributed to shortcomings of K-12
school systems. This is sometimes expressed from a deficit stance, placing blame on teachers or students. More astute scholars recognize such challenges stem from a complex of issues, such as intergenerational poverty, an already crowded curriculum, and education reforms that have had myriad negative consequences [14-16]. Regardless of origin, commonly expressed concerns about K-12 settings include that students seem to arrive at universities ill-prepared, especially in terms of mathematics skills, that they seem to lose interest in STEM fields prior to arriving at the university, and that they have had few engineering opportunities and resources in their K-12 schooling.

Based on these perceived failings, a number of strategies and activities are commonly deployed. These efforts have increasingly focused on teacher professional development, even though only 18 states have adopted the Next Generation Science Standards, which include engineering standards [17], and while some states do have engineering standards of their own, many do not. As a result, common approaches to fostering engineering with K-12 students have included focusing on informal settings or in non-engineering formal settings (e.g., science or mathematics classrooms). As a result, many have called for an integrated approach to teaching engineering in other commonly taught K-12 disciplines [18-20]. Another common argument is that engineering skills should now be considered for all students, much as reading, writing and mathematics [21, 22], and this is sometimes positioned as an early recruitment tool, with the idea that students must be recruited prior to losing interest in STEM.
This paper synthesizes literature on formal and informal engineering education in K-12 settings. Specifically, we focus on outcomes related to (1) developing interest and/or identities in engineering, including in (2) engineering careers, (3) recruitment of increased numbers of students, (4) learning and achievement of science, technology, and mathematics content/practices, (5) learning and achievement of engineering content/practices, (6) understanding the nature of engineering, and (7) broadening participation of diverse learners.

We review the findings and recommendations from our previous work [1-4] spanning 1990-2007 (n=230 papers and proceedings). In that work, we summarized the cumulative findings of research on engineering education related to students’ awareness of, knowledge about, and interest in engineers and the work of engineering; their learning and achievement in STEM fields; and efforts to broaden participation. We found young students, in particular, had little awareness of what an engineer is or does, but that engineering activities can positively impact students’ awareness of engineers, technology, and engineering, and this effect may be long lasting [23-29]. Such activities can increase students’ interest in engineering [30], and while interest has been a common measure, methodological issues limited our understanding. Few
studies used a pre/post design, and given the fact that many of the reported engineering activities involved self-selection, measuring interest only after the activity is not very informative. Further, we reported concerns about how seldom data were reported in disaggregated format. When we seek to broaden participation, it is important to disaggregate outcomes by groups to check for systematic underserving.

We found evidence that K-12 students who participated in engineering activities scored significantly higher on science and mathematics achievement tests [9, 26, 29, 31-36] and on well-aligned pre/post tests [37]. We synthesized a set of papers showing that design-oriented and scaffolded inquiry approaches tended to lead to greater gains than more scripted or traditional approaches [38-44]; students tended to learn little when they lacked access to scaffolded high quality curricula and when their teachers had not benefited from extended professional development [45-47]. In studies that compared groups or disaggregated results across subgroups, students from groups underrepresented in engineering have tended to fare well [48, 49].

Our review also revealed commonplace methodological concerns, including simply not designing a means to assess or evaluate the impact of a program, uncertainty about how to analyze data related to learning and participation, overreliance on post-assessments, self-reports and “anecdotal data,” a focus on self-selected populations, and infrequent comparison/disaggregation.

Our purpose in this paper is to update our previous review, considering papers published between 2008-2016, and to provide guidance to the community of K-12 engineering education researchers on identified gaps in understanding.

Methods

We build on our previous reviews [1-4] spanning 1990-2007 (n=230 papers and proceedings). We extend our previous review to include papers published between 2008-2016 (n=131 papers). In both cases, we conducted our review first using Google Scholar and a set of search terms; we used synonyms for K-12 settings, (e.g., elementary, secondary, P-12, etc.), informal settings (e.g., museums, afterschool, etc.), and engineering. Although we included papers that fall under the fields of electrical and computer engineering, such as designing circuits, we delimited computer programming and computational literacy papers from our focus, as these were excluded from our original review, and because this area has been reviewed elsewhere recently [50, 51]. Initially, we limited our recent review to peer reviewed journal articles. We then expanded our corpus to include proceedings, especially from the ASEE PK-12 division.

We coded each paper using the coding scheme from our original work [1-4] (Table 1). However, we omitted one category, soft skills, because very few papers included it as a goal, even in the original review (and none of those reported results related to soft skills). Multiple coders were assigned to several papers and we discussed any disagreements, per recommendations for qualitative analysis [5]. The coding scheme categorizes papers based on their goals, the data and analysis detailed, and the outcomes achieved. We identified 76 papers and proceedings with interpretable results (see Appendix). We then synthesized findings and gaps from the recent time period.
Table 1. Coding scheme

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Goals / Focus of study</strong></td>
<td></td>
</tr>
<tr>
<td>Achievement in STM</td>
<td>Goal of paper is to study student learning/achievement in a science, math, or technology area</td>
</tr>
<tr>
<td>Achievement in Engineering</td>
<td>Goal of paper is to study learning/achievement in engineering facts, concepts or practices</td>
</tr>
<tr>
<td>Recruit/Retain</td>
<td>Goal of paper is to study ways to recruit and/or retain students in engineering</td>
</tr>
<tr>
<td>Nature of Engineering</td>
<td>Goal of paper is to study something about the nature of engineering, what engineering is, what engineers do, what design is, or similar</td>
</tr>
<tr>
<td>Interest in Engineering</td>
<td>Goal of the paper is to study awareness of, interest or interest development in engineering generally (usually using survey, interview)</td>
</tr>
<tr>
<td>Interest in Engineering Job</td>
<td>Goal of the paper is to study interest or interest development in engineering careers specifically</td>
</tr>
<tr>
<td>Broaden Participation</td>
<td>Goal of paper is to study (ways to increase) diversity, inclusivity, broaden participation, or equity in engineering (gap)</td>
</tr>
<tr>
<td><strong>Data types</strong></td>
<td></td>
</tr>
<tr>
<td>Qualitative Data</td>
<td>Includes direct data, such as quotes, transcript, student work samples. Must include some indication of how data were collected.</td>
</tr>
<tr>
<td>Poor Data</td>
<td>Data were of poor or questionable quality, asking students to evaluate their learning, sharing “anecdotes” or qualitative data with no description of how data were collected, making them untrustworthy</td>
</tr>
<tr>
<td>Affective/Non-Cognitive</td>
<td>Measure of student experience, interest, self-efficacy, or similar, typically using a survey</td>
</tr>
<tr>
<td>Achievement or Learning</td>
<td>Measure of factual, conceptual knowledge or of practices, including standardized exams</td>
</tr>
<tr>
<td><strong>Quantitative methods</strong></td>
<td></td>
</tr>
<tr>
<td>Disaggregation</td>
<td>Compares sub groups (male/female; White/nonwhite students, etc.)</td>
</tr>
<tr>
<td>Control or Compare</td>
<td>Compares an experiential or intervention group top a control or comparison group</td>
</tr>
<tr>
<td>Pre</td>
<td>Includes a pre-test</td>
</tr>
<tr>
<td>Post</td>
<td>Includes a post-test</td>
</tr>
<tr>
<td>Delayed Post test</td>
<td>Includes a delayed post-test</td>
</tr>
<tr>
<td><strong>Qualitative Methods</strong></td>
<td></td>
</tr>
<tr>
<td>Analysis</td>
<td>Details how analysis was done, such as by coding data or interaction analysis</td>
</tr>
<tr>
<td>Interpretation</td>
<td>Includes interpretations of qualitative data</td>
</tr>
<tr>
<td><strong>Outcomes</strong></td>
<td></td>
</tr>
<tr>
<td>Achievement in STM</td>
<td>Results relate to student learning/achievement in a science, math, or technology area</td>
</tr>
<tr>
<td>Achievement in Engineering</td>
<td>Results relate to learning/achievement in engineering facts, concepts or practices</td>
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In our review, we found that many papers reported different nuances of the same studies. We wonder whether/how this limits our vision for what could happen in K-12 settings, in terms of engineering education.

(1) Developing interest and identity in engineering

We coded 59 papers as having goals related to developing K-12 student interest or identity in engineering. Of these, 30 reported interpretable outcomes (51%). Although this is more than half, and the importance of increasing interest in engineering generally might be considered a broad motivation, it is important that researchers identify specific goals and consequent research questions. Studies should be designed to measure and report those outcomes, and the work should be situated within the existing literature on those intended outcomes.

These papers demonstrate that various engineering experiences have potential to increase student interest in engineering generally [52-79]. Few studies have linked interest development to other well-studied constructs, such as self-efficacy [71].

Some pieces proposed theoretical frameworks or research agendas, or provided a synthesis of existing literature, e.g., Brophy et al. [80]. These are valuable in their own right, but did not add to the existing body of empirical research. Only 5 of the studies included a control or comparison group, and, although some used a pre/post design that allowed students to serve as their own controls to some extent, this remains a major limitation. Only one study involved a delayed post assessment [76], allowing researchers to shed light on the persistence of the gains measured. Of more concern was the number of studies reporting only student enjoyment or anecdotal outcomes.

Well done qualitative studies represent a gap in the literature on developing interest in engineering. We identified only one paper with a case study design [81]. Detailed, qualitative investigations are needed to complement and elucidate mechanisms for the effects identified in quantitative work.

Of note also is a single paper dealing with the development of a measurement scale [82]. The creation of a scale that will allow comparisons across interventions and techniques is a valuable
contribution. Likewise, studies using increasingly well vetted instruments, like the DAET or the MATE [68], provide more useful, generalizable findings.

Most papers focused on developing interest in engineering, and very few focused on developing identities as future engineers [82]. Research in other fields links learning and identity [83], suggesting that what one learns can changes one’s identity, and how one identifies oneself changes what one seeks to learn. For this reason, we argue that a focus of research in K-12 engineering education, especially for qualitative studies, could be on early identity development.

(2) Developing interest in engineering careers

We coded 29 papers as having goals related to developing K-12 student interest in engineering careers. Of these, 13 (45%) provided outcomes that were interpretable. One additional paper [59] reported interest in engineering careers as an outcome without stating it as an explicit goal. Broadly, these papers suggest that a range of K-12 engineering activities have the potential to at least temporarily increase students’ interest in engineering as a career [54, 59, 66, 72, 73, 75, 77, 78, 84-88].

However, many of these papers were also coded as reporting on interest in engineering as an outcome variable, and therefore have many of the same concerns that were identified in those papers. None of the studies that included interest in engineering careers as outcomes involved a delayed post assessment; as entry into a career is remote choice for most of the participants, this is of even more concern in regard to the usefulness of the data collected.

On the other hand, 7 of the 14 studies did employ a pre-post design enabling the researchers to correlate changes in career interest with interventions. Only one, Thompson et al. [54], included a control or comparison group. These authors used the DAET to study the perceptions of engineering careers on the part of African American sixth grade students who had engineering graduate students in their classrooms the previous year (intervention) as compared with a comparable group of students who did not. Although this study did not measure interest in becoming an engineer directly, it did investigate awareness of engineering careers. The authors argue that, “Ultimately perceptions affect career options, currently contributing to significant shortages in the engineering work force and inaccurate perceptions of these fields” (p. 208). Pre-test results were commensurate with other studies, showing that students have a very limited view of careers in engineering, seeing engineers as involved primarily in construction, physical activity rather than designing. In outcomes similar to those reported in other studies, post intervention perceptions were much more nuanced, reflecting awareness of multiple career options within engineering and focusing much more on mental tasks. Perceptions of the comparison group remaining essentially unchanged. This result is consistent across many studies: exposure to working (or near working in the case of graduate students) engineers enhances students’ career perceptions.

In another notable study in this group, Christiansen and colleagues [85] investigated gender differences in dispositions toward STEM careers among students attending a university-based residential science and math academy. This study employed a pre-post design and found (in alignment with other studies of students experiencing engineering education) that interest in engineering careers declined during the first year, but rose among second year students. In the
first year, male students held more positive dispositions toward engineering than female students, but this difference became statistically insignificant among second year students. Female students tended to have more interest in a STEM career throughout.

Ing, Aschbacher, and Tsai [88] also investigated gender differences in interest in engineering careers, in this case among middle school students. They found that female students were as consistent as males in their interest in careers in science, but less consistent in interest in engineering careers. Knowing an engineer was correlated with engineering career interest for male, but not female, students, but a childhood interest in engineering was correlated with career interest for both. Thompson and Lyons [54] also found an effect of familiarity with an engineer on career interest, but data from that study were not disaggregated by gender. As ‘engineer in the classroom’ interventions are commonly proposed as means to enhance career awareness and interest, a gender difference in this effect merits further investigation. Finally, Ing et al. [88] found that both male and female students were interested in careers where they could “discover new things that help the environment or people’s health” (p.1), pointing to the need to emphasize the ways that engineering benefits society reported in other work [89].

(3) Recruitment/retention of increased numbers of engineering students

We coded 25 papers as reporting a goal of recruitment and/or retention in engineering education. Of these, only 5 (20%) reported recruitment or retention outcomes of any kind. The small number of studies listing recruitment and retention as goals is a concern in and of itself, made more serious by the fact that only one-fifth of these reported results. Cantrell and Ewing-Taylor [86] report high school seniors’ intentions to focus on different areas in engineering after attending a seminar on engineering career awareness, but do not report actual matriculation results, a major limitation. This gap is understandable, given the long-term, longitudinal nature of studies that would address the issue. However, although increasing interest in, and understanding of, engineering are important goals, if we aim to increase the number and enhance the preparation of students entering engineering, then more studies of recruitment and retention are needed.

All of the major findings in regard to recruitment and retention were from large scale statistical studies. San Pedro et al. [60] used data analytics to develop a model to predict which middle school students would ultimately choose STEM majors. There was no control or comparison group (all students were experiencing the same instruction), but the regression model included characteristics such as knowledge and interest, informing the development of interventions and strategies. Although the study used a limited sample, and the model produced was only able to predict enrollment in college STEM about two-thirds of the time, the work represents a contribution in demonstrating the application of this methodology to predict engineering education outcomes.

Lee [90] used structural equation modeling on data from a large national survey of students to determine the influence of an educational strategy (computer-based learning activities in math classrooms) on the choice of a STEM major. The study also looked at the influence of teacher motivation on math self efficacy. The related construct of math identity has been shown to influence engineering enrollment [91]. A major limitation in this work is that the study did not distinguish engineering from STEM majors, such as biology, where recruitment and retention
patterns are quite different. Further, the study could not provide details of how computers were used as the survey only asked how often students used a computer in the classroom.

Tyson [92] also investigated factors influencing degree attainment using a large data set. He found, not surprisingly, that achievement in high school physics and calculus predicts achievement in college calculus and physics, engineering gate-keeper courses, as well as some aspects of earning an engineering degree. Perhaps less expected, but in resonance with other results [93], college calculus and physics grades did not directly correlate with migration out of engineering into other fields. Further, completing these engineering prerequisites at a community college had no effect on the likelihood of attaining an engineering degree. These results point toward actionable strategies to increase recruitment and retention, such as promoting the acceptance of transfer coursework from community college in engineering degree plans.

The trade-off between large, representative samples, and rich detailed, information, is inevitable, and points toward the need for more case study, focus group, and other qualitative designs. The lack of qualitative studies of how pre-college engineering education influences recruitment and retention indicates a substantial gap in the existing literature. Well done qualitative studies that focus strictly on the influence of pre-college experiences on decisions to enter and stay in engineering specifically, as opposed to STEM more broadly, are needed. These could, for example, shed light on how and what kinds of computer-based activities motivate students to enroll in engineering, or how teacher motivation translates into student self-efficacy, informing the design of pre-college curriculum and teacher training.

(4) Learning and achievement of science, technology, and mathematics content and practices

We coded 44 papers as having goals related to learning and achievement of science, technology, and mathematics content and practices. Of these, 18 (41%) provided outcomes that were interpretable. We identified few large scale and multiple small scale studies. Broadly, there is evidence that K-12 engineering activities sometimes enhance science and mathematics learning, but this is dependent on effective integration, an issue that has been noted elsewhere [20]. For instance, students who participated in Project Lead the Way had marginally significantly higher mathematics—but not science—scores [94], but only when controlling for contextual variables [95].

Smaller scale interventions have found that students make learning gains in science and mathematics concepts, based on pre/post assessments [96-99], though some such studies used a very selective or restricted sample. For instance, in an outreach program, students who participated in a short wind turbine activity learned about wind energy [100]. And using engineering examples to teach physics concepts resulted in large learning gains, in a small sample size [101]. Others have compared multiple groups, using only a post test [58] or using both pre-and post-tests [62], resulting in gains that support the use of engineering in science and mathematics classrooms. These provide examples of ways to assess learning gains, even in small interventions.

Another approach taken in recent small scale studies is to compare two or more types of instructional approach. For instance, on one study, researchers found that students were more successful at transferring their understanding when they learned how to solve an abstract
problem, compared to a contextual problem, though they favored the latter [102]. In another example of a comparison study, students in a design class made significant gains over those in a more traditional scripted inquiry class [103]. Similar results have been found in a study that controlled for interest, showing that students can learn science through designing [74].

Also helpful are papers that carefully detail the design of their curriculum and theory of learning, paired with data about a successful implementation. For instance, students learned complex chemistry concepts through an engineering design process guided by a learning cycle [77].

A particularly helpful approach to small scale studies is to assess learning gains and also analyze how students participate. For instance, in a summer robotics camp in which students made significant learning gains about systems, Sullivan analyzed how students deployed science process skills such as hypothesis testing and controlling variables to support their learning in an open inquiry setting [104].

Other studies raise concerns about student access to rich and high quality content. Findings from a study comparing how a teacher differently implemented the same engineering curriculum to a high and low tracked classroom demonstrate how few opportunities students had in the low tracked classroom to work in groups and demonstrate their ideas [105]. Students in the low tracked classroom made lesser gains.

Findings like these— from studies that combine data about learning gains with a picture of how learning was or was not supported help curriculum designers and teachers/facilitators as they design and implement engineering curricula.

Based on their findings on comparisons between PLTW and non-PLTW students, greater insight into strong and explicit integration of engineering and science/mathematics content is needed [94, 95]. This is further supported by mixed methods research showing that students only sometimes applied relevant science and mathematics content in their engineering designs [106]. Both small scale and large scale studies could continue to tackle this issue.

(5) Learning and achievement of engineering content/practices

We coded 46 papers as having goals related to learning and achievement of engineering content/practices. Of these, 15 (33%) provided outcomes that were interpretable. A number of papers demonstrate student learning gains related to engineering content and practices [52, 55, 59-61]. For instance, students who got a combination of contextualized and abstract problems performed higher on a near-transfer task than those who only got abstract or contextualized problems [68] and students who got only abstract problems preformed higher than those who only got contextualized problems [61].

Some studies provide data to show how students participate or engage in an engineering activity. For instance, Reeping and Reid created observation forms to track what students were doing as they worked on a spaghetti tower challenge [69]; helpfully, they describe the challenge and identify weaknesses based on student activity. Others have created observations protocols to observe engineering activities in a museum, finding that facilitators helped visitors engage in engineering behaviors, such as testing and revising a design [70].
Others analyzed qualitative data such as artifacts of student work [56, 67, 71] or video recorded student activity; they coded the qualitative data, including detailing how they developed the coding scheme and how reliable their coders were. For instance, one study found that students spent more time engaged in mathematical and graphical modeling than physical modeling, in contrast to previous research findings, but seldom used mathematical modeling to inform their designs, echoing findings in the previous section about the challenges to integrating engineering and mathematics content successfully [72]. In a study of high school students who had completed engineering courses, student design process was compared to expert design process, finding that the students spent significantly less time gathering information, making decisions, and evaluating the feasibility of their design ideas [73]. Others present interpreted vignettes of classroom activity and detail methods such as interaction analysis [74] or ethnography [75]. For instance, in such research conducted in an elementary school, we see how students are able to identify and frame engineering problems in their own school that affect the students, and also that even young students can make predictions and plan testing of their prototypes when they are designing with contexts they understand in mind [76]. And in research conducted using a game in which girls role-played as mechanical engineers, the girls developed engineering skills and knowledge, and these were particularly supported by having a client and reflecting on progress in a notebook [10]. Such studies provide a trustworthy depiction of how engineering activities unfolded in a classroom and can provide important insights and inspiration for curriculum designers and teachers/facilitators, sometimes revealing unexpected opportunities about the learning potential of students.

In some cases, authors included interpretations of or findings from qualitative data, but provided little detail about data collection and analysis procedures or provided no data. Standards for qualitative methods include leading the reader through the logic of the interpretive or analytic activities and providing sufficient evidence to understand data collection, analysis and interpretative procedures [5]. Another concern regarding some studies is that study participants are sometimes identified, either by including photographs or even first and last names. University Institutional Review Boards (IRB) sometimes approve the use of photographs when participants and their legal guardians have provided their consent to do so, but it is unlikely they would permit full names to be included. Our concern is that a great many published studies and proceedings lacked any IRB review. We recommend that any journal or conference proceeding require some assurance that IRB approval has been sought if data are included.

We also found a few quantitative papers that raise methodological concerns, sometimes because comparison groups were treated as control groups, and sometimes because a large number of t-tests were performed, raising the chance that significance was found where none existed (making a Type I error). In the former, authors sometimes compare two classrooms or two schools. While true random assignment in authentic educational settings is understandably challenging, it is important to acknowledge the limitations and alternative interpretations posed by a non-random comparison. For instance, the student population, teacher qualifications, or resources may be different in a way that matters. Rather than simply acknowledging these as potential issues, a strong discussion engages these by considering ways they might help or harm an intervention when it is tried in a new setting. Such information is valuable to curriculum designers and teachers/facilitators because it can guide them to understand how or where an intervention might fail when tried in a new setting.
We found no recent examples of larger scale investigations of the impact of engineering activities on student learning. The majority of papers we reviewed focused on learning more about how activities support participation and learning, sometimes from very specific lenses. Because of this, we see that further work should focus on this aspect, especially on understanding how to support students to engage in engineering practices, identifying the conditions under which students learn these practices. We did not find examples of research investigating transfer of practices following an intervention, and this would be a worthy focus for future studies.

(6) Understanding the nature of engineering

We coded 33 papers as having goals related to understanding the nature of engineering. Of these, 20 (61%) provided outcomes that were interpretable. A common measure of success for engineering activities is to investigate the degree to which students learned more about what engineers do. This has been investigated using single, open-ended questions on surveys and interviews about what engineers do, as well as the Draw An Engineer Test [77]. A number of studies have shown successful changes, with students typically shifting from viewing engineers as working on cars and trains to designing and researching [77-79]. For instance, in a large scale study of the impact of engineering graduate student outreach to middle school students, the students developed greater awareness about engineering as a design and research field [79]. Students who participated in an engineering activity at an aquarium developed more accurate descriptions of what engineers do [80]. Quasi-experimental designs have shown that this is different from general interest and suggest that deliberate exposure to engineering activities is needed to support this shift [81]. Further, some studies show shifts in their perceptions of who can be an engineer, with greater representation of non-white males following participation in engineering programs that seek to broaden participation [77].

Collectively, these studies establish that even relatively brief engineering activities can help students develop a more accurate understanding of what engineers do. Further research on this area is not warranted. However, a majority of studies have focused on this in isolation of other variables. Additional research studies could investigate whether this shift is long lasting, and if it is, whether it correlates to other variables, such as interest, STEM course taking, pursuit of opportunities to engage in additional engineering activities, and learning/achievement.

(7) Broadening participation of diverse learners

We coded 28 papers as having goals related to broadening the participation of diverse learners. Of these, 11 (38%) provided outcomes that were interpretable. However, an additional three papers, although not having broadening participation as a stated goal, did in fact report the effect of engineering interventions on groups that are underrepresented in the engineering workforce. For example, Blanchard et al. [75] measured gains in understanding of engineering design and engineering career awareness from before to after an after-school robotics intervention. These authors did not cite increased diversity in engineering as a goal, but report that their study population included a high percentage of Hispanic students, 79.71%, compared with a nationally representative sample of students. Their target population also included statistically higher numbers of students who immigrated to the US—predominantly from Mexico and Central America—as children, with or without documentation, and who speak a language besides
English at home. Likewise Reeping and Reid [59] did not cite diversity as a goal, but reported gender differences in student responses to a survey after an engineering career awareness day, with male students more likely to say that they want to be an engineer. Riskowski [107] also presented disaggregated data by gender and ethnicity, reporting that students experiencing an intervention had significantly higher gains in thinking on open-ended items and content knowledge, with students from disadvantaged groups performing equally well as more advantaged students.

Of the papers that did claim increasing diversity as a goal, Mehalik et al. [103] is of note. This study reports the ability of designed based interventions to close the equity gap in engineering education as compared to scripted inquiry, especially for African American students who previously had not been achieving as highly as other students in school. The researchers employed a pre/post design to measure changes in core science knowledge, engagement, and retention, with the conventionally taught, scripted inquiry students as a comparison group.

Also of note, Schnitka [105] presents a rare example of a well designed qualitative study among the articles we coded as having a goal of increased diversity. This study provides a detailed look at the actions of a middle school science teacher incorporating engineering into both her higher and lower ability tracked classes, and the disparate outcomes, particularly for her students with learning disabilities. Attitudes in the advanced class improved toward engineering, whereas they decreased slightly in the ‘standard’ class. Further, the standard class did not learn the content to the same conceptual level. Analysis of the teacher’s beliefs and the way she differentiated instruction between the two classrooms delves into possible mechanisms leading to the disparate outcomes. Although many studies report disaggregated outcomes, few consider the theoretical rationale for expecting differential outcomes between groups, other than traditionally reported lower levels of participation and achievement in engineering.

**Comparison with previous reviews**

Table 2 illustrates the relative category coverage in our previous reviews and the current one, indicating the percentage of total papers reviewed that provided interpretable outcomes in each category. We used similar categories across the reviews, except “soft skills” was previously reported as a separate category, whereas in this round it is consolidated into engineering practices, following the highlighting of teamwork and communication as engineering skills [108, 109].

Table 2. Percentages of total papers in each review period reporting interpretable outcomes in each category

<table>
<thead>
<tr>
<th>Category</th>
<th>1990-2007</th>
<th>2008-2016</th>
</tr>
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<tbody>
<tr>
<td>Engineering Interest</td>
<td>0.5% (1 paper)</td>
<td>23%</td>
</tr>
<tr>
<td>Interest in Engineering Careers</td>
<td>1%</td>
<td>11%</td>
</tr>
<tr>
<td>Recruitment/Retention</td>
<td>2%</td>
<td>4%</td>
</tr>
</tbody>
</table>
The percentage of total papers reporting interpretable outcomes increased markedly in each of the coding categories, although many papers still fail to report an interpretable result (note that the categories are not mutually exclusive and the total is still less than 100% of papers). Papers reporting interpretable outcomes increased by more than a factor of 10 for both interest in engineering and interest in engineering careers, indicating that previous reliance on anecdotal reports of interest and enjoyment are giving way to more reliable methods, such as more rigorous survey methodologies. It is not surprising that demonstrated increases in interest should precede documented increases in recruitment and retention, as interest is likely a predominant factor in recruitment and retention, however it is still of concern that papers reported interpretable outcomes on recruitment and retention have yet to break 5% of the total, especially if increasing the number of engineers and engineering ready students is a goal.

Table 3 compares the status of methodology reported in the previous review with that in the current review, showing the percentages of total papers that fell in each of the coding categories for methodology. Note that overall the percentage of total papers that fell in each of the coding categories was higher in the recent review. While an increased percentage of papers included more rigorous qualitative data, few papers included rigorous qualitative analysis.

Table 3. Status of methodology.

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<tbody>
<tr>
<td>Rigorous qualitative data</td>
<td>11%</td>
<td>37%</td>
</tr>
<tr>
<td>Non rigorous qualitative data</td>
<td>7%</td>
<td>21%</td>
</tr>
<tr>
<td>Quantitative data, including a pre/post design</td>
<td>10%</td>
<td>29%</td>
</tr>
<tr>
<td>Quantitative data, including a control or comparison group</td>
<td>6%</td>
<td>11%</td>
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</table>

**New Findings**
We report new findings from our recent review, which extend the scope of understanding beyond our prior review. First, it is fairly well established that students are likely express interest in engineering at the conclusion of outreach programs and other experiences that involve them in design and other engineering activities, and the interest is likely to increase from pre to post assessments, although more studies with control groups and delayed post tests are warranted. It is well established that deliberate exposure to engineering activities promotes a better understanding of what engineers do and who can be an engineer, although studies of the duration of the effect might still be warranted. For female students, childhood interest in engineering may correlate more with interest in engineering careers than knowing an engineer. Although the findings need to be corroborated, one study found that completing engineering prerequisites at a community college did not affect the likelihood of completing an engineering degree once enrolled at a four-year institution.

Broadly speaking, K-12 engineering activities promote science and mathematics learning, but the effect is far from uniform and dependent on implementation. In particular, and as has been of recent interest, integration of engineering and other content is critical. Recent findings make clear that when provided with a relevant design problem and scaffolding, even young students can design solutions and learn as they do so.

**Significance and implications**

While we found increasingly rigorous approaches to research methods, there are still opportunities for growth tied to qualitative methods in particular. However, we found a number of persistent methodological issues that have continued since our initial review. To address these, we suggest the following; journals and conferences should:

- encourage more rigorous studies by providing clearer guidelines about qualitative and quantitative methods;
- encourage more ethical human subjects research by requiring authors to submit the IRB approval number; and
- create design case strands/tracks for authors to submit clear depictions of K-12 engineering activities and lessons they have designed, with enough detail that others could reuse or adapt these. This practice is common in other fields, and journals could model their expectations for submissions on the International Journal of Designs for Learning, [https://scholarworks.iu.edu/journals/index.php/ijdl](https://scholarworks.iu.edu/journals/index.php/ijdl). Such contributions need not include data, but instead provide value by clearly depicting curricula that can be reused elsewhere.

Second, the field has often warranted studies or called for studies that contribute to understanding of how to recruit and retain learners from diverse groups, but few published studies tackle this topic in ways that contribute meaningfully. Unsurprisingly, few longitudinal studies exist to show real impacts, and while this is understandably difficult, we encourage researchers to look to examples of longitudinal studies, which commonly pair short term and long term studies. Such a project might involve master’s students conducting feasible studies as a thesis to maintain annual connection with participants.
Third, we recommend seeking partnerships with researchers who study relevant constructs in other fields, such as the learning sciences, cognitive science, anthropology, and educational psychology. By partnering with such researchers, there are great opportunities to jointly deepen understanding of important issues in engineering education (such as early identity development and how students can learn to design) as well as enhance understanding of these fundamental constructs (such as co-regulation, self-efficacy, identity development in youth, design learning).

Fourth, we recommend further qualitative study into integration of engineering content and practices into other K-12 topics. While there is evidence of some successes, deeper understanding of how such learning happens is still needed.

This review did not include research on teachers, which is a limitation. A future review could build on our findings, beginning with a focus on effective professional development broadly and understanding the state of the field for K-12 engineering education.

Acknowledgments

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References


### Appendices

#### Papers with outcomes about developing interest and/or identities in engineering

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Title</th>
<th>Journal</th>
<th>Page(s)</th>
</tr>
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<tbody>
<tr>
<td>Ren, W., Bradley, K. D., &amp; Lumph, J. K. (2008). Applying the rasch model to evaluate an implementation of the Kentucky Electronics Education Project.</td>
<td>Journal of Science Education and Technology, 17(6), 618-625.</td>
<td></td>
<td>618-625</td>
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<tr>
<td>San Pedro, M. O., Ocumpaugh, J., Baker, R., &amp; Heffernan, N. (2014, July). Predicting STEM and non-STEM college major</td>
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enrollment from middle school interaction with mathematics educational software. In Educational Data Mining 2014.


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<thead>
<tr>
<th>Papers with outcomes related to developing interest in engineering careers</th>
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<th>Papers with outcomes about increased recruitment of students into engineering</th>
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</tbody>
</table>
enrollment from middle school interaction with mathematics educational software. In Educational Data Mining 2014.


### Papers with outcomes about learning and achievement of science, technology, and mathematics content and practices


### Papers with outcomes about learning and achievement of engineering content/practices


Huffman, T., Mentzer, N., & Becker, K. (2013). High school students modeling behaviors during engineering design. In ASEE 2013 Annual Conference and Exposition, Atlanta, GA.


### Papers with outcomes about understanding the nature of engineering


Papers with outcomes related to broadening participation of diverse learners


<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Title</th>
<th>Source</th>
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<tbody>
<tr>
<td>Thompson, S., &amp; Lyons, J.</td>
<td>Engineers in the Classroom: Their Influence on African-American Students’ Perceptions of Engineering.</td>
<td>School Science and Mathematics, 108(5), 197-211.</td>
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