

A Meta-Analysis on the Effects of STEM Education on Students' Abilities

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Abstract. Does STEM education improve students' higher-level thinking and cognitive abilities? So far, empirical research has not yielded consistent conclusions. As such, this study applied the method of meta-analysis to synthesize quantitatively existing research to better understand STEM and its effects on students' abilities associated with learning. The study found that STEM education is conducive to improving students' higher-order thinking and cognitive ability levels with an effect size of ($d = 0.798$). The results indicate that teaching methods and student experiences in STEM education have a positive effect on student learning.

Sci Insig Edu Front 2018; 1(1):3-16.

Doi: 10.15354/sief.18.re005

Keywords: STEM education; Higher-order thinking; Higher-order cognitive abilities; Student learning

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Funding: (1) China Humanities and Social Sciences Research Fund Project (2018) for the Ministry of Education: Studies on the Influencing Factors and Mechanisms of STEM on Primary and Secondary School Students' (Project Approval Number: 18YJA880108); and (2) the Priority Academic Program Development of Jiangsu Higher Education (China).

Conflict of Interests: None.

SINCE the 1980's, when the National Research Council (NRC) advocated strengthening undergraduate sciences, mathematics, engineering, and technology education, STEM education was implemented in the United States. It has been gradually expanded from higher education to K-12 education. During this transition, various departments of the federal government issued large numbers of policies and reports to increase STEM education and putting in place financial inputs to ensure implementation. One of the most prominent reasons for doing so was to maintain the United States prominent roles in world politics and economics (Thomasian, 2007; CoSTEM, 2013; Honey et al., 2014). The realization of the strategic significance of STEM education had a number of other countries around the world also begin experimenting with STEM education (Marginson et al., 2013). These actions have led researchers, primarily in education, to analyze whether STEM education is conducive to improving students' learning abilities.

To this point, STEM education evaluation has mainly focused on the outcomes of students. As far as the content of the evaluation is concerned, it includes not only the students' academic achievements, but also, measurements of their abilities and tendencies towards subject learning and employment. For instance, a general assessment system built by the STEM Education Association in Portland, Oregon, required the measuring of students' use of knowledge, higher-level cognitive abilities, academic acceptance, and motivational resilience (Saxton et al., 2014). The National Research Council also reported that it was not sufficient to only be concerned with students' test scores when evaluating STEM education, but to also consider the impact on students' interests, creativity and behavior. However, there is no agreement on whether and how much STEM education affects students' abilities to learn. Yildirim (2016) systematically analyzed the improvements of students' innovative abilities through STEM education; but, failed to specify to what extent are its affects. Sarac (2018) posited that STEM education can improve students' scientific process skills ($d = 0.820$); yet, did not answer whether STEM education can help to improve the skills required by STEM professionals in the broader context. In contrast to the relatively optimistic findings of the aforementioned, Jang (2016) pointed out that STEM education did not assist the 18 important abilities of STEM professionals, and therefore, a more cautious approach to the effectiveness of STEM education needed to be taken.

Literature Review and Theoretical Framework

STEM Education

Research has not yet formed a unified understanding of STEM education. Carmichael (2017) analyzed the policy texts of various states in the United States and found that the states, for the most part, had different understandings of STEM education and how it was to be implemented. Hence, defining the operations of STEM education became a primary objective.

The STEM Education Act of 2015, defined STEM education as “education in science, technology, engineering, mathematics and other fields, including education in computer science” (US Congress, 2015). The stringent focus on subject areas failed to make a comprehensive summary of the rich connotation of STEM education (Sanders, 2009).

We believe that a more reasonable and comprehensive definition of STEM education is needed to better reflect the developmental process and full characteristics of the program. In its early stages, STEM education focused on the knowledge of subjects and ignored the links (Atkinson & Mayo, 2010), which to some degree weakened students' interest in STEM subjects and lowered their academic performance (Kelley & Knowles, 2016). For this reason, the United States has proposed further reforms, including the implementation of STEM integrated education, thus to enhance students' interest and ultimately improving their learning achievements (Honey, et al., 2014). This integration of the disciplines expanded the effectiveness by way of integrating them to real-world situations and problems, using problem-based, inquiry-based, and project-based learning.

From the perspective of STEM education, we consider that STEM education has two outstanding characteristics: first, it emphasizes the integration of science, technology, engineering and mathematics; and, secondly transforms traditional teaching models to a student-center model. As defined by the National Association of High Schools, STEM education is one that breaks the boundaries of traditional subjects and integrates teaching and learning of science, technology, engineering and mathematics as a guide that encourages students to solve problems using their newly learned knowledge. All in all, we defined STEM education as: an education approach which based on authentic environment and integrate science, technology, engineering and mathematics or more other subjects by students-centered learning model, such as project-based learning, design-based learning, inquiry-based learning and so on, to cultivate students' ability and improve their achievement.

Higher-order Thinking and Higher-order Cognitive Abilities

Bloom et al. (1956), classified educational goals as to being: knowledge, comprehension, application, analysis, synthesis and evaluation. Many scholars regard knowledge as low-order thinking and of low cognitive ability; whereas, the other remaining skills from Bloom's Taxonomy as being higher-order thinking and of higher cognitive abilities (Miri, 2007). Wood (2007) divided higher-level cognitive abilities into three dimensions: problem-solving, evidence-based discussion, and metacognitive. Considering the prominent purpose of education to develop skills more than knowledge, scholars have explored the influence of different teaching methods. Hemlo & Ferrari (1997) examined how to cultivate students' higher-order thinking based on problem-based learning. Hopson (2001) found that the application of educational technology in classroom teaching can also improve students' higher thinking abilities. Lastly, Zohar and Dori (2003) dis-

covered that after attending training projects using of high-order thinking abilities, poor performing students had a larger net increase compared to higher performing students.

The Relationship between STEM Education and Students' Abilities

In existing empirical literature, results on the relationship between STEM education and students' abilities are inconsistent. Some studies indicate that STEM education can significantly improve students' abilities levels and there is a large effect size. For example, Fan and Yu (2017) found that engineering-based technology education showed large improvement ($\eta^2 = 0.18$) in high school students' higher-order thinking. Li et al (2016) discovered that when comparing with non-STEM education, STEM education significantly improved students' problem-solving abilities ($d = 0.526$). However, other studies had noticed STEM education, though beneficial to students', was much less effective. Cakir et al (2016) found that STEM education had improved the level of students' reflective thinking abilities, but at a rate of ($d = 0.1319$). Psycharis & Kallia (2017) study on computer programming-based learning saw only a small influence on students' critical thinking ($d = 0.229$). Then, there were studies that observed no effects on students' abilities levels, such as, Choi and Hong (2015) (creative problem-solving) and Anwari (2015) (metacognition).

Further studies realized that the effectiveness of STEM education can be influenced by external factors. Inman (2011) discovered that STEM education can improve students' scientific inquiry abilities; yet, the degree of effectiveness was influenced by socio-economic factors. Taylor (2016) research showed that students' experience in STEM education would affect the improvement of problem-solving ability, and the effect of STEM education is better for novice students.

Based on the above review, this study will focus on answering the following three questions through meta-analysis:

- 1) Is STEM education conducive to improving students' abilities?
- 2) To what extent does STEM education affect students' abilities?
- 3) During the process of STEM education, what factors will be influenced?

Research Method

The method used for the study was meta-analysis which is a quantitative synthesis method to review literature. Initially, this method was applied to synthetically evaluate results of clinical psychology research. Compared with traditional methods, which often relied on subjective judgments, meta-analysis is objective, systematic, and evidence-based. Thus, gaining acceptance in the fields makes up the social sciences (Lipsey & Wilson, 2011).

On the whole, the main steps of meta-analysis are: 1) enacting inclusion criteria; 2) searching and filtering documents; 3) coding documents and extracting data; 4) assessing the quality of the included documents; 5) calculating the mean effect size; 6)

analyzing heterogeneity; and, 7) testing publication bias and sensitivity. These steps were followed to answer the research questions posed in this study.

Inclusion Criteria

We collected and screened selected literature according to the following inclusion criteria:

(a) The literature enrolled was published in English between 1996 and 2018 and the type of literatures was not limited. After all, English is an internationally accepted academic language and most of the research on the effects of STEM education is published in this language.

(b) The content focuses on STEM education and students' abilities in elementary education. As well, the impact of STEM education on the abilities of students' in elementary education, excluding special education, vocational education, and after school programs.

(c) Literature that included comparisons between STEM education and non-STEM education using effect size. Evaluations were made using the criteria of Cheung and Slavin (2013a) – large differences in pretest were excluded ($ES > 0.5$) and randomized trials without pre-test are included.

(d) At least two teachers were teaching the experimental group and the control group had to be separated to minimize the impact of teacher factors. This was done because if the two groups were taught by only one teacher, the independence of the intervention could not be guaranteed.

(e) To avoid possible deviation of experimental results, students were not alerted of the reason for doing specific functions.

(f) The sample size of the experimental group and control group were similar. This was done to avoid bias.

(g) The statistical information needed to be sufficient, so that, effect size could be calculated.

Searching and Scaffolding Documents

The key terms used during Google Scholar and ERIC searches included: STEM education, higher-order cognitive skills, higher-order thinking, creative skills, innovation capacity, creativity, problem-solving skills, problem-solving ability, ability, skill. In all, 28012 studies were found and designated for this study. A further breakdown is shown in **Figure 1**.

Coding and Data Extraction

In heterogeneity analysis, the literature should be grouped according to research design and sample characteristics. Therefore, coding was done accordingly:

(a) Gender (Ge): female code-0, male code-1. Samples containing male and female was reported as 2 and unreported samples as null.

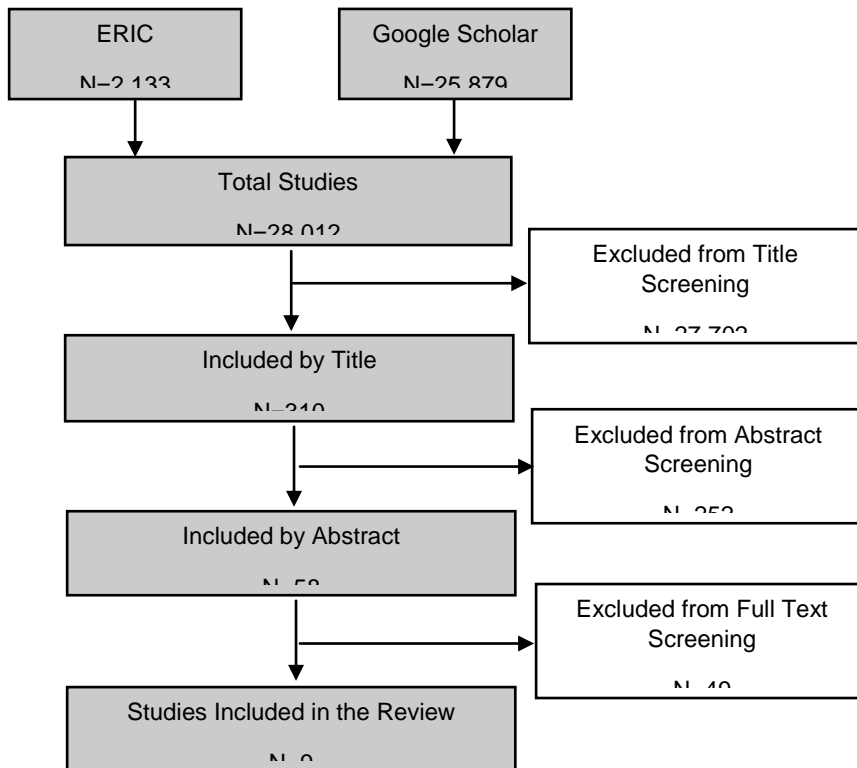


Figure1. Search and Screening Process.

(b) Family socioeconomic background (SES), Low SES coded-l, medium SES coded-m, high SES coded-h. A sample containing low, medium and high SES was coded-mix, and unreported samples coded-null.

(c) Race (E), White coded-w, Afro-American coded-b, Asian coded-a, Hispanic coded-h, and others code-o. A sample contains multiple ethnic groups code-mix, and for non-reported code-null.

(d) Grade (Gr): K-5 code-P, grade 6-8 code-m, grade 9-12 code-h.

(e) Ability type (AT)

(f) Area (Lo)

(g) STEM Teaching Method (TA), Project-based Learning coded-PBL, Problem-based Learning (PBL) coded-pbl, Inquiry-based Learning coded-IBL, Design-based Learning coded-DBL, and other STEM educational measures were coded-other.

(h) Research design (Rd), the quasi experimental design coded-QE, and the random experimental design was coded-re.

(i) Duration of intervention (D), According to the length of the experiment, it was divided into four levels: 0-2 months, 2-4 months, 4-6 months, 6 months+.

(j) Sample size (Ss), using the guidelines set out by Cheung & Slavin (2013b), studies with a sample size greater than 250 were designated as large sample studies, and studies with a sample size less than 250 were assigned as small studies. Accordingly, we coded the large sample studies as l and the small sample studies as s. (**Table 1**)

Table 1. Details of Included Research.

Study	Ge	SES	E	Gr	TA	D	AT	Lo	Ss
Childress, 1996	Null	Null	Null	M	Other	0-2 mo	Problem-solving skills	USA	Small
Eseryel, 2011	2	Null	Null	M	Other	2-4 mo	Problem-solving skills	USA	Large
Lartson, 2013	2	Mix	Mix	H	DBL	2-4 mo	Problem-solving skills	USA	Small
Kibett, & Kathuri, 2015	Null	Null	Null	M	PBL	2-4 mo	Higher-order cognitive skills*	Kenya	Small
Rehmat, 2015	2	Null	Mix	P	Pbl	4-6 mo	Critical thinking	USA	Small
Robinson, et al., 2014a	Null	Null	Null	P	IBL	6 mo+	Science process skills	USA	Small
Robinson, et al., 2014b	Null	Null	Null	P	IBL	6 mo+	Science process skills	USA	Small
Cotabish, et al., 2013	2	Null	Null	P	IBL	6 mo+	Science process skills	USA	Large
Psycharis, & Kallia, 2017a	2	Null	Null	H	Other	0-2 mo	Critical thinking	USA	Small
Psycharis, & Kallia, 2017b	2	Null	Null	H	Other	0-2 mo	Reasoning skills	USA	Small
Hashem, 2015a	2	Mix	Mix	M	Other	2-4 mo	Critical thinking	USA	Small
Hashem, 2015b	2	Mix	Mix	M	Other	2-4 mo	Critical thinking	USA	Small

*: The author does not specify which ability is tested in the higher-order cognitive ability dimension, but is generally referred to as "higher-order cognitive skills".

Quality Assessment of Studies

Considering that meta-analysis is a method of quantitative synthesis of existing research, the quality of the included literature will affect the quality of the final results. Referring to Valentine & Cooper's (2003) method for evaluating the quality of literature, this study assessed the quality from five aspects: whether the literature clearly described the interventions, research design, sample characteristics, testing tools and measurement processes (unclear-1, somewhat clear-2 and clear-3). As **Table 2** shows, the quality of the literature included was high enough to meet the needs of this study.

Table 2. Document Grades.

Study	Intervention	Research Design	Sample Characteristics	Test Tool	Measure Process	Total
Childress, 1996	2	2	1	1	2	8
Eseryel, 2011	2	2	1	2	2	9
Lartson, 2013	3	3	3	2	2	13
Kibett, & Kathuri, 2015	2	2	1	2	2	9
Rehmat, 2015	3	2	2	2	2	11
Robinson, et al., 2014a	3	2	1	2	3	11
Robinson, et al., 2014b	3	2	1	2	3	11
Cotabish, et al., 2013	2	2	2	2	2	10
Psycharis, & Kallia, 2017a	2	2	1	2	1	8
Psycharis, & Kallia, 2017b	2	2	1	2	1	8
Hashem, 2015a	3	2	3	2	3	13
Hashem, 2015b	3	2	3	2	3	13

Analysis of Result and Discussion

Combining Effects

This study used Comprehensive Meta-Analysis Vision 2 software to calculate the effects. From the selected samples, it cannot be assumed that the reported effects of all documents were consistent and the results of the heterogeneity reported a significance of ($Q = 58.950$, $p < 0.0001$). Therefore, a random-effect model (Michael Borenstein et al., 2009, p83) was used for further analysis. Used was the “one study removed” method to exclude possible outliers. The principle behind this method was to enable calculation of the average effect of the documents. If the deviation between the calculated average effect and the original value was too large, the documents were deemed as abnormal values and were not included in the final effect analysis (Young, et al., 2017). As shown in **Table 3**, the effects of the studies were distributed between 0.229 and 1.647. Eight of the effects were statistically significant and the remaining three were not significant. The combined effect $d = 0.798$ ($p < 0.0001$) in the random effect model was calculated, which was a moderate effect according to Cohen’s (1988) criteria. To a certain extent, this result can answer questions 1 and 2, STEM education is conducive to improving students' higher-order cognitive abilities and higher-order thinking abilities. It also shows that STEM education can cultivate students' ability to meet the needs of the STEM labor market.

Table 3. Effect and Combined Effect Volume.

Study	Ability	Statistics for Each Study						
		Cohens'd	SE	Variance	Lower limit	Upper limit	Z-value	p-value
Childress, 1996	Problem-solving skills	0.551	0.355	0.126	-0.145	1.246	1.552	0.121
Eseryel, 2011	Problem-solving skills	0.303	0.131	0.017	0.047	0.559	2.316	0.021
Lartson, 2013	Problem-solving skills	1.015	0.248	0.062	0.528	1.502	4.088	<0.0001
Kibett, & Kathuri, 2015	Higher-order cognitive skills	1.647	0.186	0.035	1.283	2.011	8.865	<0.0001
Robinson, et al., 2014a	Science process skills	1.437	0.276	0.076	0.897	1.978	5.211	<0.0001
Robinson, et al., 2014b	Science process skills	0.585	0.191	0.037	0.209	0.960	3.054	0.002
Cotabish, et al., 2013	Science process skills	0.497	0.077	0.006	0.346	0.649	6.430	<0.0001
Psycharis, & Kallia, 2017a	Critical thinking	0.229	0.254	0.064	-0.268	0.726	0.902	0.367
Psycharis, & Kallia, 2017b	Reasoning skills	0.502	0.260	0.067	-0.007	1.011	1.933	0.053
Hashem, 2015a	Critical thinking	0.800	0.235	0.055	0.340	1.260	3.408	0.001
Hashem, 2015b	Critical thinking	1.408	0.331	0.109	0.759	2.056	4.255	<0.0001
Mean ES		0.798	0.143	0.021	0.517	1.079	5.568	<0.0001

Analysis of Heterogeneity

We used moderator analysis (Yong et al., 2017) to explore the source of heterogeneity. Due to the insufficient sample characteristics reported in the literature, this study was unable to treat gender, SES and ethnic variables as moderators and, at the same time, Kibett & Kathuri (2005) study did not report the items under higher-order cognitive skills, so ability type was excluded. Consequently, grade level, STEM education approaches, experimental duration and sample size were chosen as moderators to test heterogeneity. Test results (see **Table 4**) showed STEM education approaches as the leading factor of heterogeneity ($Q_B = 39.101$, $p < 0.0001$), meaning different STEM education approaches had different effects on students' abilities. Teaching approaches and project-based learning had the best effects, while problem-based learning had no effect on the improvement of students' abilities. There was only one study dealing with

Table 4. Analysis of Moderators Effect Size.

Moderator		K	Q _B	ES	95% CI	p-value	
Grade level	Primary school	3	4.026 (p=0.134)	0.568	0.432	0.705	<0.0001
	Middle school	5		0.793	0.616	0.970	<0.0001
	High school	3		0.589	0.302	0.877	<0.0001
STEM education approach	DBL	1	39.101 (p<0.0001)	1.015	0.528	1.502	<0.0001
	IBL	3		0.568	0.432	0.705	<0.0001
	Other	4		0.342	0.143	0.541	0.001
	PBL	3		1.335	1.074	1.596	<0.0001
Duration	0-2 mo	3	8.024 (p=0.017)	0.401	0.085	0.718	0.013
	2-4 mo	5		0.835	0.663	1.006	<0.0001
	6 mo+	3		0.568	0.432	0.705	<0.0001
Sample size	Large	2	21.774 (p<0.0001)	0.447	0.317	0.578	<0.0001
	Small	9		0.938	0.778	1.097	<0.0001

problem-based learning and the result was that it had no effect on improving students' abilities (this area needs further study). Moderator's experimental duration and sample size indicated influence on the mean effect size ($Q_B = 8.024$, $p = 0.017$). As for experimental duration, STEM education is more efficient during 2-4 months, longer or shorter intervals had suboptimal results. Robinson and his colleagues (2014) found students during the first year of STEM education perform well in the science process skill tests but not as well in the second year. Taylor (2016), meanwhile, found that effects of STEM education can be influenced by students' learning experiences. Novice learners gained more learning than those students considered higher achievers. It appears as the STEM program goes on, the impact of STEM education on student abilities gradually declines. Grade level was the only factor that had no significant influence on the mean effect size, which means that STEM education is suitable for all K-12 students.

In regard to research question 3 of this study: it was found that STEM education approaches and students' learning experiences are the moderator variables on students' abilities. The results, though, could not identify whether the demographic factors and ability types had any impact on the mean effect size of STEM education.

Publication Biases and Sensitivity Testing

In the meta-analysis process, a funnel plot is commonly used to test for publication bias. If there is publication bias, it will lead to skewed final result and the calculated mean effect size would need to be treated with caution. The publication bias test for this study

is shown in **Figure 2**; results show a funnel plot that is basically symmetrical, meaning that there is no publication bias.

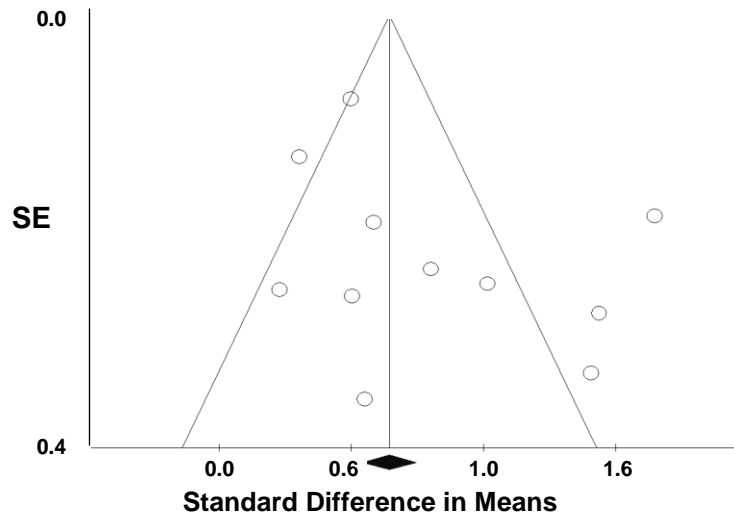


Figure 2. Publication Bias Test (funnel figure).

In order to judge the robustness of the analysis results, a classic fail-safe N test was used. This test was employed to calculate the minimum number of unpublished studies that could reverse the final results, in particular, in the area of robustness. A larger N means that the difference between the included studies and excluded studies would affect results more so; hence, the results of the meta-analysis would be more robust (Rosenthal, 1979). This study's fail-safe N was 449 ($p < 0.0001$), which means we needed to include an additional 449 studies to attain robustness.

Limitation of Research

There are two limitations in this meta-analysis. First, the number of included studies is slightly insufficient. The main reason for this deficiency is that there are few empirical studies on the relationship between STEM education and students' abilities, especially in the Asian region. Secondly, when studies were included, we limited the research design to two experimental design groups. Though, the process of exploring for causal relationships between variables are the standard, this criterion would have declined the sample size of this study's meta-analysis.

Findings and Conclusions

The meta-analysis used to synthesize existing empirical research on the relationship between STEM education and K-12 students' higher-order thinking and cognitive abilities found that STEM education is conducive to improving students' ability levels. The mean effect size ($d = 0.798$, $p < 0.0001$) is large enough to support this conclusion using Cohen (1988) principle. The results for heterogeneity analysis indicated that both STEM education processes and students' learning experiences can influence the effects of STEM education. Lastly, there was no significant difference in STEM education effect among students for different grades, indicating that STEM education is an effective model for all K-12 students' development of higher-order abilities.

Based on the research of this paper, it is concluded that there are still many gaps, yet, to be filled. First, researchers have supported the hypothesis that STEM education has more effect on students' achievement than non-STEM education (Becker & Park, 2011; Sarac, 2018), but it lacks enough studies to fully explain which STEM education practices would best fit for specific subjects and learning environments. Secondly, more research is needed to identify which factors influence the effects of STEM education in the area of human capital accumulation. For instance, groups such as women, African-Americans, Hispanics, and Asians are disproportionately underrepresented in current STEM education research (Beede et al., 2011; Koch et al., 2011; US Department of Education, 2016).

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Received: 17 July 2018

Revised: 10 September 2018

Accepted: 15 September 2018