

The Effects of STEM Education on Mathematics, Science, and English Language Development Skills

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Abstract. As STEM-related occupations and innovations continue to proliferate and expand upon the quality of life, it becomes more relevant than ever to ensure that Science, Technology, Engineering, and Mathematics (STEM) education provides the skills and benefits necessary to maintain growth through future generations. However, STEM education is heavily focused on higher education institutions rather than primary and secondary education institutions, where developmental skills are often trained. This study aims to discuss the intellectual benefits that STEM education provides through the subjects of math and science, where critical thinking and analysis skills are often exercised, as well as the benefits of STEM education in English language development. This study finds that STEM education benefits cognitive skills such as critical thinking, spatial visualization, creating hypotheses, experimentation, and drawing conclusions, as well as language skills such as register, communication, and argumentation. These effects indicate that more attention should be placed on implementing STEM education in non-higher education institutions to maximize the benefits that STEM education can bring.

Keywords: STEM education, intellectual development, mathematics skills, science skills, English language development

1. Introduction

It is no exaggeration to state that the past few decades have seen tremendous technological growth. Rapidly growing developments in the fields of science, technology, engineering, and mathematics (STEM) have resulted in invaluable improvements to the quality of life, workforce efficiency, and economic growth [1]. As a result, a keen focus has been placed on the expansion of STEM fields in hopes of progressing further and continuing current growth [1].

In the present day, sectors of America have become hotbeds for STEM-related companies and research facilities, California's Silicon Valley and Utah's Salt Lake City, to name a few. STEM-related occupations support over 60% of U.S. GDP, and over 60% of workers hold an occupation with relevance to STEM [2]. Currently, STEM fields are projected to grow by as much as 8% by 2029, as opposed to 3.7% for all occupations [3], with the field of computer science and information technology being projected to grow by over 20% by 2030 [4].

With such a commanding presence in the American economy, efforts to grow STEM-related industries and innovate further have undoubtedly seen tremendous growth [1]. In addition, to support tech startups and research developments, it is no surprise that STEM education has received similar attention on an incredible scale. Expansions in career technical education and university programs pave the way for new generations to further expand the fields of STEM in hopes of building a strong foundation for the future. As such, many educators and politicians support providing a robust system for nurturing STEM competency [1]. Nevertheless, the current American educational system seems to be imbalanced in this regard. While universities and higher-education institutions appear to be placed at the forefront of STEM development and education, secondary education institutions are lagging behind: only 4.7% of high schoolers in 37 states enroll in courses in computer science, and many high school students are averse to pursuing STEM due to lack of opportunity and discouragement [5]. At the same time, more than half of all U.S. workers working in STEM do not hold bachelor's degrees and instead opt for associate's degrees and technical certifications [2]. This imbalance suggests a rift between those working in STEM education and the ones who benefit from

it. While a focus on STEM in higher education is a profitable investment, its return on intellectual development should not be overlooked.

Because STEM fields are known for their emphasis on critical thinking and analysis skills, which are fundamental bases for intellectual development, this paper aims to discuss the effects of STEM education in the subjects of math and science, where these skills are prevalent and often assessed.

Additionally, this paper summarizes the benefits of STEM education in English language development. As STEM fields are often isolated from liberal arts subjects, observing the effects of how STEM education can affect a disconnected field can provide valuable insight into how STEM education could be expanded and improved upon in the future. While the current literature has not delved deeply into the effects of STEM on English development, enough information is present to create useful generalizations that show the future of STEM education.

2. Math and Science

This section now aims to discuss the various effects of STEM education on math and science ability by utilizing previous research analyses. Although some of the analyses may have evaluated students' cognitive ability based on an assessment model that could have introduced biases (i.e., performing well due to memorization rather than increased problem-solving capability), it is safe to assume that a trend of upward performance is generally conducive to increased cognitive capability.

2.1. Critical thinking skills

In one such analysis by Hacıoglu and Gulhan [6], 30 middle school students originating in Istanbul were exposed to five different activities designed to stimulate STEM learning. Students' critical thinking skills were evaluated utilizing the California Critical Thinking Disposition Inventory (CCTDI), which evaluates critical thinking in six different subcategories: truth-seeking, open-mindedness, analyticity, systematicity, self-confidence, and inquisitiveness. The CCTDI was utilized before and after the STEM activities to determine their effects on the student's critical thinking skills. A dependent samples t-test was then utilized [6].

Table 1. Results of CCTDI measurements before and after STEM activities

Scale-Subscale	N	X	SS	Sd	t	p
CCTDI Pre-test	30	208,37	235,145			
CCTDI Post-test	30	235,14	311,765	29	-2,571	016*
Truth-seeking	30	25,80	4,902	29	-2,684	,012*
	30	28,90	5,815			
Open-mindedness	30	49,20	8,117	29	-3,005	,005*
	30	54,67	9,834			
Analyticity	30	44,97	8,451	29	-1,615	,117
	30	47,53	7,820			
Systematicity	30	23,83	5,173	29	-2,034	,051
	30	25,77	4,297			
Self-confidence	30	26,10	5,320	29	-,543	,591
	30	26,80	5,229			
Inquisitiveness	30	38,47	6,932	29	-,291	,773
	30	38,93	6,767			

* $p < .05$

Table 1 shows a significantly improved performance post-test compared to the pre-test [6]. However, while the subcategories of truth-seeking and open-mindedness saw significant improvements, the other subcategories did not. The analysis identifies that the environment the students were placed in contributed to this result [6]. The interpreted result is that while the STEM

activities inspired curiosity within the students, they were not thorough enough to reveal significant changes in cognitive ability, and a larger sample size would yield better results.

A meta-analysis of 54 studies by Wahono, Lin, and Chang [7] on the effects of STEM education in Asia confirms these points. The meta-analysis collected and categorized papers ranging a span of 10 years and grouped studies involving problem-solving, design, creative thinking, reflection, and general thinking that ranked above the third level of Bloom’s taxonomy. Most studies were conducted among students currently in secondary education.

Calculating Cohen’s coefficient using the differences between average pre-test and post-testing scores, Figure 1 presents the general effectiveness of STEM education on these skills. The placement of the black squares represents the effectiveness of the STEM education programs, while the whiskers represent the confidence interval [7]. The results show quite clearly that STEM education positively affects critical thinking skills, although the effects vary depending on the quality and duration of the program.

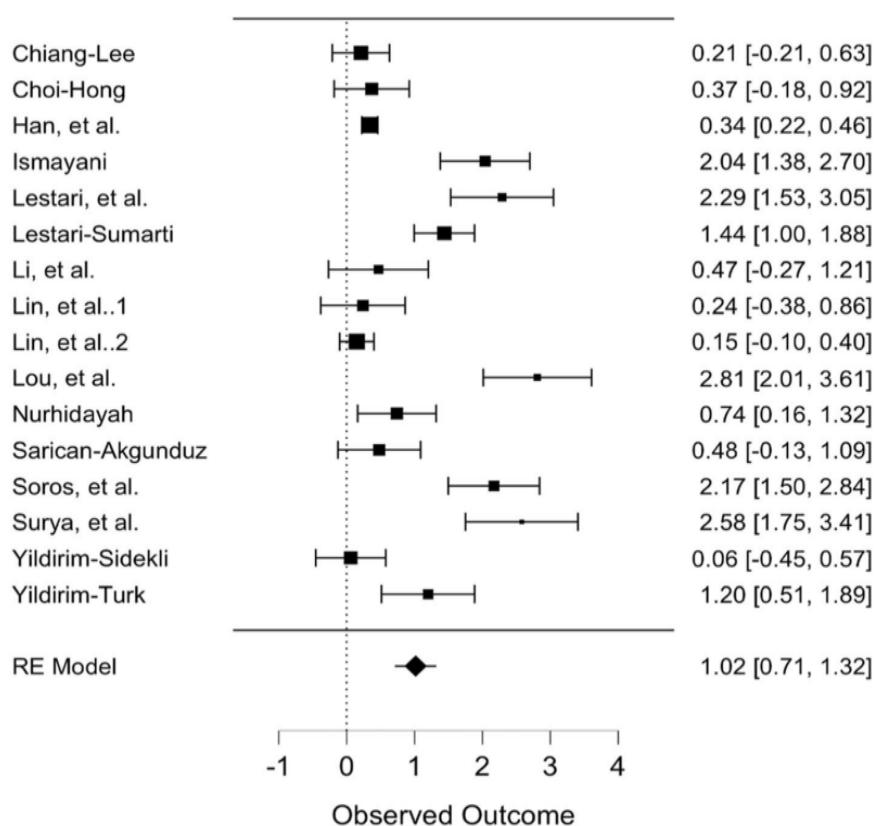


Figure 1. Forest plot of the effect of various STEM education studies on critical thinking skills

2.2. Spatial and computational ability

The effects of STEM education are not limited to critical thinking skills. A study by He, Li, Turel, Kuang, Zhao, and He [8] performed on 65 children aged 5-6 years old in an experimental kindergarten in southwest China assessed students’ mathematical ability using four activities designed to measure memory, sequencing, computational, and spatial capability. The students were separated into a control and experiment class, where the control class mainly received instruction in arts and crafts while the experiment class received STEM-related projects and teaching. Their mathematical ability in the four categories was then assessed after a two-month period based on the accuracy of the students’ choices [8].

Table 2. Results of mathematical ability tests before and after classes (M±SD)

Category		Experiment class	Control class
Number sequencing	Pre-test	0.76±0.28	0.83±0.18
	Post-test	0.84±0.19	0.73±0.27
Building block	Pre-test	0.77±0.12	0.76±0.11
	Post-test	0.82±0.12	0.77±0.11
Calculation	Pre-test	0.32±0.27	0.35±0.32
	Post-test	0.50±0.29	0.50±0.30
Backwards digit span	Pre-test	0.26±0.20	0.21±0.16
	Post-test	0.30±0.17	0.24±0.16

Table 2 displays the comparison of the students’ mathematical ability before and after the two-month period, with “Number sequencing” measuring sequencing, “Building block” measuring spatial awareness, “Calculation” measuring computational ability, and “Backward digit span” measuring memory [8]. Significant improvement can be found in the “Building block” and “Calculation” exercises, indicating that STEM education was effective in improving computational ability as well as spatial capability.

Additionally, the students in the experimental class were categorized based on their initial math ability, and the results of their improvement were analyzed. As shown in Figure 2, the students were divided into the low, middle, and high groups, formed by the lower 25%, middle 50%, and upper 50% of students, respectively [8].

Table 3. Results of mathematical ability tests grouped by initial math proficiency (M±SD)

Category		Experiment class	Control class
Low group	Pre-test	1.36±0.18	1.92±0.52
	Post-test	2.07±0.55	1.88±0.72
Middle group	Pre-test	2.07±0.22	2.15±0.45
	Post-test	2.40±0.56	2.36±0.53
High group	Pre-test	2.94±0.30	2.41±0.41
	Post-test	2.99±0.46	2.37±0.77

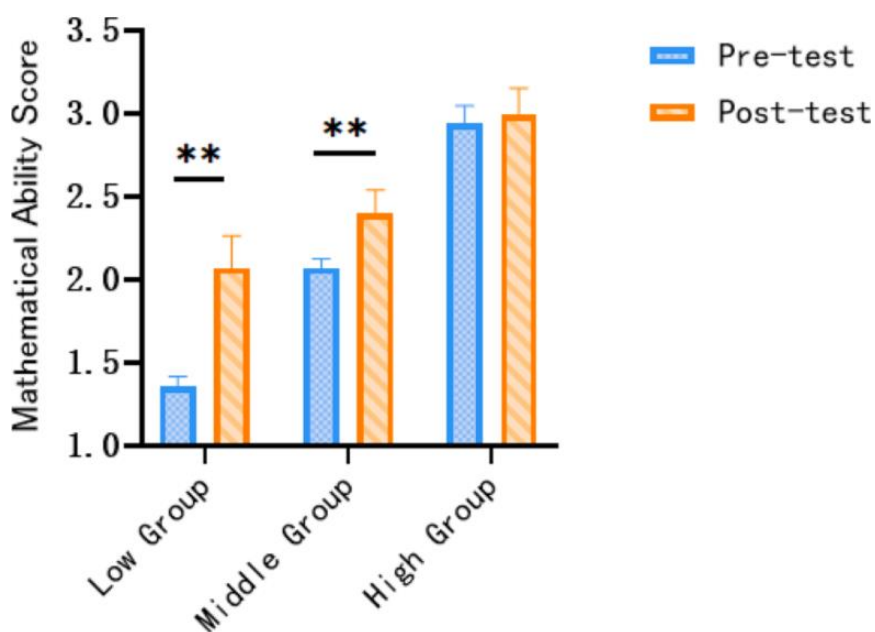


Figure 2. Results of mathematical ability tests in experiment class by initial math proficiency [8]

Table 3 displays the sum of the scores in each of the four activities, categorized by the mathematical ability of the students [8]. It can be observed here that students with initially lower

mathematical proficiency experienced greater rates of improvement than those with higher proficiency.

2.3. Science processing skills

In a study by Sari, Duygu, Şen, and Kirindi [9] comprising 39 undergraduate students at a university in Turkey, the Scientific Process Skill Test was implemented to determine students' proficiency in scientific processing skills before and after using a “simulation-based learning environment” which presented five engineering problems over a 10-week period. The Scientific Process Skill Test measures skills including defining variables, creating hypotheses, designing experiments, collecting data, and forming conclusions [10]. Using a paired samples t-test with the results before and after the testing period, Table 4 shows the instructional environment to have had a medium effect of 0.70 [9].

Table 4. Results of SPST test before and after simulated learning environment [9]

Tests	n	X	sd	df	t	p	d
Pre-test	39	19.77	3.21	38	-4.37	.00	0.70
Post-test	39	24.18	5.18				

3. English Language Development

Current literature on how STEM affects English language development tends to remain consistent, but due to the nature of English as a subjective subject, they often depend on qualitative research. Educational frameworks that build upon this research have room for improvement, as all such frameworks do, but even more so due to the subjectivity of current methods as well as the lack of attention that English language development receives in relation to other aspects of STEM education. This section aims to reveal the benefits of STEM education on English language development as well as current instructional practices that hinder these benefits.

3.1. Sophistication in language

English language learners in classroom environments typically learn new concepts in tandem with new language skills [11]. In STEM environments, learning new and more complex ideas inevitably leads to the need for more complex methods for communication and description. For example, English learners can be challenged to improve the complexity of their communication by using descriptors to specify the subject of a sentence due to the importance of specificity in a scientific environment. They can also be challenged to describe the relationships between objects in both time and space, the first of which is prevalent in math and science and the second of which is important in science and engineering [11]. The linguistic challenges that STEM environments present provide valuable opportunities for English language learners to accelerate their growth.

In addition to the expression of ideas, STEM education can also improve register, which is known as the different manners in which people communicate in response to their respective environments [11]. Different registers are a result of the linguistic choices that people make and can be interpreted as separated into three different categories: modalities, content, and relationship, as presented in Figure 3 [11].

Register: meaning-making choices related to *Content, Relationships, and Modalities*

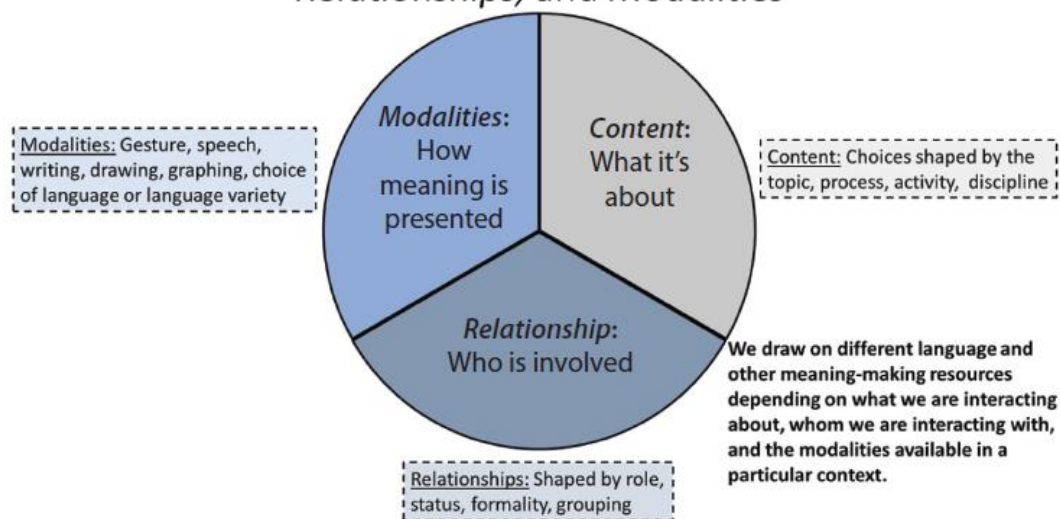


Figure 3. An interpretation of language as variation in register [11]

Different aspects of STEM education are able to touch upon all three of these categories. In classroom environments, exercises in formal and academic communication can affect both modalities and content: in formal reading, writing, and speaking, students are pushed to utilize complex sentence structure as well as specialized vocabulary to meet their needs. Formal communication also demands an understanding of body language and tone.

The relationships aspect of register is also exercised. In STEM environments, relationships are varied through exercises that demand communication among a diverse set of audiences, from small group discussions to whole-classroom settings and ranging in levels of formality [11]. The large range of relationships that STEM environments present indicates a wealth of opportunities for linguistic growth. The National Academies of Sciences, Engineering, and Medicine presents examples of variations in register that may occur in a STEM environment in response to the following mathematics problem in Figure 4 [11].

Sophia wants to make peach tarts for her friends. She needs two-thirds of a peach for each tart and she has 10 peaches. What is the greatest number of tarts that she can make with 10 peaches?

Figure 4. A sample mathematics problem to demonstrate register

The National Academies of Sciences, Engineering, and Medicine presents variations in both modalities and relationships while keeping content, the math problem, constant. In modalities, responses evolve from utilizing gestures and informal speech to describe division to written responses that use specialized vocabulary and equations [11]. Relationships vary from students interacting with peers, individuals reporting for groups, students writing responses for teachers, and formal descriptions written by authors [11].

3.2. Communication and interaction

There are many aspects of English language development that can be improved from peer interaction alone. Aside from the obvious practice and solidifying of knowledge that it can provide, classroom interaction in STEM environments specifically provides opportunities for engaging in argument [12]. In STEM classrooms where students are able to form arguments and discourse with their fellow peers, they are often challenged not just to convey their ideas using appropriate registers, but to coordinate their ideas into logical sequences that lead to a conclusion. On the other hand,

students on the receiving end of the debate can be challenged to listen to identify logical flaws in another's argument, requiring not just a basic understanding of the statements being communicated but also the complexity of applying them to a larger purpose [12]. These types of interactions are prevalent in STEM classrooms especially due to their emphasis on evidence-based argumentation and inquiry-based learning [12].

Additionally, peer-to-peer communication allows for opportunities where peers learn amongst themselves. Students have been shown to correct peers' use of language in classroom environments, allowing both the recipient to learn from their error and the one correcting the language to reinforce their understanding of English. This effect is especially useful when it is considered that English language learners often come from varied and diverse backgrounds, meaning that peers who share these diverse backgrounds are potentially able to relate to and thus understand each other better than a formal lecture would [11]. One report presents a clear example of this peer-to-peer interaction in a classroom setting [13]:

Teacher: I want you to think of questions that you have about the simulation.

Student 1: For me is the question "because the sh- the size is different."

(silence between S1 and S2)

Student 2: The size color is ... different.

Student 1: The size and color?

(pause)

Student 1: What is your question? Other, other question.

Student 2: Wait. It's not a question because you have "because." It's "WHY."

Student 1: Ah "why!"

Student 1: "Why! Why did ... Why the size and color is different?" for me is my question.

3.3. Obstacles to development

While the current benefits of STEM education on English language development are numerous, current educational systems have obstacles that hinder the potency of these effects. Although classroom environments provide many opportunities for language growth to students, they largely depend on educators to facilitate the exercises necessary to present them. In cases where educators are unmotivated to provide the necessary resources for English language learners, growth can stagnate and halt their progress. This is the case for many educators: for example, although some teachers recognize the relationships between STEM and language development, most K-12 teachers (taken from a survey in 12 different states) believe mathematics to be "devoid of language" and do not accommodate the needs of English language learners [11]. Thus, they often teach mathematics while relying on culture and exposure to an English-speaking environment and do not facilitate discussions that encourage otherwise silent and unconfident English learners to participate and grow [11]. Teachers who hold negative views toward English language learners have been known to hold low expectations for their success, hold stereotypes about their first language or ethnicity, or assume them to lack relevant knowledge or intelligence [11].

In addition to educators, curriculum materials are also a source of hindrance to English language learners. Current educational materials in mathematics that attempt to convey understanding to English learners have been shown to be disadvantageous to minorities such as low-income and Latino students [11]. Although the design of curricula catered toward English learners is not yet a well-studied topic, research has shown that STEM curricula designed with language development in mind from the beginning perform more effectively than most current curricula that have few supplemental accommodations for English learners [11].

4. Conclusion

STEM education is not an isolated subject. Although the topics present in STEM learning environments may present tasks and skills that represent specific sectors of society, the process of

learning these skills presents opportunities for students to build critical thinking skills, spatial visualization skills, computational skills, and scientific processing. STEM learning environments also have the potential to provide English language learners opportunities to build language and communication skills, including the sophistication of language, register, and argumentative skills.

Although research in STEM education is a relatively new field that has only seen popularity in the last decade [14], current findings are more than enough to reveal the invaluable benefits that STEM education can bring. In an era where STEM-related occupations are on the rise and innovations in STEM pave the way for the future, it becomes ever more important to further develop the quality of STEM education. It ensures that future generations are fit to expand upon current innovations and improve both economically and the quality of life.

American STEM education is heavily concentrated in universities and higher education institutions, while secondary education institutions are falling behind. In order to fully utilize the benefits that STEM education brings, more attention should be placed on secondary education institutions where developing cognitive and intellectual skills are able to be grown and nurtured. The potential for intellectual development that STEM education brings is currently rendered impotent due to a lack of exposure to the demographic that it most benefits.

Additionally, further implementation of STEM in primary education institutions should be considered and further explored. In addition to the cognitive skills that it develops, its benefits in English language development present an opportunity to be utilized by children, where language development occurs the fastest [15]. The relationship between STEM and language development, being two subjects that are typically regarded as unrelated, also suggests other benefits of STEM education in subjects that have yet to be explored. Further research into how STEM education affects performance or ability in diverse subjects could present beneficial opportunities to enhance intellectual and developmental growth in students further.

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