A review of literature on connections between engineering education and cognitive development in K-12 students

Joshua García Sheridan
Department of Engineering Education
Virginia Tech
Blacksburg, VA, USA
garcias1@vt.edu

***Abstract*—*This paper reviews the current body of literature comprising studies connecting engineering education in K-12 with elements of cognitive development. The process of change towards engineering being taught in K-12 classrooms involves the establishment of developmentally appropriate standards that inform curriculum. Established standards such as those of the NGSS and ITEEA STLs provide a nationally applicable framework for curricula throughout the United States. Nevertheless, it is important to critically consider what the foundations of such standards are in terms of empirical research. The development of rigorous standards for K-12 engineering education is a continuous process. Without a foundation of understanding for how children think about and learn engineering, standards will not optimally inform curricula how to teach engineering. So, do these foundations exist?*

The National Research Council (NRC) delivered a recommendation in 2010 to engage in the development of better understanding for how students learn engineering concepts in K-12. The intention of this recommendation was to facilitate effective and developmentally appropriate integration of engineering in K-12. The context of discussion in this recommendation was determining the viability and necessity of standards for engineering education in K-12. At the time, the committee determined fundamental questions were yet to be answered that would properly inform developmentally appropriate standards. This indicates that progress towards better understanding of student cognition had not occurred quickly. It is worth exploring to what extent observations such as these are currently accurate. Such shortcomings, if they exist, may critically inform initiatives within the educational research community.

This systematic literature review will seek to uncover to what level fundamental research across several major publications in the past eight years focuses on critically describing the facets of child cognition and cognitive development in relation to the context of engineering in education. The scope of the review will include empirical studies detailing the measurement of perceptions pertaining to engineering, critical assessment of knowledge transfer for and conceptual understanding of engineering content, use of language and communication by students in engineering activities, and study of systems of thinking and habits of mind affecting student performance in engineering activities.

Keywords—cognitive development, literature review, pre-college engineering

I. Introduction

A. Background

The engineering education field has become an important player in the K-12 space. Society continually experiences explosions of technology, solving and generating more problems and market niches as a result. Additionally, the prospect of automation is compromising the security of more physical jobs. The most abundant forms of work in the near future will likely involve more cerebral and social activities. As it becomes the case that students are expected to display 21st Century skills such as innovation, information and technological literacy, and socializing [1, 2], practices of engineering will constitute a strongly relevant context for students to acquire these skills while making use of math and science.

The idea of standards readily comes to mind to formalize engineering education nationally and make instructional objectives coherent for teachers in precollege education. Standards can promote the implementation of age-appropriate content into grade bands, ensuring that faculty will incorporate engineering into their curricula while doing so in a constructive and efficient manner [3]. Many states have already been implementing standards to address elements of engineering both implicitly and explicitly [4], some of which are drawn from adopted standards like that of the Next Generation Science Standards (NGSS) [5] or the ITEEA Standards for Technological Literacy [6]. Massachusetts, in particular, represents a case study of how to overcome barriers of implementation for pre-college engineering standards [4, 7], so it may be observed that establishing standards is quite achievable throughout the U.S., whether on a state-by-state basis or at a larger level.

There are, however, some notable caveats for the composition of these standards that must be considered. The National Academy of Engineering (NAE) and the National Research Council (NRC) have, in the past, looked at the research landscape of engineering education as it has progressed in implementing engineering in the K-12 space. Notably, they have discouraged the development of

978-1-5386-1174-6/18/$31.00 ©2018 IEEE

independent engineering standards for a number of reasons, one of which being a gap of knowledge in critical research spaces that would inform learning progressions [8]. One of the key recommendations in that report, repeating a previous calling for research, urged researchers to pursue a deeper understanding about how children learn engineering and when is the most effective time to learn what, specifically asking: "How do children come to understand (or misunderstand) core concepts and apply (or misapply) skills in engineering?" and "What are the most effective ways of introducing and sequencing engineering concepts and skills for learners at the elementary, middle, and high school levels?" [3, 8]. Two years later, the framework that aided the development of the NGSS, for lack of major evidence to support sequencing of the core ideas and concepts presented in it, still placed emphasis on founding standard progressions on existing research whenever possible to assure age appropriateness [9].

It was clear that these entities regarded the matter of using cognition studies to inform the selection of appropriate content for children seriously, and that not a lot of research was present to support the creation of standards at the time. Other figures also note a disparity in translating cognition studies to something specific as engineering, particularly for K-12 teachers [10]. This is certainly not helped by the fact that sometimes teachers are unqualified to judge what is an appropriate level of application of math in engineering or technology activities that must employ it [11]. Considering the need for clarity in what we tell educators to teach children with engineering, it must then be asked: What do we know about how students are able to learn engineering? How can we know when and what to teach them? The answers may lie in understanding the application of theories in cognitive development.

B. *Cognitive Development and Engineering Learning*

If we considered suddenly implementing engineering curricula across the country, we would be introducing it to many students who may never have heard the term engineering, regardless of grade level. Additionally, they all have different levels of competency in performing various cognition tasks. The ways that students are able to think about their world or about their own thinking are important to consider for a thought-intensive discipline such as engineering. Some studies on how children think have been performed for us to draw from [12], but evidence of this understanding within K-12 engineering education studies is not conveyed often, nor have all cognitive angles of engineering learning necessarily been discovered to cite in the first place. It is not necessarily the work of a separate community of scientists to determine for us what cognitive features are most relevant to engineering learning, when they have developed sufficiently in a child to make learning possible, or what is capable of being learned. The STEM (Science, Technology, Engineering, and Mathematics) education communities have developed solid content and pedagogical frameworks with which to undertake the introduction of engineering with K-12 students [2], [13] – [16], but they must also formulate progressions grade-by-grade to integrate these frameworks into a curriculum. Studies that connect cognitive development with engineering learning will be crucial to bringing about effective education by illuminating possibilities for such progressions.

Cognitive development was pioneered by Jean Piaget, who created the theory of cognitive development to explain how children create mental models of the world they live in [17]. One of the principle concepts used to describe the process of this model-building was "schema" (or its plural, schemata), which is a unit of knowledge that adds to another to form a network of interconnected knowledge pieces relating abstract and concrete notions together [17]. Another idea of Piaget's was the progression of a child through discrete stages of cognitive development, characterized by certain competencies as the brain develops through age [17], but other cognitive theorists such as Lev Vygotsky instead eschewed stages in place of more open frameworks like the zone of proximal development in which a learner progresses in their ability through a scaffold, but only once they are prepared in other necessary areas of ability [18]. It was also Vygotsky's idea that socialized learning precedes development in this way through a "more knowledgeable other", which will, generally, be a teacher or another student [18]. In both these cases, attaining new competencies at an appropriate point, whether a process of social learning or brain growth defines said point, is the theme of cognitive development's significance to learning. It is from this general understanding of cognitive development that this literature review seeks to know to what extent the engineering education community has been able to discover cognitive features and developments in children and what the nature of those cognitive features are.

C. *Purpose of Study*

This systematic literature review will seek to uncover to what level fundamental research across several major publications in the past eight years focuses on critically describing the facets of child cognition and cognitive development in relation to the context of engineering education. The study seeks to answer two research questions: "To what extent and in what topics has the engineering education community performed cognitive development studies since 2010?" and "What have engineering educational researchers established about K-12 students in terms of cognitive features that define their capacity to learn engineering at their particular age?" In part, this study seeks to answer to the recommendations of the NAE [3, 8] that more study of student cognition in engineering be performed to better situate learning objectives in particular grade bands for application in standards. It also aspires to inform community members of work performed in research and highlight both advancements and areas for improvement in research coverage for this facet of K-12 engineering education.

II. METHODS

A. *Journal selection and search protocols*

The first stage of the selection process was to identify publications appropriate for the search. It was considered that, while articles related to the concern of this review may exist elsewhere, the review should focus upon articles that have entered publications with high impact for STEM research communities such that academic awareness of said articles would be most likely. Such articles would constitute a "mainstream" representation of the importance of cognitive development study in these research spaces. By performing a journal search with the terms "engineering education", "STEM", and "technology education" in a university's online library search engine, publications were considered for targeted article searches.

Five major publications selected for the review were identified from this initial search, and their consideration was supported via conversation with those considered experts in the field: the Journal of Engineering Education (JEE), the Journal of STEM Education: Innovations and Research (JSE: I&R), the Journal of Technology Education (JTE), the International Journal of Engineering Education (IJEE), and the Journal of Pre-College Engineering Education Research (JPEER). Conference proceedings from the ASEE Annual Conference & Exposition were also included in the search using the ASEE PEER website.

Search protocols varied for each of these journals. The nature of university access privileges enabled some, but not all, of the journals to have their articles found with the university's online library search engine. In addition, some result pools were excessively large or restrictively small to consider all results for particular search term combinations, so only searches that resulted in the consideration of at least one paper are included. The particular protocols used for each publication and initial search results are indicated in Table I.

TABLE I. LITERATURE REVIEW SEARCH PROTOCOLS

Publication	**Search protocols and terms**		
	Search engine/protocols	***Search term(s)***	***Total Results***
JEE	Wiley Online Library, search	systematic review k-12	61
		elementary school	169
		middle school	258
		k-12	73
IJEE	University Online Library, search	(PublicationTitle:("international journal of engineering education")) AND ((k-12) OR (elementary school) OR (middle school) OR (high school) OR (primary school) OR (secondary school))	74
	IJEE website, manually searched all volumes from 2010-present	N/A	1,306
JPEER	JPEER website, search	abstract:cognitive OR abstract:cognition OR abstract:understanding OR abstract:perception OR abstract:conception OR abstract:curriculum OR abstract:development OR abstract:discourse	64
JTE	University Online Library, search	(PublicationTitle:("Journal of Technology Education")) AND (SubjectTerms:(engineering)) OR ((SubjectTerms:(k-12)) OR (Abstract:(elementary school)) OR (SubjectTerms:(middle school)) OR (SubjectTerms:(high school))) NOT (PublicationTitle:(Journal of Science and Technology Education)) NOT (PublicationTitle:(International Journal of Technology Education))	24
	JTE website, incidental selections from same issues as searched articles	N/A	10 selected
JSE: I&R	University Online Library, search	(PublicationTitle:(Journal of STEM Education)) AND (SubjectTerms:(engineering)) AND ((SubjectTerms:(k-12)) OR (Abstract:(elementary school)) OR (SubjectTerms:(middle school)) OR (SubjectTerms:(high school))) NOT (PublicationTitle:(International Journal of STEM Education))	61
ASEE PEER	ASEE PEER website, search	"cognitive development", cognition, "k-12"	75

B. Procedures and criteria for article selection

Articles from 2010 to most recent issues of publications were considered in the search to characterize research not available to the NRC at the time of their recommendations delivered in 2010. Beyond this date range, the only inclusion criterion initially set during consideration of titles and abstracts for articles found in the search were that considered articles address both of the following research questions:

1. *What realms of cognitive competence for children at particular grade levels are important to understanding how they receive engineering content?*
2. *How are said competencies characterized?*

A number of articles were excluded on these grounds after initial accepted via title and abstract review. After initial selection by title and abstract content, summaries and reflexive remarks about each article considered were composed to ensure that the review process was adherent to the established criterion. 44 articles were initially accepted after full text review as a result of this process.

After searching through all selected publications, the inclusion criteria were expanded upon and refined such that the remaining 44 articles would be reconsidered to more thoroughly reflect the intentions of the review. These criteria required that the answer be "yes" to all following questions for each article:

1. *Is the study about a mental competency of some sort in relation to engineering knowledge or skill?*
2. *Is there qualitative data collection and analysis/coding involved OR does it involve a quantitative instrument that has been previously validated to determine mental competencies?*
3. *Does the paper focus on cognition that is not merely affective in nature?*
4. *Does the paper's purpose or research questions mention anything beyond assessment of an instructional or pedagogical intervention?*
5. *Does the paper study and focus upon K-12 students?*

Upon application of these criteria, the accepted articles were reduced to 32. During said application, each paper considered was re-read in the full text and summarized in a separate document with its content, including the purpose of the study, the participants, data collection and analysis methods, and major findings from results. Some initial memos of noticed patterns were composed and retained for the analysis process. The sequence of review and numerical depiction of considered studies in this procedure is shown in Fig. 1.

C. *Analysis*

After the finalization of selections for the review, coding was performed to identify major features of each article according to summaries and specific probing of the full text. These codes were partly open in the sense that no framework was applied, but often followed emergent labeling procedures such that labels reflected previously noticed patterns attributable to more general constructs. Multiple coding runs were performed to fully account for studies that retrospectively fit into these these emergent codes. The codes reflected cognition topics explored by the articles, the age and grades of the participants studied, and the prior experience of said participants and their teachers. Selected frequencies of these codes are displayed in Table II**.** Frequencies of school ages by academic tier (elementary/middle/high school) and grade (K-12) are displayed in Fig. 2 and Fig. 3**.**

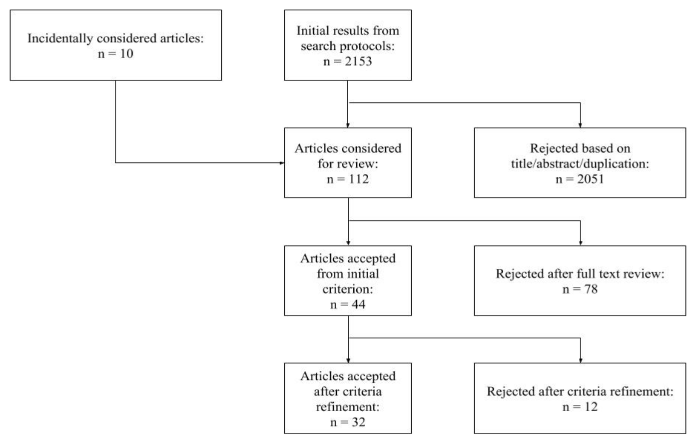

Fig. 1. *PRISMA flowchart of review procedure [19]*

TABLE II. DESCRIPTIVE CODES

Codes	**Description**	**Frequency**
Engineering systems of thinking	Study focused on evident competencies for thinking in design or other engineering approaches	18
Knowledge	Study focused on understanding of knowledge related to specific engineering tasks; distinct from engineering schemata as knowledge *not* related to engineering overall as a discipline and career	9
Transfer	Study focused on ability of student to use knowledge in engineering context; is highly associated with knowledge code, but distinguished by the application of said knowledge in a novel task	7
Engineering schemata	Study focused on student pre-existing conceptions of engineering as a discipline or career	7
Temporal design emphasis	Study particularly focused on how much time was spent in particular design tasks as a way of viewing what students would focus on	3
Metacognition	Study assessed students' self-awareness and control over their own learning	2
Discourse	Study focused discussion around how students were communicating as a way of determining competence	5
Social development	Study focused on social competencies displayed by students in teams	6

Codes	Description	Frequency
Epistemology	Study focused on student's understanding of the nature of engineering knowledge and knowing rather than the knowledge itself or engineering itself	1
Information schemata	Study explored student competencies in information-seeking tasks related to engineering design	1
Emotional development	Study focused on emotional competencies of students relevant to social engagements	1
Engineering/technology experience/class	Students in study were stated to have had prior or present engineering/technology/integrated STEM instruction or exposure	23
Teacher with Professional Development	The teacher(s) directing the class during study were stated to have received professional development training in engineering/technology/integrated STEM instruction prior to study	6

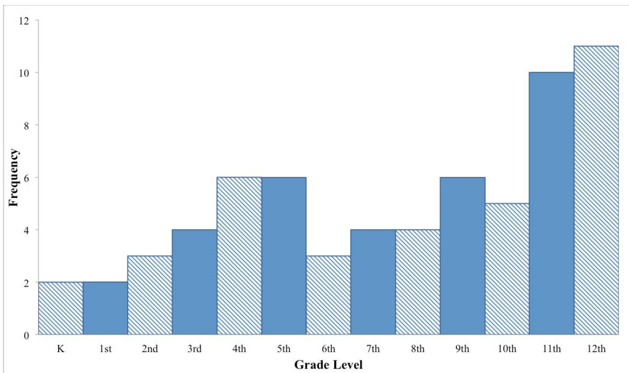

Fig. 2. *Distribution of study coverage by grade level*

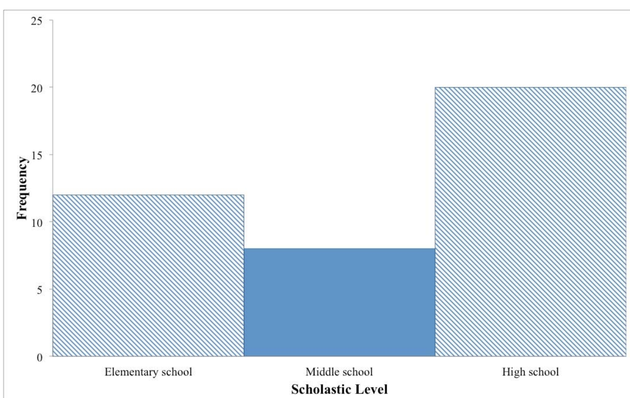

Fig. 3. *Distribution of study coverage by scholastic level*

D. *Limitations*

This study bears a number of limitations to its validity and reliability. Firstly, only a single author is primarily involved in its selection and analysis procedure. It is to be considered that having two or more researchers performing independent assessment of studies decreases the possibility of bias, which may result in the exclusion of potentially relevant studies. Adding to this, the criteria established in the course of the selection process may involve interpretation that is subject to bias as well, also affecting results. Because of the considered scope of the review and possible biases resulting from criteria, many possible publications and articles that might offer relevant studies to cognitive development in engineering activity have most likely been omitted; it should be considered that the number of accepted articles here do not necessarily reflect the true level of advancement of this topic in research. The intention is that this review reflects the most visible and representative advancements.

III. RESULTS

As shown by previous figures and tables, the pool of accepted articles covered a wide range of grade levels and provided adequate coverage of each scholastic level. A variety of cognitive features and study characteristics worthy of remark came up in the course of the review as well. Discussion of these results follow in the proceeding sections.

A. *Grade and Scholastic Coverage*

One of the purposes of this study was to determine the extent to which study of cognitive development has been conducted in K-12 engineering education research. To address this, the scholastic and grade levels at which studies were conducted were noted. In general, there are a great number of high school level studies performed [20] – [39], of which there are significantly more samples composed of upperclassmen. This pattern arises often because of the nature of many engineering education initiatives focusing on pre-engineering programs that transition directly to undergraduate pursuit of engineering. A common feature of convenience as a result of choosing upperclassmen is that students from school systems that offer pre-engineering coursework have attained some experience with engineering content. 17 of the 20 high school studies conducted note a level of engineering-related coursework or experience, which is the highest proportion among scholastic groups. High school studies only mention profession development training of the presiding teacher once, but with so many of the studies involving formal coursework in engineering, it may be surmised that teachers heading those classes also have appropriate training or experience in those cases.

Elementary school level studies [25], [28], [40] – [49], which are also adequately represented in the selected articles, have gradually rising counts of particular grade or age levels, which is probably because students in this developmental period are easier to manage as research subjects as they get older [50]. Despite such difficulties, the number of elementary school studies is not particularly low. While the involvement of elementary-level engineering curricula or other experiences are certainly one factor, this does not account for all occurrences; only 6 of 12 elementary school studies note that their subjects had prior engineering experiences. On the other hand, elementary school studies are somewhat likely to be studies where teachers received specific professional development training for engineering education; 4 of 6 studies that reported classroom teachers having had professional development in engineering are situated in elementary school age ranges.

There are fewer middle school level studies than any other scholastic level. This may have more to do with the relative briefness of the grade range (generally, only 3 years of life are spent in middle school versus 6 years and 4 years in the other two categories). Of the 8 studies situated in middle school age ranges [23, 25, 26, 28, 44, 47, 51, 52], 4 are with subjects bearing prior experience in engineering, and 1 involves a teacher stated to have professional development in engineering instruction.

B. *Topics of cognitive development*

This study sought to answer to what topics of cognitive development are engineering education studies at the K-12 level performed. In answering this question, it is also useful to consider the general intention behind most of these studies.

College preparedness and gauging the advancement of students towards expertise in engineering knowledge, skills, and abilities appears to be the most prevalent motivation driving the study of cognitive developments in students. Cognition studies of un-initiated students in the context of engineering appear to be greatly oriented around simply understanding what children know about engineers. Not many studies spontaneously present a design task to students without some assurance that they have been instructed on design principles to see what happens. Notably, this review did not specifically use the search term “habits of mind” to determine if such developmental work has been performed at these levels, but one would have supposed that with the general search terms provided, such a paper would have been found among the publications.

Regarding topics of cognitive development, the most prominent are those dealing directly with student competencies in thinking practices tied directly to engineering tasks and content. Systems of thinking [20], [26], [28] – [30], [32], [36] – [40], [43], [45], [46], [48], [49], [51], defined as cognition practices associated with engineering strategy and logic, seem to be the major concern in many studies. A grand majority of these cases have purpose statements oriented around understanding how students go about performing design and what their thought processes are. On occasion, a different approach within design process studies is to look at students’ design emphasis on the basis of how much time is spent during a particular stage of design [22, 37, 38]; this has been the case a number of high school studies as a way of gauging how close students are to resembling expert engineers in the process.

Transfer [20, 23, 26, 27, 35, 43, 46], knowledge [20, 21, 23, 26, 27, 29, 30, 35, 43], and the established schemata for engineering in students [21, 24, 25, 31, 41, 42, 44] constitute more fundamental cognitive considerations. Separate from systematic thought processes, transfer and knowledge are aspects of thought that apply to single instances of engineering learning; knowledge relevant to an engineering task is retrieved from memory, and if this unit of memory is derived from an entirely different context of learning, that defines transfer. Engineering schemata, on the other hand, are retrieved when approaching the subject of engineering as a general entity or domain. When a student is primed to learn something about engineering, this prompts associations for the student such that they consider various traits and knowledge being associated with that domain; it is then important to understand what the student thinks engineering is so that their expectations are properly met or challenged. These small-scale aspects of cognition are less frequent individually than design thinking analyses in coverage by research studies, but, in total, they are of similar prominence as topics of study. Several cases of these studies apply the Draw An Engineer Test (DAET) to determine engineering schemata [41, 42, 44]; this test, having been applied primarily in elementary school studies, has students draw what they think an engineer at work looks like. In the cases of transfer and knowledge, which often go hand-in-hand, there are an adequately diverse number of different forms of knowledge and contexts of transfer to suggest that these rudimentary areas of cognition bear many possibilities for study. In addition to these prominent topics, one study investigated information schemata, which involved understanding what students would do when looking for information in print or online to gather necessary data for engineering tasks [29]. Information literacy and research techniques are important for engineering designs to be theoretically substantiated, making the process of iteration generally quicker and more efficient.

Some topics of study focused on aspects of cognitive development that would be associated with professional skills, which is notoriously neglected in college settings. Social development, being important to teaming activities engineers are expected to engage in, has an adequate presence among the considered articles [23, 34, 40, 47, 52]; such a cognitive aspect of development is something that educators in all fields have been concerned about in K-12 for a long time, but understanding what it means for engineering activity is a valuable undertaking. One study sought to understand emotional development more particularly for an at-risk demographic set of students, which was used to begin uncovering the role technology education was playing for such students given their high levels of participation in technology education [34]; emotional development bears strong relation to social development, but also touches realms of cognition that are more transient and affective in nature, such as engagement or motivation. Discourse analysis of students directly talking with one another [40, 43, 45, 51, 52] is a realm of study that also has a moderate presence among reviewed articles. One could call student discourse an application of social and emotional developments, and a few of the discourse studies focus particularly on the social dynamics of students while engaged in engineering tasks as a determination of why design projects might fail either in terms of completion or learning outcomes [40, 52]. The remainder of discourse analyses focus upon how students expressed themselves in thinking processes tied to engineering design tasks rather than specifically extracting meaning for their social synergy. Notably, the discourse-focused studies are situated exclusively in elementary school or middle school age groups.

Perhaps because they are rather advanced realms of cognition, metacognitive [35, 36] and epistemological [24] foundations of learning are rare in the studies sampled. While studies of these sorts have gained some level of prominence for college-age sample populations, there doesn't appear to be as much of a focus at the K-12 level. In fact, these features are only analyzed in high school level subjects. Metacognition has been considered by theoreticians to be a cognitive feature that develops within adolescence and adulthood rather than early ages [53]. This might explain a lack of publishing of lower scholastic level studies in the high profile publications of this review, since clear results for interventions or observations for younger age groups trying to determine metacognitive abilities would be difficult to obtain. Metacognitive studies included both metacognition applied to assessing one's systems of thinking in engineering tasks [36] and self-regulated learning practices for engineering coursework [35].

C. Findings

With the topics and extents to which studies have investigated cognitive development in K-12 engineering education defined, the last question of this review remains to be addressed: "What have engineering educational researchers established about K-12 students in terms of cognitive features that define their capacity to learn engineering at their particular age?" While many studies featured in this review are inconclusive, a number of assertions can be made through triangulation of some findings with others.

Starting from early age studies, we can see how students conceive of engineers from the outset. DAET studies [41, 42, 44] suggest that, while students can change their perceptions of what engineers are, these often do not develop into fully accurate conceptions. Most often, students without additional instruction tend to view engineering as a discipline performed by laborers or mechanics rather than designers, although more sophisticated perceptions increase by about 5th or 6th grade [41, 44]; instructing students in engineering practices and content appears to promote the view of engineers as designers [42]. Early interactions with students to teach engineering can have a significant effect on student impressions of what an engineer is, which can help inform future career aspirations. Students who don't know engineering as a practice well enough to determine what characterizes the discipline may not know that it is a highly social practice, which many students would be able to find interesting and worth pursuing as a career [25]. Unlike culturally distinct careers such as being a doctor or a police officer, the primary activity of engineers is often more obscured for children because media especially do not often present artifacts or clear modes of work definitive of engineering much less address the occupation aloud. When it does present forms of engineering practice and artifacts to students, it can often mislead students to have a rather naïve view of the work that goes into design [21].

Studies observe that elementary school students have tendencies to not notice failures of design or other taskwork they engage in [40, 46, 49]. They will, however, still perform other analytical tasks involved in design to a noticable degree, particularly when judging their designs. Often, they compare and evaluate pros and cons for their devised solutions [40, 45, 49]. Through middle school, students may tend to compare their designs against others' [26]. In this practice, there are opportunities for students to promote each other's growth, but there may be a risk of students giving too much regard for how others perform in comparison to themselves; social competition can impede students' abilities to engage in design thinking strategies such as reflective decision making [40]. Encouraging analysis practices and explicitly engaging young students in addressing failure logically and with moderated social comparisons may augment their learning as a result.

More observations of sophisticated cognitive skills exist for high school level students in systems of thinking, knowledge, and transfer. High school students as studied are shown to have rudimentary information-seeking skills, for instance, but they do not often find information relevant to understanding the problem at hand, instead choosing to focus on using the information to define materials, specifications, and other aspects of practical implementation of designed solutions [29, 39]; they can also be rather time inefficient when gathering information as a result of lacking in this skill [38]. At these ages, students also seem to believe that they understand how things work to the point where they will not explicitly discuss or document scientific or mathematical ideas, instead relying on expected behaviors of components they use in design [33, 39]. They do not generally spend as much time on various aspects of design the way experts would aside from problem definition, for which they expend significant amounts of time [22, 38]. Students at this age also do not show great sophistication or completeness in their documentation of their design processes and outputs [37, 39]. Admittedly, these negative characteristics arose from students not often being able to explicitly exhibit targeted features of their thinking systems that researchers desired to probe. Students tended to document or behave in manners that implicitly demonstrate effective forms of design thinking, however unpolished they might be. In fact, in some study pools, high school students even appear to reach the most promising stages of design thinking [30]. Additionally, potential for further application of knowledge for engineering exists as students mature such that their connections to family, community, and culture strengthen and become powerful tools to contextualize engineering instruction. One study showed that students' funds of knowledge in relation to these social connections are readily drawn when students are prompted to select and solve problems related to them; this approach personalizes the design experience and promotes transfer of knowledge in eye-opening ways for the students themselves such that they realize that engineering can have impacts on their communities, making such approaches to teaching particularly potent for minority students [20]. Nothing at the high school level really presents an indication of incompetency as much as it reflects the relative "rawness" of the age group, even in the context of having prior engineering experiences. Many pre-engineering programs focus at the high school level rather than lower levels, which may explain some of the difficulties in observing more ideal developmental outcomes at this point.

Throughout the age groups, there appear to be capacities to consider whom solutions are meant to benefit as real people with real needs and sensitivities [33, 34]. While this is a positive indication of empathy development, it is also important that students be able to show consideration to fellow teammates as they work together in groups to accomplish tasks. A handful of studies remark upon social developments in team settings specifically, most of which involved middle school aged children [23, 47, 52]. Apprehension of engineering learning obstacles for girls appears to have led to studies determining that being able to engage in discourse with knowledgable participants promotes their learning significantly, and this applies particularly in mixed gender groups more than in gender homogeneous groups [23, 52]. Children, even in earlier age groups, are capable of cooperating and collaborating in projects, especially if it involves something engaging and tactile such as robotics [47], but inequities in social status or attitudes and subsequent interaction styles may disrupt some learning outcomes in group work [52]. Negotiating the social development of students to teach teamwork practices or enable learning through group projects and activities at young ages poses a challenge for engineering educators. Finding ways to prevent problems rooted in social inequities or elevate students' social awareness and sensitivity will contribute greatly to instructional efforts.

IV. Conclusions

This review sought to determine current major topics of cognitive development as explored within K-12 engineering education and disseminated through mainstream engineering education publications. It has verified the extent of coverage in these topics and what may be said regarding cognitive development at the K-12 level. A significant motivation behind this review was to seek evidence of knowledge through empirical engineering education research that informs the age-appropriateness of core engineering principles and skills that could be taught to students at the pre-college level, thus supporting the logical creation of standards. As a result of this review, key takeaways were discovered; however, additional lines of inquiry exist that may be worthwhile for the research community to consider approaching as further research in cognitive development is pursued, of which a few will be presented below for consideration.

Metacognitive thinking practices do not appear to be well-studied. This paper suggests that the community explore such practices further towards the beginning of adolescence and in greater frequency so that trends may be found to suggest when students may be reasonably expected to reflect upon their engineering design practices and use these reflections to reinforce their learning and decision making. This review also notes a lack of consideration for emotional development and its role in promoting learning of empathy in engineering design and teamwork. Additional study also appears possible for understanding the interplay of more sophisticated engineering schemata and learning outcomes at various age levels. Finally, while implementation of engineering in public school systems across the U.S. escalates, it is worth considering that schools yet to receive interventions of engineering education remain, and if standards are devised for uninitiated districts or schools, students may generally have no background in engineering design, possibly leading to unique learning conditions from those typically considered. As such, more cognition-based studies should consider the reception of engineering instruction or engagement in engineering tasks by such students because this will support educational initiatives to formally introduce engineering in unacquainted districts and schools.

Acknowledgment

The author would like to thank Dr. Kenneth Reid from Virginia Tech for his professional advice in the composition of this paper.

References

[1] Partnership for 21st Century Learning, “Framework for 21st Century Learning,” *P21*. [Online]. Available: http://www.p21.org/about-us/p21-framework. [Accessed: 21-Apr-2018].

[2] M. C. Linn, "Designing Standards for Lifelong Science Learning," *Journal of Engineering Education,* vol. 99, *(2),* pp. 103-105, 2010.

[3] National Academy of Engineering and National Research Council of the National Academies. *Engineering in k-12 education: understanding the status and improving the prospects*. Washington, D.C.: The National Academies, 2009

[4] R. L. Carr, L. D. Bennett and J. Strobel, "Engineering in the K-12 STEM Standards of the 50 U.S. States: An Analysis of Presence and Extent," *Journal of Engineering Education,* vol. 101, *(3),* pp. 539-564, 2012.

[5] *Next Generation Science Standards*, April 2013.

[6] *Standards for Technological Literacy: Content for the Study of Technology*, 2007.

[7] C. B. Rogers, K. Wendell and J. Foster, "A Review of the NAE Report, Engineering in K-12 Education," *Journal of Engineering Education,* vol. 99, *(2),* pp. 179-181, 2010.

[8] National Academy of Engineering of the National Academies. *Standards for k-12 engineering education?*. Washington, D.C.: The National Academies Press, 2010.

[9] National Research Council of the National Academies. *A framework for k-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, D.C.: The National Academies Press, 2012.

[10] D. P. Crismond and R. S. Adams, "The Informed Design Teaching and Learning Matrix," *Journal of Engineering Education,* vol. 101, *(4),* pp. 738-797, 2012.

[11] J. Flowers and M. A. Rose, "Mathematics in Technology & Engineering Education: Judgments of Grade-Level Appropriateness," *Journal of Technology Education,* vol. 25, *(2),* 2014.

[12] S. Grover and R. Pea, "Computational Thinking in K—12: A Review of the State of the Field," *Educational Researcher,* vol. 42, *(1),* pp. 38-43, 2013.

[13] T. J. Moore, A.W. Glancy, K.N. Tank, J.A. Kersten and K.A. Smith, "A Framework for Quality K-12 Engineering Education: Research and Development," *Journal of Pre-College Engineering Education Research (J-PEER),* vol. 4, *(1),* pp. 2, 2014.

[14] C. D. Denson and M. Lammi, "Building a Framework for Engineering Design Experiences in High School," *Journal of Technology Education,* vol. 26, *(1),* 2014.

[15] R. L. Custer, J. L. Daugherty and J. P. Meyer, "Formulating a Concept Base for Secondary Level Engineering: A Review and Synthesis," *Journal of Technology Education,* vol. 22, *(1),* 2010.

[16] C.M. Cunningham and C.P. Lachapelle, “Engaging all students in engineering,” In *Proceedings of the 2012 ASEE Annual Conference & Exposition, June, 2012, San Antonio, TX* [ONLINE]. Available: ASEE PEER, https://peer.asee.org/.

[17] J. Piaget, *The origins of intelligence in children*. New York: International Universities Press, 1952.

[18] L. S. Vygotsky and M. Cole, *Mind in society: the development of higher psychological processes*. Cambridge: Harvard University Press, 1978.

[19] A. Liberati, D. G. Altman, J. Tetzlaff, C. Mulrow, P. C. Gøtzsche, J. P. Ioannidis, M. Clarke, P. J. Devereaux, J. Kleijnen, and D. Moher, "The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration," *PLoS medicine*, vol. 6, *(7)*, 2009.

[20] A. Wilson-Lopez, J.A. Mejia, I.M. Hasbún and G.S. Kasun, "Latina/o adolescents' funds of knowledge related to engineering," *Journal of Engineering Education,* vol. 105, *(2),* pp. 278-311, 2016.

[21] K. Tang, "Out-of-school media representations of science and technology and their relevance for engineering learning: out-of-school representations of science and technology," *Journal of Engineering Education,* vol. 102, *(1),* pp. 51-76, 2013.

[22] N. Mentzer, K. Becker and M. Sutton, "Engineering design thinking: high school students' performance and knowledge," *Journal of Engineering Education,* vol. 104, *(4),* pp. 417-432, 2015.

[23] P. B. Hudson, L.D. English. and L.A. Dawes, "Female students' interactions in a middle school engineering project: a case study," *International Journal of Engineering Education*, vol. 29, *(4)*, pp. 814-821, 2013.

[24] N. Balta, S. Yerdelen-Damar and A.R. Carberry, "Vocational high school students' engineering epistemological beliefs," *International Journal of Engineering Education*, vol. 33, *(1)*, pp. 420-429, 2017.

[25] M. M. Hynes, C. Joslyn, A. Hira, J. Holly Jr and N. Jubelt, "Exploring diverse pre-college students' interests and understandings of engineering to promote engineering education for all," *International Journal of Engineering Education*, vol. 32, *(5)*, pp. 2318-2327, 2016.

[26] P. Hudson, L. D. English and L. Dawes, "Engineering-based problem solving in the middle school: design and construction with simple machines," *Journal of Pre-College Engineering Education Research (J-PEER),* vol. 3, *(2),* 2013.

[27] C. G. Valtorta and L.K. Berland, "Math, science, and engineering integration in a high school engineering course: a qualitative study," *Journal of Pre-College Engineering Education Research (J-PEER),* vol. 5, *(1),* 2015.

[28] P. J. Weinberg, "Mathematical description and mechanistic reasoning: a pathway toward STEM integration," *Journal of Pre-College Engineering Education Research (J-PEER),* vol. 7, *(1),* 2017.

[29] M. J. Fosmire and N. Mentzer, "Quantifying the information habits of high school students engaged in engineering design," *Journal of Pre-College Engineering Education Research (J-PEER),* vol. 5, *(2),* 2015.

[30] P. Blikstein and M. Worsley, "Reasoning strategies in the context of engineering design with everyday materials," *Journal of Pre-College Engineering Education Research (J-PEER),* vol. 6, *(2),* 2017.

[31] S. Brown, V. Whritenour and D. B. Montfort, "Secondary students' conceptual understanding of engineering as a field," *Journal of Pre-College Engineering Education Research (J-PEER),* vol. 3, *(2),* 2013.

[32] J. Wells, M. Lammi, J. Gero, M.E. Grubbs, M. Paretti and C. Williams, "Characterizing design cognition of high school students: initial analyses comparing those with and without pre-engineering experiences," *Journal of Technology Education,* vol. 27, *(2),* 2016.

[33] M. Lammi and K. Becker, "Engineering design thinking," *Journal of Technology Education,* vol. 24, *(2),* 2013.

[34] J. V. Ernst and J. J. Moye, "Social adjustment of at-risk technology education students," *Journal of Technology Education,* vol. 24, *(2),* 2013.

[35] R. A. Dixon and R. A. Brown, "Transfer of learning: connecting concepts during problem solving," *Journal of Technology Education,* vol. 24, *(1),* 2012.

[36] O. Lawanto, D. Butler, S.C. Cartier, H.B. Santoso, W. Goodridge, K.N. Lawanto and D. Clark, "Pattern of task interpretation and self-regulated learning strategies of high school students and college freshmen during an engineering design project," *Journal of STEM Education : Innovations and Research,* vol. 14, *(4),* pp. 15, 2013.

[37] K. H. Becker, N. Mentzer, K. Park and S. Huang, "High school student engineering design thinking and performance," in *Proceedings of the 2012 ASEE Annual Conference & Exposition, June, 2012, San Antonio, TX* [ONLINE]. Available: ASEE PEER, https://peer.asee.org/.

[38] N. Mentzer and K. Park, "High school students as novice designers," in *Proceedings of the 2011 ASEE Annual Conference & Exposition, June, 2011, Vancouver, BC, Canada* [ONLINE]. Available: ASEE PEER, https://peer.asee.org/.

[39] A. A. Wilson, E. Smith and D.L. Householder, "High school students' cognitive activity while solving authentic problems through engineering design processes," in *Proceedings of the 2013 ASEE Annual Conference & Exposition, June, 2013, Atlanta, GA* [ONLINE]. Available: ASEE PEER, https://peer.asee.org/.

[40] K. B. Wendell, C. G. Wright and P. Paugh, "Reflective decision-making in elementary students' engineering design," *Journal of Engineering Education,* vol. 106, *(3),* pp. 356-397, 2017.

[41] B. M. Capobianco, H.A. Diefes-Dux, I. Mena and J. Weller, "What is an engineer? Implications of elementary school student conceptions for engineering education," *Journal of Engineering Education,* vol. 100, *(2),* pp. 304-328, 2011.

[42] B. M. Capobianco and I.B. Mena, "Longitudinal profiles of children's conceptions of an engineer," *International Journal Of Engineering Education*, vol. 29, *(2)*, pp. 415-425, 2013.

[43] L. D. English and D. King, "Engineering education with fourth-grade students: introducing design-based problem solving," *International Journal of Engineering Education*, vol. 33, *(1)*, pp. 346-360, 2017.

[44] P. Chou and W. Chen, " Elementary school students' conceptions of engineers: a drawing analysis study in Taiwan," *International Journal of Engineering Education*, vol. 33, *(1)*, pp. 476-488, 2017.

[45] D. Hammer and M. E. McCormick, "Stable beginnings in engineering design," *Journal of Pre-College Engineering Education Research (J-PEER),* vol. 6, *(1),* 2016.

[46] A. W. Glancy, T.J. Moore, S. Guzey and K. A. Smith, "Students' successes and challenges applying data analysis and measurement skills in a fifth-grade integrated STEM unit," *Journal of Pre-College Engineering Education Research (J-PEER),* vol. 7, *(1),* 2017.

[47] T. T. Yuen, M. Boecking, E.P. Tiger, A. Gomez, A. Guillen, A. Arreguin and J. Stone, "Group tasks, activities, dynamics, and interactions in collaborative robotics projects with elementary and middle school children," *Journal of STEM Education : Innovations and Research,* vol. 15, *(1),* pp. 39, 2014.

[48] A. Dasgupta, A.M. Rynearson, S. Purzer, H. Ehsan and M.E. Cardella, "Computational thinking in K-2 classrooms: evidence from student artifacts (fundamental)," in *Proceedings of the 2017 ASEE Annual Conference & Exposition, June, 2017, Columbus, OH* [ONLINE]. Available: ASEE PEER, https://peer.asee.org/.

[49] A. L. M. Kendall, "Evaluate-and-redesign tasks: using interviews to investigate how elementary students iterate (fundamentals)," in *Proceedings of the 2015 ASEE Annual Conference & Exposition, June, 2015, Seattle, WA* [ONLINE]. Available: ASEE PEER, https://peer.asee.org/.

[50] Z. Aguirre-Muñoz and M. L. Pantoya, "Engineering Literacy and Engagement in Kindergarten Classrooms," *Journal of Engineering Education,* vol. 105, *(4),* pp. 630-654, 2016.

[51] S. Guzey and M. Aranda, "Student participation in engineering practices and discourse: an exploratory case study," *Journal of Engineering Education,* vol. 106, *(4),* pp. 585-606, 2017.

[52] C. Schnittka and J. Schnittka, ""Can I drop it this time?" Gender and collaborative group dynamics in an engineering design-based afterschool program," *Journal of Pre-College Engineering Education Research (J-PEER),* vol. 6, *(2),* 2016.

[53] E. Fox and M. Riconscente, "Metacognition and Self-Regulation in James, Piaget, and Vygotsky," *Educational Psychology Review,* vol. 20, *(4),* pp. 373-389, 2008.