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Explicating the Characteristics of STEM Teaching and Learning: A Metasynthesis

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Abstract

This metasynthesis focused on STEM teaching and learning practices in middle and high school classrooms and in informal settings. Research artifacts between 2005 and 2012 were examined. Fifty-eight unique artifacts were classified into four categories: *reform-based teaching and learning*, *informal education*, *teacher factors*, and *technology use*. Promising pedagogical reform-based practices included inquiry-based learning, engineering design, project-based learning, problem-based learning, and hands-on practices. The most common intervention identified was increasing teacher content knowledge. Even though STEM informal activities attempt to recruit underrepresented or low achieving students, the reality is that access to informal STEM activities is often based on students' expressed high interest, prior academic achievement, teacher recommendation, time and travel availability and flexibility, and overall levels of ambition or motivation. Positive outcomes, due to technology, appeared to covary with other factors such as teacher content knowledge, the presence of campus support, or active engagement within a learning community.

Keywords: Informal learning; Learning; Metasynthesis; Middle and high school; Teachers; Technology

The term *STEM* was first used in the 1990s and was frequently used to label anything that involved one or more of the following four disciplines: science, technology, engineering, or mathematics (Bybee, 2010). Mathematics and science have been the focus of practical applications of STEM. The current emphasis on STEM education, the formation of a cyber-learning funding stream, and the funding emphasis on STEM at the National Science Foundation and at the Institute of Education Sciences requires a greater understanding for what is known about STEM teaching and learning (cf. Capraro, Capraro, & Morgan, 2013). Interdisciplinary STEM education creates a synergy expanding beyond the four individual subject areas toward the solving of problems that overlap the four disciplines and among the subcategories within those disciplines.

However, providing this high-quality education that prepares students for majors and careers in STEM fields remains challenging for educators. Over the last 8–10 years, there has been increased interest in exposing students to integrated studies in STEM areas to better prepare them to solve 21st century problems that require knowledge in multiple fields (Bicer, Boedeker, Capraro, & Capraro, 2015). New or modified teaching strategies that emulate real-world work situations may be required to successfully implement the new experiences in learning through integrated STEM programs. The purpose of this study is to determine attributes that are common to STEM programs reported in the literature.

Metasynthesis as Mode of Aggregation

The term *artifact* has been used in association with meta-analysis (Cooper, Hedges, & Valentine, 2009; Glass, 1976; Hunter & Schmidt, 2004) for decades. The rise in interest in aggregating qualitative findings into meaningful and interpretable insights has brought metasynthesis and the term *artifact* to prominence and alignment (Cutcliffe & Harder, 2009; Given, 2008; Onwuegbuzie, Leech, & Collins, 2012; Sandelowski, 2004). In fact, the term *artifact* in both meta-analysis and metasynthesis has become ubiquitous across many fields. However, one common issue with any meta-analytic technique, whether quantitative or qualitative, is the *file drawer problem*: a recognized bias in a metatechnique that favors published research (Easterbrook, Gopalan, Berlin, & Matthews, 1991; Rosenthal, 1979). To partially address this problem, researchers interested in meta-analytic research have chosen to include as broad a swath of literature as possible. There are some instances in which the scope of the work might be limited, for example, when considering experimental studies in which causal attribution is either intended or implied. However, many published studies are correlational at best, and generally speaking, qualitative studies are not intended to be generalized to some broader population. Therefore, metasynthesis has been used to aggregate studies and qualitative narrative texts to build a better understanding of research results as ideas, themes, and theories begin to emerge. The generalizability aspect of any metasynthesis is therefore limited to techniques, strategies, practices, attributes, characteristics, and methods and not to a broader population of participants. A *meta-analysis* is "the bringing together and breaking down of findings, examining them, discovering essential features, and, in some way, combining phenomena into a transformed whole" (Schreiber, Crooks, & Stern, 1997, p. 314). The broader term *metasynthesis* also involves combining and synthesizing the characteristics identified in the aggregation of findings.

Methodology

Metasynthesis is a systematic approach to reviewing and integrating findings from multiple qualitative or quantitative studies. Metasyntheses are integrations that are more than the sum of parts and offer novel interpretations of findings (Polit & Beck, 2012). The overall purpose of this metasynthesis is to generate new holistic interpretive meaning while preserving the uniqueness of the original studies to the extent possible and while aggregating methods and techniques to allow comment on practices, methods, attributes, and techniques (cf. Mays, Pope, & Popay, 2005).

The research question that framed this metasynthesis was: What are the attributes and their characteristics commonly linked in qualitative and correlational reports of STEM research regarding middle and high school STEM teaching and learning? To answer this question, a metasynthesis

was conducted. We attempted to identify attributes from the literature linked with successful STEM teaching, learning, interest, and attitudes.

Artifact Selection Procedures

Our comprehensive search of STEM practices in teaching middle and high school was conducted using the following search terms: "STEM practice" OR teaching OR learning OR education OR "high school" OR "middle school" OR research NOT cell NOT cells.

The idea of integrated STEM first became prominently used in classrooms around the United States in 2005; as a result, the criterion for the time period surveyed was set for January 1, 2005 through the date of the search, August 28, 2013. We did not require the word *STEM* in the title because the term was not widely used in the early years of the STEM movement. We considered any artifacts (e.g., journal articles, papers, poster presentations, dissertations, reports, and book chapters) that included substantial integration of at least two of the fields to be STEM.

Two comprehensive search engines were used: Google Scholar and EBSCO. The Google Scholar search returned 1,128 hits, and the EBSCO Academic Search Complete (with medical journals eliminated) returned 7,621 hits. Studies were screened to eliminate those related to an agricultural or medical meaning of the word *STEM* (e.g., plant stems, stem cell research); elementary level, undergraduate level, or graduate level STEM education; and studies dealing only with STEM careers. References were also checked on each coded study to locate additional artifacts. All artifacts available that appeared to relate to middle or high school STEM education were collected. This resulted in a total of 509 artifacts, with 58 of these artifacts fulfilling the inclusion criteria of (a) including substantial integration of at least two of the STEM fields, (b) having been published between 2005 and 2013, and (c) being empirical studies (i.e., studies that collected and analyzed data were included, whereas theoretical studies were not). Substantial integration was defined as addressing the relevant content area standards for at least two STEM fields (Laboy-Rush, 2007). For example, the use of technology with mathematics, science, or engineering was not considered a substantial integration because the technology was assistive and not a focus of the learning. Therefore, the search for integrated STEM artifacts would not have located the numerous studies that failed to note that integration in the keywords or abstracts.

The artifact coding process was composed of three parts. For the first part, the five coders were randomly assigned articles, and each article was assigned a categorizing word or phrase that characterized the contents of the manuscript. For example, one categorizing phrase was "reform-based teaching and learning," and another was "informal STEM." These phrases were brought back to the group, and the coders compared each other's categorizing phrases and discussed their intent and meaning. Through consensus, the group arrived at four categories that characterized the contents of the manuscripts. Then, one person read each of the manuscripts contained in a category and coded it for content and effects. Finally, the group met to reconcile their codes and justify their analyses. After consensus was reached, the team realigned the initial categories to better reflect the themes of the study artifacts.

More specifically, 58 unique artifacts were classified into four categories: *reform-based teaching and learning* (see Table 1), *informal education* (see Table 2), *teacher factors* (see Table 3), and *technology use* (see Table 4). Within these tables, some artifacts were repeated because different aspects of the artifacts were examined to shed light on one of the four areas of STEM teaching and

learning mentioned above. Therefore, the sum total of artifacts coded for each category was greater than the total number of artifacts because one artifact often contained information about more than one category. Finally, themes within each category were identified through an iterative process of constant comparison among the artifacts (Strauss & Corbin, 1990). Early in the analysis process, tentative linkages were developed between categories and evidence of effectiveness. As the coding progressed, themes for each category emerged. Upon saturation, the coding process shifted toward verification (Lincoln & Guba, 1985). Artifacts were revisited and reviewed again as additional themes emerged.

Background of the Categories That Emerged

Reform-based teaching and learning. Improving teaching and learning can involve practices that are student-centered and constructivist in nature (e.g., inquiry-, project-, and problem-based learning). These practices encourage students to (a) learn about the world around them, (b) engage knowledgeably in public discussion about issues of scientific and technological concern, and (c) increase their economic productivity as a result of knowledge and skill acquisition (National Research Council [NRC], 1996). Furthermore, reform-based teaching and learning practices have a history of producing positive outcomes (Anderson, 2002) such as increases in cognitive achievement, skills (Shymansky, Kyle, & Alport, 1983), scientific literacy, vocabulary knowledge, conceptual understanding, critical thinking, and positive attitudes (Haury, 1993). The results of these practices, however, are mixed. Strobel and van Barneveld (2009) conducted a metasynthesis of extant meta-analyses comparing reform-based practices to traditional classroom instruction. They found that, in general, reform-based practices promoted long-term retention of content knowledge and developed 21st century skills, whereas traditional practices were more effective for short-term retention of knowledge. However, in another metasynthesis, Clark found "that the failure to provide strong learning support for less experienced or less able students could actually produce a measurable loss of learning" (Clark, 1989; as cited in Kirschner, Sweller, & Clark, 2006, p. 81). In a different metasynthesis, he also found that "when learners are asked to select between a more or a less unguided version of the same course, less able learners who choose less guided approaches tend to like the experience even though they learn less from it" (Clark, 1982; as cited in Kirschner et al., 2006, p. 82).

Informal STEM learning opportunities. Informal STEM learning environments generally provide occasions for scientific learning without the time constraints commonly found in more formal settings (Hofstein & Rosenfeld, 1996). Informal learning settings (e.g., museums, zoos, science centers, and science camps) often have the tools, resources, and expertise to support STEM learning opportunities. The advantages of flexible time constraints in informal learning environments facilitate greater chances to augment conceptual learning, reflection time, assessment of subject matter, and informal discussions. These environments provide opportunities to facilitate student understanding and transform learning processes and concepts. Within informal settings, there are many opportunities for scaffolding student knowledge, attitudes, and STEM career options.

National and international interest has focused attention on informal learning opportunities. International comparisons have indicated that U.S. informal education opportunities may have been overlooked because there is a great deal of emphasis on formal STEM learning (Lee, 1998). However, there is a movement in the United States to examine the usefulness of STEM learning that can occur in informal learning environments. Informal STEM environments can account for

a considerable amount of student learning (Gerber, Marek, & Cavallo, 2001). National education groups have examined the impact of informal opportunities on STEM knowledge. Informal learning can complement and scaffold STEM teaching and student learning and increase participation in STEM for the underrepresented (National Academy of Sciences, National Academy of Engineering, & Institute of Medicine, 2007; NRC, 1996; National Science Board, 2010).

Informal science learning has gained traction as a possible contributor to student learning. Informal environments can be mechanisms for linking formal and informal efforts to improve student learning in STEM areas (Falk et al., 2012; NRC, 1996). Community resources have been useful in students' and adults' pursuit of STEM understanding (Bell, Lewenstein, Shouse, & Feder, 2009).

Teacher factors. "Many factors contribute to a student's academic performance . . . . But research suggests that, among school-related factors, teachers matter most" (RAND Education, 2012, p. 1). Some of the teacher factors that were considered in this study include attitudes, knowledge, beliefs, and practices that impact student learning and instructional practices. Examples include teachers' willingness to integrate technology (Yoon & Liu, 2010) and teachers' perceptions of students whom they would encourage to pursue engineering studies (Nathan, Tran, Atwood, Prevost, & Phelps, 2010). Teacher factors also included classroom factors fostering students' team skills through teacher designed collaborative learning activities.

Technology. Technology should be explored not only in concert with other STEM disciplines but also for its contribution to student learning. Generally, technology is one STEM component included in various combinations of interdisciplinary STEM education. Technology plays a vital role enabling students to relate science and mathematics knowledge across STEM disciplines (Sanders, 2009). In the 21st century, students need to be familiar with technological developments in order to understand changes in the world around them (Bybee, 2010). Developments in technology make our world more complex, and students need an appropriate technology rich education. In STEM education, the integration of technology with science, engineering, and mathematics enables students to relate these subject areas to the real world (Capraro et al., 2013).

Results

The four categories gave rise to the aggregated findings. Within the aggregated findings, counts of artifacts comprising each category, the generalized method, and the outcomes were identified. The findings were then reorganized for interpretation into themes that clearly illustrate the common practices and expected outcomes from the extant literature on middle and high school STEM teaching and learning.

The category of reform-based teaching and learning practices contained 25 of the 58 artifacts (see Table 1). The practices were classified as inquiry, engineering design, project-based learning (PBL), problem-based learning, the Legacy Cycle, or hands-on activities. Students were exposed to reform-based practices in a variety of settings at different grade levels, explored a variety of STEM-related subjects, and were immersed in these STEM-related learning environments for different lengths of time. In addition, different target groups of students were the focus of the studies, and some teachers received professional development (PD). Students were exposed to these reform-based strategies in both formal and informal settings. Fourteen of these studies took place in formal classrooms, and the remaining 11 took place in informal settings, including after

school or weekend programs (3), summer programs (5), or combined after-school and summer programs (3). Students were in middle school (12), high school (11), or both (2). These students were involved in different subjects related to STEM integration along with writing, reading, and social studies. Students were engaged in STEM-related projects using six different reform-based practices for 1 week or less (3), 2 to 5 weeks (6), 6 weeks to one semester (6), or more than 1 year (6). Four of the studies did not describe the length of time that students were engaged. Groups of females (10) and underrepresented students (8) were samples of interest. In nine of the 25 studies, the students' teachers received PD designed to support them in the implementation of the reform-based practices. Most of these reform-based teaching and learning practices focused on: enhancing students' content knowledge (17), developing students' skills (8), increasing students' use of technology (3), promoting students' interests in STEM-related college majors and careers (8), examining students' perceptions and attitudes (12), and providing rich learning environments for students (1).

In the category of informal education, there were 22 unique artifacts (see Table 2). The venues for informal learning included after-school or evening programs and clubs (8) or summer camps (14), some including follow-up mentorships. The lengths of the activities varied: 3 hours (1), 40 hours (2), 80 hours (1), 2 days (1), 3 days (1), 4 days (1), 1 week (1), 2 weeks (5), 1 month (2), 7 weeks (1), 10 weeks (2), 18 months (1), and longitudinal (one 3-year and one 5-year activity). A total of 1,965 participants were included within 21 of the studies that provided demographics with a range from 21 to 239 participants within each study. Some of these participants were from underserved, underrepresented, low SES, and minority populations (6 studies, 576 students); some were chosen randomly or by lottery (3 studies, 390 students); and others only attended if they had a high aptitude, high STEM interest, or high scores in mathematics and science (7 studies, 550 students). Many informal activities had more than one focus with one activity using as many as seven different teaching pedagogies. These pedagogies included: inquiry, hands-on activities, PBL, small and large group activities, field trips, modules, discussions, collaborations, and projects. They also included experts such as mentors and role models. Most of these informal activities contained a combination of two or more of these pedagogical strategies. The subjects were some combination of science, mathematics, engineering, technology, music, and robotics with some containing more than two of these specific subject areas. Most of the artifacts described interventions dealing with (a) increasing student knowledge and understanding, (b) increasing the STEM pipeline by developing a wider breadth of understanding for STEM careers, and (c) improving student attitude and confidence in STEM areas.

Twelve artifacts were classified as pertaining to the influence of teacher factors on STEM learning (see Table 3). Six principle themes for teacher factors emerged: (a) enhanced teacher content knowledge, (b) deep understanding of STEM teaching practices (effective pedagogy), (c) frequent and effective integration of technology, (d) effective use of team skills and collaborative learning, (e) high teacher self-efficacy, and (f) emphasis on deliberate instructional practice. Team skills and collaborative learning were discussed in five of the 12 artifacts. Of these five, three made reference to the importance of collaboration and how collaborative teams were structured within the outreach or PD programs, but they did not measure student outcomes based on levels or degree of collaboration. One artifact, however, described in detail how they structured teams, activities, and criteria for the primary purpose of fostering multiple layers of collaboration while discouraging passive cooperation and negative competition (Nag, Katz, & Saenz-Otero, 2013).

Table 1

Attributes of Reform-Based Teaching and Learning Strategies in Artifacts Reviewed (n = 25)

Reference	Reform-based strategy	CK[a]	Skill[b]	Technology use	Majors/ careers	Perceptions and attitudes	Learning environment
Brown et al. (2010)	Project		✓			✓	
Duran & Şendağ (2012)	Problem		✓				
Duran et al. (2014)	Inquiry	✓	✓	✓	✓	✓	
Heggen et al. (2012)	Inquiry	✓		✓	✓	✓	
Hudson et al. (2012)	Engineering design						✓
Hylton et al. (2012)	Inquiry	✓				✓	
Kampe & Oppliger (2011)	Project		✓	✓	✓	✓	
Kanter & Schreck (2007)	Legacy Cycle	✓					
Ketelhut (2007)	Inquiry	✓				✓	
Kim et al. (2011)	Inquiry	✓				✓	
Klahr et al. (2007)	Engineering design	✓				✓	
Klein & Sherwood (2005)	Legacy Cycle	✓					
Little et al. (2009)	Inquiry	✓	✓		✓		
Lou, Liu, et al. (2011)	Project	✓	✓			✓	
Lou, Shih, et al. (2011)	Problem	✓	✓		✓		
Mehalik et al. (2008)	Engineering design	✓					
Menzemer et al. (2007)	Hands-on	✓				✓	
Mosina et al. (2012)	Hands-on				✓		
Olivarez (2012)	Project		✓				
Richards et al. (2007)	Engineering design	✓					
Ricks (2006)	Inquiry	✓			✓	✓	
Schnittka (2009)	Engineering design	✓				✓	
Williams et al. (2007)	Inquiry	✓	✓				
Wimpey et al. (2011)	Inquiry	✓					
Zhe et al. (2010)	Problem				✓		

Note. ✓ = present.

[a] CK = content knowledge.

[b] Skill = technology, inquiry, critical thinking, reasoning, and problem solving.

Table 2
Attributes of Informal Education Artifacts Reviewed (n = 22)

Reference	Participants	Venue	Length	Selection	Pedagogies	Focus
Adamchuk et al. (2009)	147 MS	SC & AS	40–80 hours		R, Inquiry, PS, GIS	Attitudes, CK
Duran et al. (2014)	77 HS	Summer & AS	18 months	Special needs, F	T, Collaboration, Inquiry	CK, Careers, Perceptions, Attitudes
Cantrell et al. (2009)	130 HS	Seminar	5 years (L) 8 weeks	Interest in STEM	Seminars	Careers
Heggen et al. (2012)	21 MS	AS	10 weeks	Minority, low SES	T, Problem-based	TS, Careers
Hirsch et al. (2006)	36 T & S	Summer PD	2 weeks		Career awareness	Attitudes, CK
Hoyles et al. (2011)		AS		UK	Collaboration	Attitudes
Hubelbank et al. (2007)	129	SC	2 weeks	Lottery	PS, Role models, Hands-on	SE, Careers, Courses
Hylton et al. (2012)		SC	1 month	High STEM interest	Inquiry, PS, Enrichment	Courses, Confidence
Javidi & Sheybani (2010)	87 MS	SC & Saturdays	3 years	Low SES, Rural, Urban	R, Gaming, CP	Attitudes, Interest, Careers
Johnson et al. (2013)	133	SC	2 weeks	Talented	Research, Field trip, Scientists	Courses, Attitudes
Kim et al. (2011)	100	Summer	1 week	Underrepresented	Inquiry, Hands-on, Modules	Attitudes
Marle et al. (2012)	32	SC	4 days	Average	Real life exposure to science careers	Confidence, CK
Menzemer et al. (2007)	26 (11 LD)	Summer & AS	Varied	Special pop./LD	Hands-on, Technology	Attitudes, Careers, CK
Miller et al. (2011)	9 T & 84 S	Summer PD	2 days	Low SES, Minority		CK
Mosina et al. (2010)	239 HS	Summer & AS	10 weeks	Low SES, Minority	Projects, Mentors, Research, Exhibits	Courses
Nugent et al. (2011)	72 MS	Clubs	Episodic	M, White, Urban	R, Collaboration, PS	21st CS, CK, SE
Nugent et al. (2011)	147	SC	40 hours	Urban, Rural, Diverse	R, LEGOs, Hands-on	
Nugent et al. (2011)	141	One event	3 hours	Mixed abilities	Stations	Attitudes, Motivation
Nourbakhsh et al. (2005)	28 HS	SC	7 weeks	Application process	R, Challenge-based, Hands-on	CK, PS, CP, Collaboration
Prins et al. (2010)	48 MS	SC	3 days		Projects, Mentors, Exposure to careers	Career
Ricks (2006)	50	SC	4 weeks	High STEM interest	Hands-on, PS, Field trips, Inquiry	CK, Attitudes, Courses
Welsh (2009)	58	AS	6 weeks	Existing members	R, Competition	Attitudes

Reference	Participants	Venue	Length	Selection	Pedagogies	Focus
Williams et al. (2007)	21	SC	2 weeks	Average	Inquiry, Hands-on, Discussions	Content
Zhe et al. (2010)	33 HS	SC	10 weeks	High STEM interest	Problem-based, Collaboration, Hands-on	Confidence, Career

Note. MS = middle school; HS = high school; T = teacher; S = Student; SC = summer camp; AS = after school; PD = professional development; F = female; M = male; SES = socioeconomic status; UK = United Kingdom; STEM = science, technology, engineering, & math; LD = learning disabled; R = robotics; PS = problem solving; GIS = geographic information system; CP = computer programming; CK = content knowledge; TS = technology skills; SE = self-efficacy; 21st CS = 21st Century Skills.

Table 3
Attributes of Teacher Factor Artifacts Reviewed (n = 12)

Reference	Teacher CK	STEM teaching practices	Technology	Collaborative learning	Teacher self-efficacy	Deliberate instructional practice
Duran et al. (2014)			✓	✓		
Finson, Pederson, & Thomas (2006)		✓				
Hotaling et al. (2012)	✓		✓			✓
Hoyles, Reiss, & Tough (2011)		✓	✓		✓	
Lambert (2006)	✓					
Moskal et al. (2007)	✓	✓		✓		
Nag et al. (2013)		✓	✓	✓		
Nourbakhsh et al. (2005)			✓	✓		
Ragusa (2012)		✓			✓	✓
Silverstein et al. (2009)	✓	✓			✓	
Yoon & Liu (2010)	✓	✓	✓		✓	
Zhe et al. (2010)				✓		

Note. ✓ = present
[a] CK = content knowledge

Table 4
Attributes of Technology Related Artifacts Reviewed (n = 27)

Reference	Technology used	CK	Technology skills	Teaching strategy	Majors/ careers	Perceptions and attitudes	21st century skills
Adamchuk et al. (2009)	R, HH, CP			Inquiry ‡			PS
Brown et al. (2010)	Simulations		✓	Project-based		✓	
Chapman (2012)	Simulations	S				✓	PS
Duran & Şendağ (2012)	R, CP		✓	Problem-based	✓		
Duran et al. (2014)	R, CP	S	✓	Inquiry	✓	✓	Collaboration
Heggen et al. (2012)	HH		✓	Inquiry	✓		
Hotaling et al. (2012)	HH, CP	T, S		Problem-based ‡			PS
Huang, Liu, & Shiu (2008)	CAI	S		Cognitive conflict			
Javidi & Sheybani (2010)	R, CP		✓	Games	✓	✓	
Johnson-Glenberg et al. (2011)	Simulations			Problem-based ‡, Games	✓		
Kampe & Oppliger (2011)	R, HH		✓	Project-based	✓	✓	PS
Kay, Zucker, & Staudt (2013)	Simulations	S					
Kim et al. (2011)	CP			Inquiry			
Klahr, Triona, & Williams (2007)	Simulations	S		Engineering design		✓	
Lawless, Brown, & Boyer (2011)	Simulations	S	✓				
Lou, Liu, et al. (2011)	Solar Trolley		✓	Project-based	✓	✓	PS
Moskal et al. (2007)	R, HH, CP	T, S	✓	Hands-on ‡		✓	Collaboration
Nag et al. (2013)	R, Simulations	S					PS, Collaboration
Nourbakhsh et al. (2005)	R, CP		✓				PS, Collaboration
Nugent et al. (2011)	R, CP		✓			✓	PS, Collaboration
Stephen, Bracey, & Locke (2012)	R, HH				✓		Collaboration
Strautmann (2011)	R		✓		✓	✓	
Sumners, Handron, & Jacobson (2012)	Simulations	S	✓	Inquiry ‡, Games			
Tan et al. (2013)	Simulations		✓				
Welch (2010)	R			Competition		✓	
Wyss, Heulskamp, & Siebert (2012)	Recordings				✓		
Yoon & Liu (2010)	Simulations	T					

Note. ‡ = The match between Table 4 (technology) and Table 1 (reform-based artifacts) may not be exact. Pedagogical practices are listed in this table only when the artifact reviewed discussed student gains in technology skills, attitudes about technology, frequency of technology use, or technology content knowledge in relation to the pedagogical practice. R = robotics; HH = handheld technology device; CP = computer programming; S = science; T = technology; ✓ = present; P&A = Perceptions and Attitudes; PS = problem solving. NELS = National Education Longitudinal Study; HS = high school; MS = middle school; PBL = Project-based Learning; Tech = technology.

Participants were grouped by level of collaboration. The degree of collaboration was linked to knowledge and skills.

There were 25 artifacts that discussed the integration of technology with mathematics, science, or engineering (see Table 4). More than half (13 of 25) of the artifacts that discussed the use of technology as part of STEM integration described robotics projects. Three of the studies addressed content knowledge, eight focused on technology skills, nine discussed STEM interest, and nine others concentrated on 21st century skills. All of the robotics projects were implemented in informal environments, summer camps, and after-school programs. Nine of the 25 artifacts described projects that used simulations of some type. Many were not well characterized; however, one specifically mentioned robotics (Nag et al., 2013), and one involved simulations in games (Sumners, Handron, & Jacobson, 2012). One project used a 5-week simulation project to address national standards for middle school students in persuasive writing and social studies as well as science. The simulation addressed water resources and solving a crisis in the availability of clean water. Seven of the nine artifacts that mentioned programming used it in connection with a robotics project.

Themes From Higher Level Abstractions

In order to make the findings more accessible and more applicable for researchers and practitioners, we examined the findings through an iterative process of recategorization and discovered a higher level of abstraction. This abstraction more closely matches important areas for research and school practice. The emergent themes were (a) student content knowledge and skills, (b) teacher content knowledge, (c) perceptions and attitudes, (d) majors and careers, and (e) technology integration.

Student content knowledge and skills. The predominant purpose was to increase student content knowledge. Findings from several studies showed positive gains on student content knowledge across various subject areas (Duran, Höft, Lawson, Medjahed, & Orady, 2014; Heggen, Omokaro, & Payton, 2012; Hylton, Otoupal-Hylton, Campbell, & Williams, 2012; Marle, Decker, Kuehler, & Khaliqi, 2012; Ricks, 2006; Williams, Ma, Prejean, Ford, & Lai, 2007; Wimpey, Wade, & Benson, 2011). The duration of the program and the direct confrontation of STEM misconceptions were related to changes in student STEM conceptions (Miller, Ward, Sienkiewicz, & Antonucci, 2011; Ricks, 2006). The duration of the intervention was related to better improved student outcomes (cf. Bicer, Navruz, et al., 2015; Capraro et al., 2016; Cetin, Corlu, Capraro, & Capraro, 2015). However, there was no evidence that engineering and technology knowledge were influenced by reform practices (e.g., Little & León del la Barra, 2009).

Engineering-design-based practices appeared to offer benefits for student development of content knowledge. Findings from several engineering-design-based studies showed increased student content knowledge (Mehalik, Doppelt, & Schuun, 2008; Richards, Hallock, & Schnittka, 2007; Schnittka, 2009). Furthermore, science content knowledge was more often influenced by engineering-design-based practices than by inquiry practices (e.g., Nite, Capraro, Capraro, Morgan, & Peterson, 2014; Han, Capraro, & Capraro, 2014; Han, Yalvac, Capraro, & Capraro, 2015). Engineering design was often associated with greater affect and academic interest for formerly low achieving African American students than for any other group of students. Virtual and nonvirtual engineering design practices were equivalent with regard to engineering content knowledge (e.g., Klahr, Triona, & Williams, 2007). Engineering-design-based practices were closely aligned with improved proficiency with technology (Duran et al., 2014; Little & León de la Barra, 2009).

There were significant positive differences between student content knowledge and procedural knowledge when students participated in PBL, and this extended to special populations (e.g., Duran & Şendağ, 2012; Klein & Sherwood, 2005; Lou, Liu, Shih, & Tseng, 2011; Menzemer, Lam, Zhao, Zhe, & Doverspike, 2007; Olivarez, 2012). In general, students with learning disabilities tended to benefit from reform techniques (e.g., Menzemer et al., 2007). Some results were broadly defined but with mixed results showing that content knowledge could be heavily moderated by other factors (e.g., Kanter & Schreck, 2007; Lou, Shih, Diez, & Tseng, 2011). Further, PBL had a positive impact on student writing and technology knowledge (Brown et al., 2010).

Teacher content knowledge. Teacher content knowledge had a substantial impact on student outcomes. Artifacts established a positive relationship between teacher content knowledge and student learning (Hotaling et al., 2012; Lambert, 2006; Moskal et al., 2007; Ragusa, 2012; Silverstein, Dubner, Miller, Glied, & Loike, 2009). The outcomes were correlational at best because it was not possible to aggregate the effect due to the lack of detail in the reporting (no means or standard deviations reported or insufficiently reported statistical tests) or reporting percent gains or gain scores alone. However, the greater the teacher subject matter knowledge reported in the articles or time given building teacher subject matter knowledge, the better the student outcomes (Hotaling et al., 2012). Most studies included prolonged and systematic PD of STEM teaching strategies (e.g., problem-based learning, inquiry, or engineering design). Students who were weaker academically tended to benefit to a greater extent from increases in teacher content knowledge (Lambert, 2006; Silverstein et al., 2009).

Perceptions and attitudes. Generally, this higher order factor focused on how perceptions and attitudes changed with regard to various aspects of STEM teaching and learning. Overall, students who engaged in inquiry-based practices had positive attitudes and perceptions toward STEM. It was also found that there were positive attitudes toward learning science (Ricks, 2006), engineering careers (Hirsch, Kimmel, Rockland, & Bloom, 2006) computing (Heggen et al., 2012), and mathematics skills and self-confidence (Hoyles, Reiss, & Tough, 2011; Hylton et al., 2012; Zhe, Doverspike, Zhao, Lam, & Menzemer, 2010). When attitudes toward STEM subjects were overwhelmingly positive, these attitudes did not change during interventions (Duran et al., 2014; Heggen et al., 2012). There were no gender differences with regard to attitude or affect toward STEM (Marle et al., 2012). After a STEM intervention, males showed more positive attitudes toward science and scientists, but females remained anxious, although their views were more positive. One possible reason for this difference was that females reported that technology made science learning interesting, data gathering more accurate, and improved visualization and understanding (Kim et al., 2011). In comparison, an engineering-design-based study showed that females had a greater increase in positive attitudes toward engineering than did males (Schnittka, 2009). However, another study found that confidence level differed by gender with females having a lower confidence with regard to hands-on or virtual activities (Klahr et al., 2007). Studies focusing on PBL practices showed consistent results. Students had positive attitudes toward their summer workshop experience (Kampe & Oppliger, 2011), and STEM PBL practices had a positive influence on students' behavioral intentions, attitudes, and desire to learn (Lou, Liu, et al., 2011). However, PBL did not have an impact on students' self-efficacy toward STEM subjects (Brown et al., 2010). Both mainstream and learning disabled students were satisfied with their STEM instruction, more interested in the lessons, and had a higher self-efficacy toward STEM subjects when hands-on practices were used.

Majors and careers. One goal of many STEM reform-based practices was to increase student interest in STEM majors and future careers. Programs designed to increase student interest in STEM careers and STEM majors tended to be persuasive. First, students who were involved tended to already be somewhat positive toward STEM careers and majors. However, females tended to recognize that their embodiment of the characteristics aligned with a STEM-related career (knowledge development, affinity for STEM-related activities, and interest in STEM) through the programs (e.g., Heggen et al., 2012; Hubelbank et al., 2007; Lou, Shih, et al., 2011; Ricks, 2006). One specific difference was related to confidence, which tended to influence males and females equally (Zhe et al., 2010). Again, it is important to note that underrepresented students tended to be more heavily influenced toward STEM careers and majors. In general, informal activities focusing on STEM topics had a positive effect on students' impressions of STEM careers and were indicative of students wanting to pursue a STEM major or career (Cantrell & Ewing-Taylor, 2009; Hubelbank et al., 2007; Hylton et al., 2012; Johnson et al., 2013; Mosina, Belkharraz, & Chebanov, 2012; Ricks, 2006; Wyss, Heulskamp, & Siebert, 2012; Zhe et al., 2010).

Increased technology use. Researchers examining the implementation of STEM reform-based practices incorporated technology use as an outcome measure. Mobile phones and computers were shown to be tools valued by students in inquiry-based environments. The increased emphasis on mathematical and scientific problem solving precipitated increased technology understanding (Heggen et al., 2012). Engagement in inquiry-based learning activities increased students' use of basic technology tools, and about half of the students broadened their repertoire to include advanced STEM technologies (Duran et al., 2014; Young & Young, 2013). Students who were engaged in STEM PBL increased their use of database software; robotics and programming; modeling; computer game development; and communication technologies such as blogs, podcasting, and social networking (Kampe & Oppliger, 2011). Technology became more of an integrated tool that students learned to use to further their accomplishments in science, mathematics, and engineering.

Teacher use and integration of technology was paramount for student learning in STEM-related activities. Three factors led to classroom adoption and integration of technology: (a) sufficient time to assimilate the technology, (b) institutional support, and (c) active engagement within the learning community (Yoon & Liu, 2010). The primary challenge mitigating the impact of technology was the cognitive demands of learning about the technology placed on the teacher (Silverstein et al., 2009). This barrier ensured that students would not have the opportunity to use the technology.

Conclusions

Our conclusions are based on the prevalence and preponderance of qualitative evidence presented in the research artifacts. Almost all studies included a form of inquiry. This may not be surprising because inquiry can be found across all STEM disciplines. In many cases, the inquiry was encased within stringent curricular components that were carefully assessed and highly structured. In other studies, inquiry was semistructured with more fluid curricular components and more dynamic and spontaneous teaching episodes. Regardless of the flavor of inquiry being enacted, it was commonly associated with qualitative outcomes of increased affect toward a STEM subject or subjects, greater interest in STEM fields, and more positive feelings about learning. Inquiry was broadly defined and included problem-based learning, project-based learning, engineering design, discourse, and enactivism. Broad definitions of inquiry were used in these studies, which made identification reasonably easy, but it is troubling that there was no definition of inquiry presented in

four studies (e.g., Duran et al., 2014; Heggen et al., 2012; Hylton et al., 2012; Wimpey et al., 2011). However, the description of the activities, processes, and assessments made it clear that the studies were inquiry based. For example, some studies described their model as focusing on questioning and using hands-on and minds-on activities (i.e., Little & León de La Barra, 2009), whereas others characterized their work as being student centered, active learning, requiring critical thinking, and developing problem solving skills (cf. Ricks, 2006). Only three of the studies described inquiry according to the *National Science Education Standards'* definition of scientific inquiry (e.g., Ketelhut, 2007; Kim et al., 2011; Williams et al., 2007):

> Scientific inquiry refers to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world. (NRC, 1996, p. 23)

Studies in which informal learning programs were used yielded interesting and unexpected sets of aggregated findings. Generally, every study that reported on informal STEM education activities (i.e., after-school clubs, camps, university visits, and on-line mentoring by STEM professionals) was aligned qualitatively with positive outcomes. Most common were self-reports of greater access, interest, and competence in STEM fields. Although most informal activities primarily indicated that students felt better connected to STEM fields, some showed students possessing greater awareness of STEM careers and increased motivation to pursue postsecondary STEM schooling. Some programs were designed specifically for women or minorities with findings indicating that this group preferred informal activities that highlighted social aspects, support structures, and building new friendships.

The single most common component for teachers who participated in STEM PD was increasing teacher content knowledge, making it one of the greatest perceived needs by researchers. This was followed by improving teachers' pedagogical practices for STEM teaching and learning. Teacher content knowledge was most effective when it was broad, covered a range of disciplines, and integrated. After teachers had acquired new content knowledge, it took additional time to translate the content knowledge to educational practices.

Many of the studies focused on students' STEM learning that followed their teachers' PD, which was focused on STEM content knowledge, reform-based STEM teaching practices, or STEM research experience for teachers. However, it was difficult to attribute student performance solely to teacher content knowledge. Although this metasynthesis included quantitative artifacts, they were correlational in nature, so no estimate of effect was warranted.

The purpose for many of the studies was to improve affect, and of those, many did not address academic performance at all. Many of the artifacts dealt with engaging students in STEM learning, experience with or comfort with various technologies, increasing interest in STEM studies and careers, and improving attitudes about STEM. In general, long-term projects produced positive results for student interest in STEM majors and careers, but these projects were most often conducted in informal environments, primarily with voluntary involvement. Projects designed to familiarize students with engineering, engineering design, and careers in engineering had an impact on the desirability of an engineering major and career. The single most common study characteristic dealing with affect was informal education, often hosted by or at a university in collaboration

with a school or school district. Perhaps the informal settings were selected to provide additional educational support and foster collaboration between universities and K–12 schools.

Informal education experiences were fraught with equity issues. Equity issues related to "closing the gap" involve strategies for access to equal participation as well as strategies for access to equal success. Even though informal education (i.e., STEM summer camp opportunities and after-school activities) attempts to recruit underrepresented or low achieving students, the reality is that access to informal STEM activities is often based on students' expressed high interest, prior academic achievement, teacher recommendation, time, travel availability, flexibility, and ambition or motivation. Promising components within those informal programs that are recurrent and noteworthy for future study include having students identify and solve authentic problems, content-focused field trips, interactions with experts in STEM fields, experience with STEM-centric technologies, long-term projects (2-weeks or more), STEM subject integration, product-focused outcomes, and students learning to justify results and conclusions.

Implications for Educators

Teachers should capitalize on the creativity and the curiosity of students to integrate STEM into classroom activities. Teachers might ask, "How can I do that? There are already too many objectives and standards to cover." Preservice and in-service teachers need to take a closer look at the standards. Of course, just because the standards allude to integrating subjects, classroom enacted lessons do not automatically become integrated. Therefore, teachers need to be voracious consumers of PD opportunities that meet STEM integration needs from education service centers, STEM centers, STEM partners, and universities.

The STEM school development movement has gained momentum recently in K–12 classrooms as evidenced by the funds supporting the creation of a large number of new STEM-focused schools (Bicer, Navruz, Capraro, & Capraro, 2014). The theory behind this movement is that students learn less when individual subjects are taught than when subjects are integrated. What better place to start than in middle and high school to integrate STEM curriculum? In order for STEM integration not to remain just verbiage, teachers need to ask their PD providers to present strategies for making meaningful connections between disciplines. Science and mathematics teachers are prepared in teacher training programs with a single subject focus; therefore, teachers tend to impart that same perspective to their students. As a result, both science and mathematics teachers have difficulty viewing mathematics and science as an integrated whole and synergistically with engineering and technology. Teachers should not feel inadequate about their abilities to facilitate learning in the classroom. Unfortunately, most teachers do not feel comfortable integrating content. Until teachers feel confident and have time to practice this STEM integration, it will not happen. Teachers should ask their administrators and university partners to provide STEM integration training.

Imagine how much learning could take place if a team of middle school students were working on a task developing paper airplane gliders for a company (engineering)? Artifacts developed could include graphs comparing flight distances or weight vs. length of wings (mathematics and technology) and calculations of how the air pressure pushing on the wings of the glider keeps it from coming straight down (science). This integration at the middle school level can serve as a natural progression to more rigorous high school level science, technology, engineering, and mathematics coursework. These same energetic, curious, and creative students might then be more likely to choose STEM majors in college and ultimately careers in STEM fields!

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[1] Asterisks are used to indicate the studies that were used in the metasynthesis.

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