12-2022

Estimating the Effects of Forms of Computer-Based Scaffolding in Problem-Centered STEM Instruction

Mason Reed Lefler
Utah State University

Recommended Citation

Lefler, Mason Reed, "Estimating the Effects of Forms of Computer-Based Scaffolding in Problem-Centered STEM Instruction" (2022). *All Graduate Theses and Dissertations*. 8684.
https://digitalcommons.usu.edu/etd/8684

ESTIMATING THE EFFECTS OF FORMS OF COMPUTER-BASED SCAFFOLDING IN PROBLEM-CENTERED STEM INSTRUCTION

by

Mason Reed Lefler

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Instructional Technology and Learning Sciences

Approved:

Andrew E. Walker, Ph.D. Major Professor	Steven P. Camicia, Ph.D. Committee Member
Jody Clarke-Midura, Ed.D. Committee Member	Karl White, Ph.D. Committee Member
Hillary Swanson, Ph.D. Committee Member	D. Richard Cutler, Ph.D. Vice Provost for Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2022

ABSTRACT

Estimating the Effects of Forms of Computer-based Scaffolding in Problem-Centered STEM Instruction

by

Mason Lefler, Doctor of Philosophy

Utah State University, 2022

Major Professor: Andy Walker, Ph.D.
Department: Instructional Technology & Learning Sciences

This multiple paper dissertation addressed several issues revolving around the estimation of effect sizes for computer-based scaffolding in problem-centered STEM education. STEM jobs are outpacing all other jobs and STEM workers are expected to solve complex problems. However, students often struggle with complex problem activities. Research on computer-based scaffolding has been shown to produce large learning gains in STEM fields. Yet, previous meta-analyses have not been able to pinpoint which scaffolding characteristics impact learning gains the most. This lack of insight impedes researchers and learning designers from developing more effective computer-based scaffolds.

This dissertation (a) provides insights on the gaps in computer-based scaffolding syntheses, (b) reveals the conflation of terminology that has been used to characterize scaffolding, (c) details a taxonomy for the various forms of computer-based scaffolding, and (d) conducts a meta-analysis to estimate which scaffolding forms and combinations of computer-based scaffolding forms produce the largest learning gains in collegiate engineering education.

(168 pages)

PUBLIC ABSTRACT

Estimating the Effects of Forms of Computer-based Scaffolding in Problem-Centered STEM Instruction

Mason Lefler

Much like Post-Sputnik 1950s era there is a lot of interest in making sure that United States does not fall behind in Science, Technology, Engineering, and Mathematics (STEM) education. STEM learners are often presented with complex problems to solve both as part of their education and their work. Engineering education suffers from student dropout often due to how difficult it is to support students through solving problems. This dissertation is a close look at computer-based scaffolding, a method of supporting learners during problem solving through computer software. The first paper in this dissertation examines and resolves some of the debate about key terms in scaffolding. The second paper looks across all of the collegiate engineering education research to date and measures the unique and combined contributions of scaffolding forms on learning using a technique called meta-analysis.

ACKNOWLEDGMENTS

I would like to thank all of those who have endured me as I have endured this process. Earning a doctorate while trying to start a family and career was difficult on everyone involved, and I profusely apologize for putting you all through it.

Thank you, Andy Walker, my dissertation chair and department head. Thank you for being patient as I slowly balanced the demands of family, career, and education. Thank you for not giving up on me. Thank you for being so kind, so generous, and a friend.

Thank you, dissertation committee members Dr. Jody Clarke-Midura, Dr. Hillary Swanson, Dr. Steven Camicia, and Dr. Karl White for providing me with critical feedback and guidance. Your insights made this work better and me a better academician in the process.

I thank my peers, teachers, and friends in the USU ITLS department and at Bridgerland Technical College for creating such a warm and wonderful communities.

Next, my parents. Thank you, Laura Lefler and Tom Lefler, for instilling in me a love of knowledge. I get my “genius jeans” from you. Thank you for your feedback. Thanks for keeping me on 850,000 prayer rolls. I am sure I would not have made it without some help from angels. I have known from a very young age that I got the two best parents a boy could ever be blessed with!

I apologize and thank my babies Noodle, Yay Yay, Bug, and Bear. The biggest regret of my life, so far, is trading in time with you for this dissertation. I wish I could get

it back. I love you all so much and I will figure out a way to make up for lost time. Get ready to play!

Foremost, I would like to thank my wife. I wish I could tear this dissertation in two and give you half because you worked just as hard (and possibly more) than I did. Please forgive me for taking too long. Thank you so much for sticking it out with me. I love you so much!

Finally, I would like to thank my God who told me to “launch out into the deep” when I was exhausted and fresh out of hope. Thank you for whispering faith into my soul.

Mason Reed Lefler

CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Wood et al. (1976) conducted a project with a sample of 30 toddler boys and girls to gain a better idea of the tutorial process. Specifically, these researchers wanted to characterize the ways in which an expert (in this case a parent) could help a novice (3- to 5-year-old child) acquire the knowledge and skills required to complete the task of constructing a 6-tiered tower of 21 interlocking blocks. Wood et al. saw that more capable human tutors could transfer their expertise to their students by supplying the student with targeted contingent help. These temporary supports allowed the children to have success that would have been otherwise impossible if the child had been left unaided. The researchers labeled this tutorial process *scaffolding* – a term that provides a powerful metaphor for how learning happens.

In the nearly 40 years since that landmark article, the scaffolding construct has expanded beyond its original specific context of children building block towers to include new types of tutorial relationships, age groups, and content areas (Pea, 2004; Sherin et al., 2004). In particular, especially since the mid-1990s, there has been a large amount of primary research investigating whether scaffolding could be effectively delivered by computers thus allowing many students to receive tutorial help at scale (Belland, Walker, Kim, & Lefler, 2017).

The purpose of this multiple paper dissertation is to offer further insight into which computer-based scaffolding interventions produce the largest learning gains in collegiate engineering education. Before outlining the research questions and methodologies followed in this dissertation, I will briefly (a) define scaffolding, (b) describe theoretical origins of the scaffolding construct, (c) enumerate the critical features that constitute scaffolding, (d) explain the rise of computer-based scaffolding, (e) explain the connection between scaffolding and problem-centered instruction in STEM (Science, Technology, Engineering, and Mathematics) content areas, and lastly (f) review the prior meta-analytical outcomes of computer-based scaffolding on STEM learning outcomes.

Theoretical Origins of Scaffolding

At its inception scaffolding was decidedly a social, constructivist, and situated construct (Stone, 1998). As a reaction to behaviorism, researchers in the 1970s and 1980s began to develop a different theoretical approach to describe learning. Rather than the traditional behaviorist/instructionist paradigm of children memorizing decontextualized facts in a teacher-centered classroom, theorists such as Jerome Bruner, Barbara Rogoff, Jean Lave, Etienne Wenger, John Seely Brown, Allan Collins, and Paul Duguid (Collins et al., 1989; Lave & Wenger, 1991; Rogoff et al., 1995; Wood et al., 1976) started describing alternative theories of instruction which viewed *learners* as active participants and *learning* as a sociocultural phenomenon.

In constructivism, the goal of education is to create independent, self-directed, problem solvers (Y. S. Chen et al., 2003). Instead of a cognitivist/instructivist perspective where knowledge exists outside of the learner, constructivism begins at the interpersonal level and then proceeds to the intrapersonal level (Pea, 2004). At the interpersonal level, learning happens as students both mediate and are mediated by their environment.

Learners engage with more knowledgeable others and appropriate that knowledge while simultaneously moving into full participation with a community of practice (Lave, 1991).

Brown et al. (1989) likewise criticized the artificial disconnection between knowing and doing in regular instructivist classrooms as inherently flawed and underproductive. The authors argued against the tacit underlying assumption of traditional instruction which viewed learning as some abstract substance that was to be poured out of the teacher and into a passive receptacle: the student. Instead, Brown et al. argued that learning was inseparable from both activity and context. Powerful learning experiences arose when learners reconnected the *know-how* with the *know-what.*

From this socio-constructivist perspective, teachers who deliver scaffolding cease being the main player on center stage and shift that main role to students so that the students can engage in the play of learning, fundamentally engaged, and fundamentally situated in context. No longer the focus, teachers shift into a supportive role (van de Pol et al., 2010; Wood et al., 1976) where they apprentice students into full knowledge and community participation through active enculturation. In this sense, when talking about scaffolding, the focus of learning is on the learner, their meaning making, and their full participation in the community. Consequently, a teacher's role from the constructivist perspective is one of supportive facilitation as the student discovers their own learning (C. C. Liu & Chen, 2010, p.65).

Perhaps it is this *guide on the side* view of teaching, as well as their similar powers of descriptive utility, scaffolding, and the zone of proximal development (ZPD) have often connected in literature (Palincsar, 1998; Stone, 1998; van de Pol et al., 2011).

Despite being developed independently of one another (Stone, 1998), Vygotsky's ZPD and scaffolding similarly posit that learning happens in a space between what the student has previously mastered and what they cannot accomplish independently without help (Lantolf, 2000). In this developmental zone, students are assisted by a more expert "other" to successfully accomplish what would have been impossible if attempted without assistance. With success students gain proficiency, and their individual ZPD then expands outward to encompass their newly developed knowledge, skills, or abilities. Since its original description and connection to Vygotsky's ZPD, scaffolding has been reinterpreted by many scholars in order to emphasize various aspects of the construct. Regardless of interpretation, the scaffolding relationship between a tutor and tutee has been guided by a few key features.

Critical Features of Scaffolding

It is important to consider the theoretical roots of the scaffolding metaphor because, as I will describe further, it is in the absence of this foundational knowledge that gives rise to many of the misconceptions and alternative ways scaffolding has been used over the past 40 years. These alternative uses of scaffolding dropped critical principles and characteristics of the scaffolding framework such as contingency, fading, and gradual release of responsibility. I will explain these critical features of scaffolding before introducing the rise of computer-based scaffolding.

Contingency is the idea that the scaffolding must be continually tailored to the student and the task (Belland, 2014). Providing just-in-time support, within a student's zone of proximal development, necessitates that the tutor can accurately estimate the student's capacity to solve the current problem as well as identify where that student is at in the problem-solving process. Without a clear model of the student's current knowledge, skill, and ability, the teacher runs the risk of providing too much help, too little help, or help that is misaligned to the task at hand. Too much scaffolding support may rob the student of their chance to engage with the task and grow in knowledge and/or self-efficacy. Too little scaffolding support may leave the student without the requisite help to successfully complete the task which may lead to frustration and a lack of self-efficacy. In addition to moderating *how much* scaffolding is extended to the student, contingency also moderates *when* scaffolding is extended to the student. While there is not an established term for the delivery of scaffolding there is one for the removal of scaffolding.

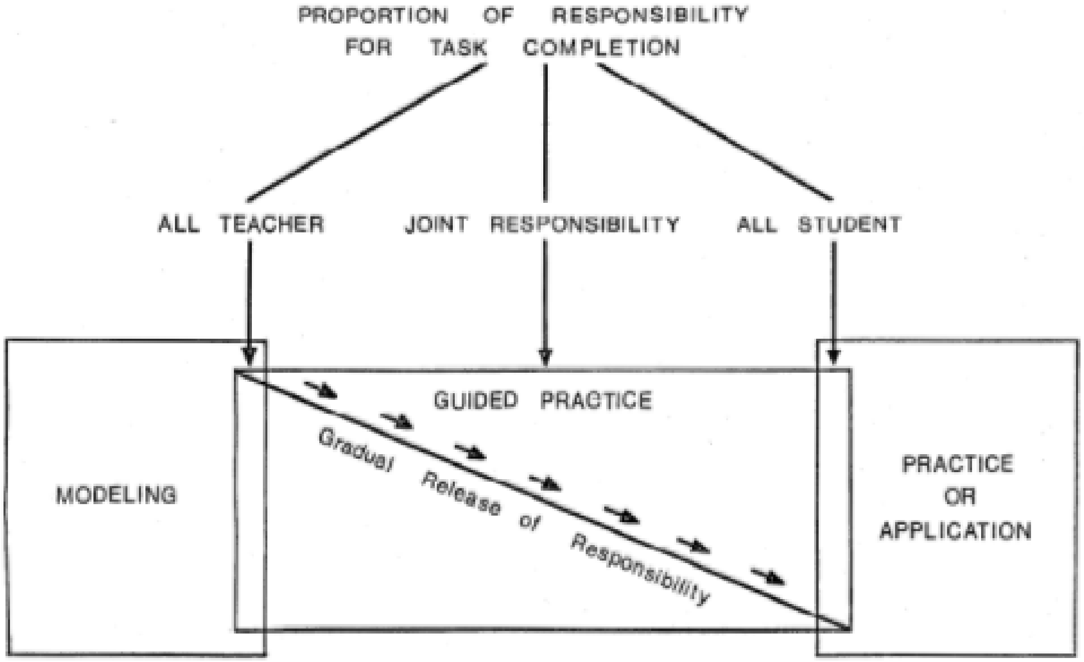
Fading is the term most commonly used in scaffolding literature to describe the expectation that a tutor should remove their scaffolding from the tutee over time. The gradual removal of the scaffold ensures that the student is both gaining in knowledge and skill while also simultaneously avoiding becoming dependent upon the scaffold for continued success. In other words, fading ensures that scaffolds are temporary helps and not long-term crutches. While fading has been the most popular term describing this removal of support, there have been other terms, such as gradual release of responsibility, which further explains this concept.

Gradual release of responsibility, also referred to as transfer of responsibility, was first introduced by Pearson and Gallagher (1983). Transfer of responsibility more fully conceptualizes what is actually being “faded” in a scaffolding intervention. Rather than just a simple removal of the scaffold, transfer of responsibility clarifies that fading is a shift of responsibility or ownership over the task from the teacher to the student. Pearson and Gallagher included a diagram in their 1983 article that demonstrates instruction as beginning with teachers “owning” the majority of the responsibility over a particular knowledge base or skill and then relinquishing more and more responsibility to the student as the instruction progresses. Figure 1.1 illustrates a key characteristic of transfer of responsibility (fading); that fading happens over successive problem-solving exercises in which a proportion of task responsibility shifts from teacher to student. For example, to start the scaffolding process, a math tutor may begin with a model/worked example of how to multiply fractions. At this stage the teacher is completely responsible over the learning space as they deliver a scaffold (worked example) to the student (see Figure 1.1 - “All Teacher”). The next step in the scaffolding process may include the removal of the full model and an introduction of a partially worked example where the teacher completes a few steps of the algorithm but expects the student to take ownership of other steps (see Figure 1.1 - “Joint Responsibility”). The student and teacher continue to engage in guided practice. As the student demonstrates increased knowledge and skill, the teacher may replace the partially worked examples with hints or question prompts. During this last phase, at some point the student has taken ownership over the task (see Figure 1.1 - “All Student”).

Another simple example of transfer of responsibility of scaffolding is found in the aid offered by a parent to a child as they learn to ride a bike. Learning to ride a bike

Figure 1.1

Model of Gradual Release of Responsibility

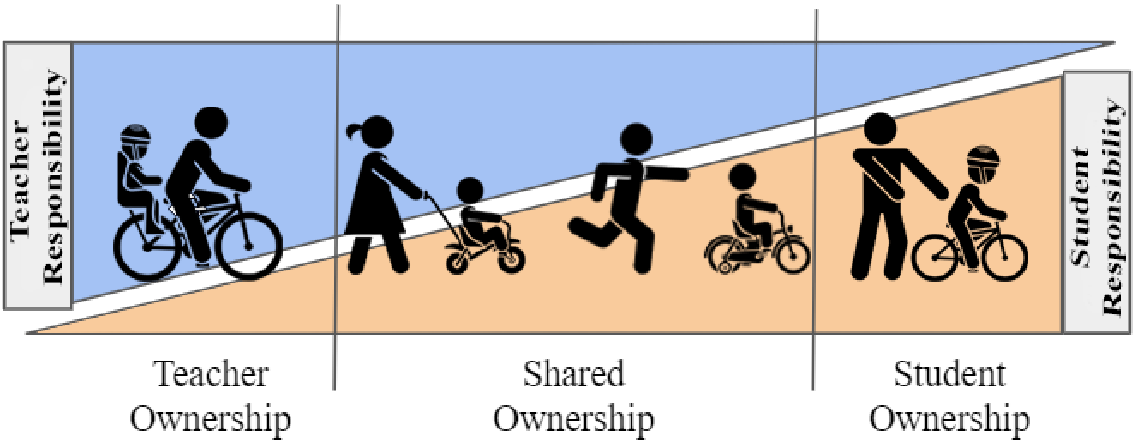


Note. From “The instruction of reading comprehension” by P. Pearson & M. Gallagher, 1983. *Contemporary Educational Psychology*, *8*(3), p. 317–344.

requires a child to learn how to pedal, balance, and steer among other skills. For a novice, mastering all of these skills simultaneously is unreasonable, and as such, various types of scaffolds have been developed as part of the bike itself to help a child learn to ride a bike. For example, there are starter bikes which include not only training wheels but also include a parent push bar which gives the parent the ability to manage the speed and the steering (all parent). Once a student has learned to pedal and steer, the push bar is removed, which allows the child to take more ownership over steering and speed of the bike without becoming totally responsible for the balancing of the bike. The child continues to gain expertise until they are ready to remove the training wheels. However, at this stage the parent steps back in to help the child balance, often running alongside the child. Ultimately the parent lets go and the child begins to take full responsibility over all aspects of riding the bike. Figure 1.2 illustrates how a parent delivers scaffolds through the three major phases of transfer of responsibility.

Figure 1.2

Gradual Release of Responsibility and Scaffolding when Learning to Ride a Bike



Looking at scaffolding from the context of transfer of responsibility reiterates a few key concepts from this prescriptive instructional theory. First, the goal of scaffolding is the shift of ownership of a task from tutor to tutee. Second, the form of the scaffolding is contingent on an ever-shifting capability of the learner. Third, scaffolding can take the form of a support that is added to the learning environment, but it can also take the form of a task structuring (i.e., riding a tricycle before riding a bicycle). Finally, depending on where the student lies on the continuum of novice to mastery, the form of scaffolding will differ. For example, novices (left frame and lower ownership) may benefit from more directive guidance, whereas learners who are approaching mastery (i.e., right frame and higher ownership) will benefit from scaffolding that supports self-regulation (Chernikova, Heitzmann, Fink, et al., 2020).

Another apt example of scaffolding from nature is shared by Kirschner and Hendrik (2020) in their book "*Seminal Works in Educational Psychology and What They Mean in Practice.*" In the book the authors share how a meerkat parent delivers contingent scaffolding support as they teach a young meerkat to kill scorpions. This process begins as the adult meerkat supplies the child meerkat with a dead scorpion with the stinger attached. Next the young meerkat is presented a live scorpion but with its stinger removed. Once the parent deems the child meerkat is ready, the parent meerkat introduces a live scorpion with the stinger attached. Similar to the bicycling example above, meerkat parents create scaffolds that gently transfer responsibility from the parent to the child as the young meerkat increases in mastery.

While a child learning to ride a bike or a meerkat learning to hunt and kill scorpions are easily accessible analogies for understanding scaffolding, transfer of responsibility, and fading, much of the original research using gradual release of responsibility and scaffolding arose out of person-to-person tutorial relationships in the language arts (S. Li, 2001; Stone, 1998). Palincsar and Brown (1984) developed conceptualizations of fading/gradual release of responsibility through their work on reciprocal reading groups and human teachers. These researchers were interested in developing scaffolding that assisted novice readers in developing strategies that were present in expert readers such as making connections, summarizing, generating questions, clarifying concepts, and making predictions. Over time, the scaffolding construct expanded into other subjects (e.g., STEM), learning contexts, and sources (e.g., peer-based scaffolding, paper-based scaffolding, computer-based scaffolding, etc.). However, as a conception of fading, gradual release of responsibility did not become widely used outside of reciprocal reading groups and the language arts.

Contingency, fading, and gradual release of responsibility are all related and essential components of what makes scaffolding unique from regular instruction. Scaffolding must be focused on the capacity of the student and employ just the right amount of temporary support as the student engages in problem solving. Otherwise, it is not scaffolding. However, critiques about the absence of fading and contingency have been omnipresent as the scaffolding construct has spread (Belland, 2014; Pea, 2004; Stone, 1998). These critiques have been especially potent as scaffolding began being delivered by computer tutors in STEM contexts (Quintana et al., 2004).

Rise of Computer-Based Scaffolding

One-to-one tutoring has been considered one of the most effective instructional strategies ever since Bloom's famous article "2 Sigma Problem" was published over 35 years ago. In the article, Bloom (1984) detailed how one-to-one human tutoring resulted in a 2.0 effect size growth in cognitive outcomes over traditional classroom instruction. Researchers have defined tutoring as instructional activities between a teacher and a student characterized by a process that includes iterative cycles of student-centered activity, formative assessment, and robust targeted feedback (Bloom, 1984; Chi et al., 2001). However, in regular classrooms where teacher-to-student ratios approach 30:1, it is impossible for a single teacher to monitor and offer targeted contingent one-to-one tutoring to every student in their class simultaneously (Sharma & Hannafin, 2007). When 20-30 students are all engaged in solving problems, teachers are physically incapable of simultaneously delivering feedback to each student to help them self-correct or "repair misconceptions" (VanLehn, 2011, p. 211). Scaffolding, as described by its originators and other researchers (Chi et al., 2001; Wood et al., 1976), is a formalized way of replicating the tutorial process.

Researchers have since turned to computer-based scaffolding within computer learning environments to approximate one-to-one tutoring at scale (Ross, 2020; VanLehn, 2011). Computer-based scaffolding, like one-to-one human tutoring, is still the process by which a tutor diagnoses need and delivers contingent help to a struggling learner with one large difference; there is both a physical and temporal distance between the human tutor and the student. However, just because the needs assessment and subsequent scaffolding are delivered by a computer should not obscure the presence of a human tutor in the design and delivery of the tutorial assistance. A human not only designed the scaffolding but also designed the system of delivery.

Tutorial help, in the form of scaffolding, has been delivered through these computerized learning environments. Over the years, these environments have taken on many different forms and labels such as technology-enhanced learning environments (TELEs; Sharma & Hannafin, 2007), computer aided-instruction (CAI; VanLehn, 2011), computer-supported intentional learning environments (CSILE; A. Cohen & Scardamalia, 1998), computer-based learning environments (CBLEs; Winters et al., 2008), computer-supported collaborative learning (CSCL), hypertext (Puntambekar et al., 2003), hypermedia (Lajoie, 2005), guided learner-adaptable scaffolding (GLAS; Jackson et al., 1998), open learning environments (OLEs; Hannafin et al., 1999), software-realized scaffolding (Guzdial, 1994), and intelligent tutoring systems (VanLehn, 2011) among others. This work will consistently use the term computer-based learning environments (CBLEs) to refer to an environment in which learning is supported and in which computer-based scaffolds can be employed.

CBLEs allow for the possibility of all students to be engaged in a learner-centered curriculum within their respective ability levels, skills, and backgrounds (Jackson et al., 1998). While a single teacher cannot create an individualized lesson plan along with individualized scaffolding simultaneously for each learner in their classroom, it is possible to automate this process with a CBLE. CBLEs, such as intelligent tutoring systems, have consistently been shown to produce statistically significant learning outcomes (VanLehn, 2011). A meta-analysis by Kulik and Fletcher (2015) found that intelligent tutoring systems raised test scores 0.66 standard deviations over regular instruction. Those outcomes might not rival Bloom's *2 Sigma Problem* (1984) overall effect size for one-to-one tutoring but are considered large using Kraft's (2020) updated effect size benchmarks for educational interventions. Beyond the usage of CBLEs to enhance one-to-one tutoring, they have also been utilized in complex learning scenarios. In these instances, CBLEs deliver computer-based scaffolding to help students develop complex problem-solving skills (Belland, Walker, Kim, & Lefler, 2017; N. J. Kim et al., 2018).

Problem-Centered Instruction and STEM Education

There has been an expressed need for the educational system to place greater emphasis on complex problem solving (National Governors Association Center for Best Practices, & Council of Chief State School Officers, 2010). This is especially true when it comes to problem-centered instruction solving in STEM occupations which are expected to grow two to three times the rate of non-STEM occupations (Fayer et al., 2017). Furthermore, policy makers and researchers have been anxious to resolve the lagging STEM learning outcomes of U.S. K-12 students as well as overhauling STEM education in higher education (National Academies of Sciences & Medicine, 2022). However, problem-centered curriculum and STEM educational coursework, which often centers around problem-centered instruction (Jonassen et al., 2006), can be both intimidating as well as frustrating for students (Q. Li et al., 2009).

Curricular theories that focus on rigorous problem-solving scenarios, like problem-based learning, have been criticized for throwing students into complex situations without the requisite assistance to help them succeed (Kirschner et al., 2006). Many learning scientists have looked to computer-based scaffolding (Hmelo-Silver, 2004) as a way to provide students with the help they need to have success amidst the rigor of problem-centered curricular activities (Chinn & Duncan, 2021; N. J. Kim et al., 2018; Reiser, 2004). In problem-centered pedagogies, computer-based scaffolding can provide structure, guidance, and feedback to students so that they are able to accomplish tasks that would have been impossible had the student been left unaided.

Review of Previous Meta-Analytical Research

For several decades, researchers and practitioners have engaged in many studies investigating whether computer-based scaffolding is effective at increasing learning gains. Several meta-analyses have sought to estimate the effects of computer-based scaffolding on problem-solving learning outcomes in STEM fields. Table 1.1 illustrates the mean effect size estimates from prior meta-analyses on computer-based scaffolding along with the number of included studies and outcomes.

Table 1.1

Effect Size Estimates of Previous Meta-Analyses on Computer-Based Scaffolding

Short citation	Content focus	Analysis type	Context of use	# of studies/ outcomes	Mean effect size estimate
(Cai et al., 2022)	Learning Outcomes in All Content Areas	Meta-analysis	Digital Game-Based Learning	49/154	(*g* = 0.43)
(Chernikova, Heitzmann, Fink, et al., 2020)	Learning Outcomes Medical & Teacher Education	Meta-analysis	Problem Solving	145/409	(*g* = 0.88)
(N. J. Kim et al., 2020)	STEM Learning Outcomes	Meta-analysis	Group Problem Solving in CBLEs	145/333	(*g* = 0.46)
(Doo et al., 2020)	Learning Outcomes in All Content Areas	Meta-analysis	Online Learning	18/64	(*g* = 0.87)
(N. J. Kim et al., 2018)	STEM Learning Outcomes	Bayesian Network Meta-analysis	PBL Various	21/47	(*g* = 0.39)
(Chernikova, Heitzmann, Stadler, et al., 2020)	Learning Outcomes Medical & Teacher Education	Meta-analysis	Problem Solving	29/35	(*g* = 0.39)
(Belland, Walker, Kim,& Lefler, 2017)	STEM Learning Outcomes	Meta-analysis	Problem Solving in CBLEs	144/333	(*g* = 0.46)
(Belland, Walker, & Kim, 2017)	STEM Learning Outcomes	Bayesian Network	Problem Solving in CBLEs	56/218	(*g* = 0.74)
(Belland et al., 2015)	STEM Learning Outcomes	Meta-analysis	Problem Solving in CBLEs	7/17	(*g* = 0.53)

Note. Kim et al., 2018 and Belland et al., 2017 are Bayesian network meta-analyses and model population statistics rather than employ inferential statistics. They are also based on mean differences within groups (pre-post gains) rather than between groups (treatment vs control conditions).

A review of these meta-analyses reveals a few themes. First and foremost is the size and relative consistency among the mean effect size estimates across the meta-analyses. Scaffolding consistently produces medium effect size according to Cohen's benchmarks (J. Cohen, 1988). However, even Cohen suggested that this benchmark should only be used in the absence of a better contextualized benchmark (J. Cohen, 1988). Kraft posits that Cohen's benchmarks are high when compared to effect size estimates in education (Kraft, 2020). Kraft's sets lower benchmarks (< 0.05 = Small; < 0.20 = Medium; and > 0.20 = Large) the places computer-based scaffolding interventions between the 90-99th percentile of all effect size estimations found in the K-12 education (Kraft, 2020).

Beyond the large overall effects, Table 1.1 also shows the relative consistency between effect size estimations. Consistency between meta-analyses could potentially come from an overlap in data sets. However, there is very little overlap outside of two traditional meta-analyses generated by one research group (Belland, Walker, Kim, & Lefler, 2017; N. J. Kim et al., 2020). The remaining meta-analyses look at scaffolding from the context of different technologies, content areas, group size, and age groups. Or because they examine within group (pre-post) gains, they contain a non-union set of studies and outcomes. (Belland et al., 2017; N. J. Kim et al., 2018).

A second theme is that despite scaffolding's origins and popularity in the language arts, there has been a significant interest from practitioners and researchers to investigate the ability of computers to increase learning outcomes by delivering computer-based scaffolding to students who are engaged in STEM problem solving activities. Only two of the meta-analyses included content areas outside of STEM fields. There were no syntheses found looking at reciprocal reading groups or the language arts.

Third, there is inconsistency across moderator analyses performed in each of the meta-analyses. This inconsistency shows up both in terms of which moderators were included under each meta-analysis (i.e., very little overlap) and the terminology employed to refer to each moderator (especially in reference to characteristics of the intervention). Each meta-analysis in Table 1.1 included moderator analyses to research the contexts and variations in which scaffolding is most effective. However, despite considerable efforts, very few moderator analyses have produced statistically significant results. Table 1.2 displays the moderator analyses from each study organized by those moderators that were statistically significant and those that were not.

Prior Moderator Analyses

Moderators can be broken into types such as study characteristics (region/location of study, type of community, type of school, study quality), participant characteristics (age, prior knowledge, socioeconomic status, grade level, sex, gender, etc.), outcome characteristics (type of assessment, assessment level, content area, etc.), and intervention characteristics (form of scaffold, function of scaffold, duration, group size, etc.). A closer look at the results of each of these types of moderators is discussed below.

Study Characteristics Moderators

Study region was employed in one study (Cai et al., 2022) and found nonstatistically significant. Publication type was studied in one study and found to be

Table 1.2

Moderator Analyses Outcomes of Previous Meta-Analyses on Computer-Based Scaffolding

Short citation	Statistically significant moderators	Nonsignificant moderators
Cai et al., 2022	Grade Level, Game Type	Subject Domain, Study Region, Intervention Time, Publication Type, Publication Year, Scaffolding Form
Chernikova, Heitzmann, Fink, et al., 2020	None Reported	Year of Publication, Publication Type, Study Design, Type of Control, Domain, Scaffold+Simulation, Education Level
N. J. Kim et al., 2020	Collaboration Scaffolding, Group size (pairs vs small group)	Scaffolding Function, Group Size
Doo et al., 2020	Scaffolding Function, Scaffolding Source, Publication Location, Subject Domain	None Reported
N. J. Kim et al., 2018	Scaffolding Form (Question Prompts, Modeling, Feedback), Scaffolding Functions (Metacognitive, Strategic)	Subject Domain, Scaffolding Types/ Functions, Scaffolding Customization, Intended Outcome, Scaffolding Strategies/Forms, Higher-order Thinking Skills
Chernikova, Heitzmann, Stadler, et al., 2020	Scaffolding Forms (Problem-solving Instructions, Role Taking, Reflection), Participant Prior Knowledge	Scaffolding Forms (Examples), Group Size
Belland, Walker, & Kim, 2017	Education Population (Prior Knowledge)	Grade Level, Instructional Approach, STEM Discipline, Assessment Level
Belland, Walker, Kim, & Lefler, 2017	Participant Prior Knowledge, Validity Reporting, Fading/Adding	Scaffolding Logic, Scaffolding Function, Assessment Level, Type of Problem Solving, Study Design, Assessment Reliability Reporting
Belland et al., 2015	Validity Reporting, Fading/Adding	Generic vs Context Specific Scaffolding, Skills vs Knowledge, Scaffolding Function, Type of Problem Solving, Study Design, Assessment Level

Note. Kim et al. (2018) and Belland et al. (2017) are Bayesian network meta-analyses and model population statistics rather than employ inferential statistics. They are also based on mean differences within groups (pre-post gains) rather than between groups (treatment vs control conditions).

statistically significant. The design of the study was analyzed in two meta-analyses (Belland et al., 2015; Belland, Walker, Kim, & Lefler, 2017) and found to be nonsignificant. Publication year was also analyzed and found to be non-significant. Reliability reporting, an evaluation of an article’s ability to report the reliability of the evaluation assessment, was only measured by one article and not found to be statistically significant. However, validity reporting was included in two articles as a moderator and found to be statistically significant in each study. The articles with less validity evidence, perhaps because they lacked alignment with the construct being measured, were associated with lower effect sizes.

Participant Characteristics Moderators

Participant characteristics such as participant prior knowledge and education level were included in moderator analyses. Education level (e.g., elementary, secondary, collegiate, and graduate) was included in two studies (Belland, Walker, Kim, & Lefler, 2017; Chernikova, Heitzmann, Fink, et al., 2020). While differences were found among the different levels, they were not statistically significant. However, the differences between students' prior knowledge were investigated in two studies and found to be significant. Both meta-analyses found that students with less prior knowledge benefited more from scaffolding than students with high prior knowledge. These meta-analytic results are in line with other studies that reference the expertise reversal effect which has shown that support/scaffolding that works well with novices has the inverse effect on students with more prior knowledge/expertise (Kalyuga, 2007; van Merriënboer & Sweller, 2005).

Intervention Characteristics Moderators

Characteristics of the intervention were the most inconsistent of the moderator analyses. Intervention moderators included the impact of scaffolding change (i.e., Adding, Fading, Fading/Adding, and None), scaffolding logic (i.e., Performance-adapted, Self-selected, Fixed, and None), and scaffolding intervention (i.e., Conceptual, Metacognitive, Motivation, and Strategic). Despite coding for various moderators, there was a lack of results detecting systematic differences across interventions that would point to which scaffolding interventions work best. However, missing from many of the meta-analyses was a moderator analysis of how the various forms of the scaffolds moderated STEM learning outcomes.

Missing Moderator: The Form of Scaffolding

The form of the scaffold (or type of tutor action) could potentially account for the distribution of effect size estimates. The authors of these previous computer-based scaffolding meta-analyses acknowledged the difficulty of coding computer-based scaffolding interventions found in the literature (Belland, Walker, Kim, & Lefler, 2017; N. J. Kim et al., 2018). This difficulty is due in part to the complexity of the scaffolds delivered by CBLEs but also due to the language surrounding scaffolding. More specifically stated, several obstacles must be resolved in order to estimate the effects of various forms (and combinations of forms) of tutorial interactions of computer-based scaffolds in the literature.

First, the original taxonomy of scaffolds enumerated by Wood et al. (1976) inadequately distinguish between the action of the tutor and the intended effect of the scaffolding intervention on the student. Second, due to the popularity of the theoretical construct, scaffolding has become laden with jargon and lacks consensus especially with respect to descriptions of scaffolding forms. Third, neither the original taxonomy of scaffolding (Wood et al., 1976) nor subsequent versions account for the technology enhanced forms of scaffolding found in recent literature. Fourth, the complexity of computer-based scaffolding interventions has been resistant to meta-analytic coding. In most cases, CBLEs support students through a conglomeration of tutorial interactions called "distributed scaffolds" (Tabak, 2004) with varying frequencies of scaffolding deliveries and various fading schedules.

These obstacles surrounding scaffolding language account for the lack of a comprehensive taxonomy of computer-based scaffolds. Without a common language, meta-analytic researchers have been impeded from investigating which computer-based scaffolds (or combination of scaffolds) lead to the greatest learning gains in students (Belland, Walker, Kim, & Lefler, 2017; Lajoie, 2005). Without these results, practitioners and CBLE designers lack the information needed to design the most effective interventions for STEM problem solvers. As mentioned by Kim, Belland, and Walker, "a more nuanced study with more specific categorization of scaffolding forms may be beneficial" (Kim et al., 2018, p. 419).

Multiple Paper Dissertation Outline

The overarching goal of this multiple paper dissertation is to offer insight into scaffolding forms and which ones produce the largest learning gains in STEM education. This will be accomplished through a sequenced investigation through two research papers. Each paper seeks to help overcome the aforementioned research gaps which have previously impeded researchers from estimating the effects of the various forms or combinations of computer-based scaffolding interventions.

The first research paper (Chapter 2) consists of a systematic literature review to resolve language issues plaguing the scaffolding construct. In particular, I will address the following research questions.

1. What terms have researchers used to describe the tutorial actions and the intended effects in prior syntheses and seminal works on scaffolding since 1976? Is there consistency among the terms employed?
2. What are the forms of computer-based scaffolding in extant experimental computer-based scaffolding literature in STEM fields?

After proposing a comprehensive list of computer-based scaffolding forms in STEM education, in the second paper (Chapter 3), I will apply the new coding framework for scaffolding forms to collegiate engineering computer-based scaffolding interventions. Through a traditional meta-analysis of computer-based scaffolding interventions comparing between group (treatment vs control) mean differences, I will address the following questions:

1. What is the overall contribution of computer-based scaffolding on engineering learning gains and how much variability is present in the findings?
2. To what extent do single computer-based scaffolding forms make individual contributions to collegiate student engineering learning gains?
3. Which combinations of computer-based scaffolding forms, as observed in individual studies, make contributions to collegiate student engineering learning gains?

Table 1.3 defines the data sources and analyses preformed for each research question.

Table 1.3

Research Questions, Data Sources, and Analyses by Chapter

Research question	Data source	Analysis
Chapter 2 RQ1	109 Articles (9 Literature Reviews, 26 Seminal Papers, and 74 Empirical STEM Papers on Scaffolding)	Systematic Coding in NVivo
Chapter 2 RQ2	236 Empirical Articles on Computer-based Scaffolding	Systematic Coding in NVivo
Chapter 3 RQ1	13 Empirical Articles on Computer-based Scaffolding in Collegiate Engineering Education	Meta-analysis in Stata
Chapter 3 RQ2	13 Empirical Articles on Computer-based Scaffolding in Collegiate Engineering Education	Meta-analysis in Stata
Chapter 3 RQ3	13 Empirical Articles on Computer-based Scaffolding in Collegiate Engineering Education	Meta-analysis in Stata

Definition of Terms

The following terms are defined for this study.

Tutoring: An umbrella term used to describe the instructional activities between a teacher and a student characterized by a process that includes iterative cycles of student-centered activity, formative assessment, and robust targeted feedback (Bloom, 1984; Chi et al., 2001).

Scaffolding: A socioconstructivist prescriptive learning theory which describes the parameters under which tutoring should happen (i.e., with contingency, fading, and transfer of responsibility; Pea, 2004). In short scaffolding has been defined as temporary tutorial assistance offered to a student which enables the student to successfully complete task(s) beyond their unassisted capability (Wood et al., 1976).

Computer-based scaffolding: Temporary tutorial assistance (scaffolding) that is delivered to a student by/through a computer (Belland, Walker, Kim, & Lefler, 2017).

Computer-based learning environments (CBLE): An instructional environment where the majority of the content and tutorial support is offered by the computer environment. Computer-based learning environments often include various representational formats such as animations, video, and graphics (Devolder et al., 2012).

Scaffolding form: A descriptor for the type of temporary tutorial assistance offered to the student from the tutor. A term that defines in what package the scaffold is delivered to the student (i.e., prompt, modeling, etc.).

Scaffolding Function: A descriptor for the intended effect of the temporary tutorial assistance on the student. Scaffolding function describes the nature of the student support (i.e., metacognitive, conceptual, strategic, procedural, motivational, etc.).

Problem-centered instruction (PCI): In contrast to lecture, problem-centered instruction is a student-centered approach that prioritize problem-solving when delivering content to students (e.g., problem-based learning, case-based reasoning, modeling, etc.) (Rico & Ertmer, 2015).

Effect size: An effect size has been defined as “the degree to which the sample results diverge from the null hypothesis” (L. Cohen et al., 2011, p. 617). In other words, an effect size is the extent to which two populations differ (Cooper, 2015).

CHAPTER 2

THE FORMS OF COMPUTER-BASED SCAFFOLDING IN STEM EDUCATION: A SYSTEMATIC REVIEW

Abstract

Computer-based scaffolding assists students as they develop solutions to complex problems. Several meta-analyses have shown that computer-based scaffolding is effective at increasing the cognitive outcomes of STEM problem solvers. However, very few moderator analyses have provided insight into which aspect of scaffolding interventions produce the largest effects. This lack of moderator analyses on scaffolding forms has been due to a) conflicting language around the form versus intent of scaffolding and b) the lack of a taxonomy for scaffolding forms which can account for the variations and combinations of computer-based scaffolding interventions found in experimental literature. Through a systematic review of scaffolding literature, this study clarifies language between the form and function of scaffolding. Additionally, the paper proposes a new taxonomy of scaffolding forms grounded in a review of the past 40 years of empirical research of computer-based scaffolding interventions in STEM education.

Keywords: scaffolding, systematic literature review, problem-centered instruction

Introduction

The term scaffolding was coined in an article by Wood et al. (1976). These authors defined scaffolding as a temporary assistance which would allow a student to accomplish tasks beyond their unassisted capabilities (Wood et al., 1976). Scaffolding was guided by several core principles: contingency, fading, and transfer of responsibility. Contingency is the idea that the scaffolding must be continually tailored to the student as well as the task (Belland, 2014). Fading is the term most commonly used in scaffolding literature to describe the expectation that a tutor should remove their scaffolding from the tutee over time so that scaffolding never becomes a crutch. Transfer of responsibility more fully conceptualizes what is actually being "faded" to include a shift of ownership over the task from the teacher to the student.

The guiding principles of contingency, fading, and transfer of responsibility clarified that students should only receive help when necessary. Once a student was able to operate independently of the tutorial help, the support would be "faded" just as scaffolding is removed once a construction project is completed (Wood et al., 1976). In addition to these guiding principles, Wood et al. identified six different ways a tutor could scaffold a learner.

Wood et al. (1976) listed six types of tutor actions/moves (Chi et al., 2001) as *recruitment, reduction in degrees of freedom, direction maintenance, marking critical features, frustration control, and demonstration* (Wood et al., 1976, p. 89). Each of these tutorial interactions assisted the tutee in different ways. *Recruitment* enlisted the attention of the student. *Reduction in degrees of freedom* offloaded unreasonably demanding portions of the task onto the teacher. *Direction maintenance* helped students continually move towards the problem solution. *Marking critical features* pointed students' attention towards salient features of the task while *frustration control* moderated the rigor of the problem to the optimal level of the student's current capability. Lastly, *demonstration* was the tutor’s tool for providing the learner with an expert model to follow.

Expansion and Effectiveness of Scaffolding

Scaffolding originated with parent-child relationships but then quickly moved to the language arts (Cho & Schunn, 2007; Stone, 1998). However, since those early days, scaffolding has been applied to different age groups and from everything from business management (Winkler et al., 2019), midwifery (Austin et al., 2020), and even (Lin et al., 2021) billiards. Similar to the expansion of scaffolding to many different content areas, scaffolding has also been applied with various types of delivery methods such as paper-based scaffolds (Ruzhitskaya, 2011; Yoon et al., 2012) and peer-delivered scaffolding (Lai & Law, 2006; Pifarre & Cobos, 2010). However, for the past few decades, researchers have increasingly delivered scaffolding through computer applications.

Computer-based scaffolding has been researched in various forms of computer-based learning environments (CBLE; Belland, 2014; Quintana et al., 2004; Saye & Brush, 2002). Computer-based scaffolding happens as a software delivers a temporary help to a student as they are engaged in a learning activity. Frequently computer-based scaffolding interventions take the form of an expert model, a prompt, or a visualization that is offered to the student during the problem-centered activity. For example, if collegiate engineering students built electrical circuits incorrectly inside a CBLE, the software would provide corrective feedback (Parchman et al., 2000). If they continued to incorrectly build circuits, the program would then provide the students with a step-by-step annotated solution to follow until the student correctly builds the electrical circuit

(Parchman et al., 2000). In this example, the corrective feedback and step-by-step expert modeling provided the students with a temporary scaffold (contingent upon their capacity) to build the circuit on their own. This example is typical of the types of computer-based scaffolding intervention that have been developed in STEM fields for the past four decades.

Because of the large body of computer-based scaffolding research, there have been several literature reviews that have further developed the construct and revealed large positive effects of scaffolding on self-regulation (Zheng, 2016), argumentation (Haro et al., 2019), and cognitive learning outcomes in STEM subject areas (Belland, Walker, Kim, & Lefler, 2017). However, some very central aspects of this theoretical construct have continued to evade synthesis.

Perhaps because of the large amount of primary experimental research or the proliferation and complexity of computer-based learning environments, researchers have struggled to communicate efficiently with regards to scaffolding. Researchers have not yet united around a simple list of terms to describe the differing actions a tutor can make in order to scaffold a student. There have been many new labels used to characterize the categorizations of computer-based scaffolds such as distributed (Puntambekar & Kolodner, 2005; Tabak, 2004); fixed or dynamic (Azevedo & Jacobson, 2008); soft or hard (Saye & Brush, 2002; Sharma & Hannafin, 2007); first order and second order (Haro et al., 2019); explicit and implicit (Hadwin & Winne, 2001); domain-general and domain-specific (Bulu & Pedersen, 2010); problematizing and structuring (Reiser, 2004); and conceptual, metacognitive, procedural, and strategic (Hill & Hannafin, 2001).

While these frameworks and labels have legitimized the value of the scaffolding construct, they have also collectively made it increasingly difficult to concisely define the theory and effectively communicate across theoretical perspectives. Continuous expansion of usage and terminology has brought the scaffolding construct to a place where the same terms are often used to describe different aspects of the theory. In addition to the confusing terminology, researchers have criticized how essential characteristics of the original scaffolding theory, such as dynamic assessment and fading, have been altogether left out of subsequent variations (Belland, 2014; Puntambekar & Kolodner, 2005). It is no wonder then that for roughly the past twenty years researchers have been noting this theoretical drift and calling for a more common, concise language, and a comprehensive theoretical model for scaffolding (Chernikova, Heitzmann, Fink, et al., 2020; Pea, 2004).

Without a simple list of types of computer-based scaffolds, researchers have lacked a common mechanism to classify the various forms of scaffolding in computerized learning environments. Without a common language, meta-analytic researchers have been impeded from investigating which computer-based scaffolds (or combinations of scaffolds) lead to the greatest learning gains in students (Belland, Walker, Kim, & Lefler, 2017; Lajoie, 2005).

Scaffolding's overgrowth of language and theoretical drift is not unlike other educational theories. Over time, theories (especially popular ones) need a good hedging so that researchers avoid "ambiguous terms, obfuscated constructs, atheoretical research, and inaccurate or invalid claims" (Loughlin & Alexander, 2012, p. 274). When usage and terminology surrounding a theoretical construct, such as scaffolding, is used haphazardly, the rise of new terminology can lead to serious consequences for a theory (Alexander et al., 1991). Systematic literature reviews have been used by researchers as a mechanism to both realign theories to their original constructs as well as to coalesce language into succinct frameworks (Dinsmore, 2017; Dinsmore et al., 2008; Grossnickle, 2016; Loughlin & Alexander, 2012).

The purpose of this systematic literature review is to take the first step towards simplifying and clarifying the language used to characterize computer-based scaffolds in computer-based learning environments. Through a review of theoretical, review, and experimental research literature on computer-based scaffolding over the past few decades, I will provide a succinct taxonomy of computer-based scaffolds. However, before explaining the methodology of this review, I will first define the extent of the confusion surrounding scaffolding terminology.

Inconsistent Scaffolding Language

One of the major criticisms of computer-based scaffolding is that the expansive proliferation of usage and terminology has led the scaffolding construct to become inconsistent, confusing, and potentially meaningless (Pea, 2004; Puntambekar & Hubscher, 2005; Quintana, 2021; Quintana et al., 2004). There is a considerable inconsistency surrounding the terminology theorists, researchers, and practitioners have used to label computer-based scaffolds. At its core, this lack of agreement is due to inconsistencies in the original taxonomy offered by Wood et al. (1976).

Scaffolding Function: Tutor Action or Intended Effect?

Wood et al. (1976) originally enumerated the six functions of scaffolding as recruitment, reduction in degrees of freedom, direction maintenance, marking critical features, frustration control, and demonstration. These scaffolds were described as the “tutorial interactions" that were delivered to the tutee by the tutor (Wood et al., 1976, p. 98). However, a closer look at the six titles reveals that some of these terms describe the actions taken by the tutor as part of the intervention while the other terms seem to be describing the intended effect of the scaffold on the tutee (see Table 2.1).

Table 2.1

Original Scaffolding Labels, Revised Classification, and Corresponding Definitions

Original scaffold label (revised classification)	Definition
Reduction in degrees of freedom (tutor action)	“simplifying the task by reducing the number of constituent acts required to reach solution . . . tutor fills in the rest and lets the learner perfect the component sub-routines that he can manage.” (p. 98)
Marking critical features (tutor action)	“A tutor . . . marks or accentuates certain features of the task that are relevant. His marking provides information about the discrepancy between what the child has produced and what he would recognize as a correct production.” (p.98)
Demonstration (tutor action)	“Demonstrating or "modelling" solutions to a task. . . ‘idealization’ of the act to be performed and it may involve completion or even explication of a solution already partially executed by the tutee himself.” (p.98)
Recruitment (intended effect)	.” . . enlist the problem solver’s interest in and adherence to the requirements of the task” (p.98)
Direction maintenance (intended effect)	“The tutor has the role of keeping them in pursuit of a particular objective. . . tutor also maintains direction by making it worthwhile for the learner to risk a next step.” (p.98)
Frustration control (intended effect)	"Problem solving should be less dangerous or stressful with a tutor than without.” Whether this is accomplished by "face saving" for errors or by exploiting the learner's " wish to please" or by other means, is of only minor importance. (p.98)

As seen in Table 2.1, three of the original scaffold functions describe what assistance was delivered to the student. Constraining a problem space (i.e., *reduction in degrees of freedom*) is something that a tutor/teacher does to the student. *Marking a critical feature* in a problem is also an act of the tutor to help the student attend to what is necessary for the solution. Modeling effective problem-solving strategies (i.e., *demonstration*) is also a description of the help that the tutor is providing to the student. These three scaffolds are all descriptions of the tutor's actions.

However, the remaining three scaffolds from this initial taxonomy describe the intended impact of the scaffold on the student rather than describing the tutor's action. For example, *recruitment* describes the impact of the scaffold on the student (i.e., student's attention is now enlisted). Similarly, *direction maintenance* describes the state of the student after having received the scaffold. The scaffold *frustration control* places more emphasis on the impact of the scaffold on the state of the student (i.e., a reduction in stress) and places less importance on which mechanisms are used to achieve that state.

In some cases, there also seems to be a conflation between describing a tutor's action describing the intended effect on the tutee. For example, a tutor *reducing degrees of freedom*, offering *demonstrations*, and *marking critical features*, will be helping with the *frustration control* of their student. As originally defined, the terms comprising the original taxonomy of scaffolding straddled both the tutor's action as well as intended effects of the scaffold. Furthermore, commonly accepted scaffolds (such as prompts or hints) can simultaneously fit within each of these original scaffolding labels. For example, a prompt offered to a student which suggests next steps will fit into the categories of *reducing degrees of freedom*, *direction maintenance*, and *frustration control*.

This conflation has not only decreased the ability of researchers to discuss these constructs, but it has also impeded meta-analytic researchers from accurately estimating the effects of scaffolding on learning. Without a taxonomy that distinguishes between the tutors' action and the intended effect of the scaffold, meta-analytic researchers are neither able to accurately code the forms of the scaffolding nor estimate their impact on learning.

Despite the popularity of scaffolding, little attention has been paid to this problem. One of the only direct attempts to bring light to this issue was by van de Pol et al. (2010) in their 10-year synthesis of scaffolding. These researchers suggested using the terms *means* (tutor action) and *intentions* (intended effect) to disambiguate between the original scaffolding functions enumerated by Wood et al. (1976). However, the scaffolding research community has not coalesced around the *means* and *intentions* terminology since it was introduced (van de Pol et al., 2010). Rather, there have been even more terms employed to describe the various types of tutor actions and intended effects of scaffolding. Despite the influx of conflicting terminology, some aspects of the scaffolding construct (i.e., intended effects) have experienced more research progress than others (i.e., types of tutor actions).

Syntheses of Intended Effects of Scaffolding

Of the meta-analyses that have been conducted on computer-based scaffolding, there has been progress estimating the intended effects of scaffolding interventions. Hannafin et al. (1999) that categorized the intended effects of scaffolding as procedural, conceptual, metacognitive, and strategic. The labels and definitions are included in Table 2.2.

Table 2.2

Categories of Intended Effects and Corresponding Definitions

Label for intended effect	Definition
Procedural scaffolds	“guide the student in addressing operational aspects of the learning environment rather than investing cognitive resources in negotiating routine procedures and navigation” (M. C. Kim & Hannafin, 2011, p. 408)
Metacognitive scaffolds	Target a student’s ability to assess their own “state of understanding, reflect on their thinking, and monitor their problem-solving processes” (M. C. Kim & Hannafin, 2011, p. 408)
Conceptual scaffolds	Target a student’s ability to “identify essential knowledge gaps between what they already know and what they need to know. They guide students' understanding about the problem content, provide support to enhance students’ understanding of the problem and related knowledge.” (M. C. Kim & Hannafin, 2011, p. 408)
Strategic scaffolds	Target a student’s ability “to consider alternative approaches to addressing problems. Based on preliminary or tentative solutions, strategic scaffolds prompt students to consider alternatives to framing, addressing and resolving problems, and often involve different stakeholder perspectives and cultural interpretations.” (M. C. Kim & Hannafin, 2011, p. 408)
Motivational scaffolds	Target a student's “desire and willingness to deploy effort toward and persist in the learning task.” (Belland et al., 2013, p. 244)

In addition to Hannafin et al. (1999), there have been other breakdowns of the intended effects of scaffolding interventions such as supportive scaffolding, reflective scaffolding, and intrinsic scaffolding (Jackson et al., 1998). However, over time, it seems that the list of terms coined by Hannafin et al. has remained more constant (M. C. Kim & Hannafin, 2011) and been more broadly applied in subsequent meta-analyses (e.g., Belland et al., 2017; N. J. Kim et al., 2018).

For example, in recent meta-analyses on computer-based scaffolding, researchers employed a modified version of Hannifin’s (M. C. Kim & Hannafin, 2011) list where procedural scaffolds were excluded from the analysis and replaced with motivational scaffolds (N. J. Kim et al., 2018, 2018). There were no statistically significant differences found between the intended effects of scaffolding (Belland, Walker, Kim, & Lefler, 2017). Despite the lack of statistically significant differences between the various types of intended outcomes, these efforts are an important step to characterize not just effective contexts for scaffolding but to explore the differential effects of key parts of the scaffolding process, made possible by a generally accepted definitional framework from Hannafin et al. (1999).

Syntheses of the Tutorial Actions of Scaffolding

As mentioned previously, several of the initial scaffolding “functions” defined the action taken by the tutor (e.g., *demonstration, marking critical features, and reduction in degrees of freedom*). Over the past 40 years of scaffolding research on CBLEs and their computer-based scaffolding interventions, the effects of these early labels have not been estimated. Nor has there been a parallel attempt to Hannafin et al. (1999) with a focus on synthesizing the broad range of computer-based scaffolding interventions that have been developed since the original work of Wood et al. (1976) and further expand on scaffolding forms.

This is most likely due to the lack of a taxonomy which obfuscates the tutor’s actions and their intended effects. Additionally, a taxonomy of scaffolding must also account for the complexity of computer-based scaffolding interventions. Some CBLEs computer-based scaffolding interventions offer single supports. However, in most cases

CBLEs offer what researchers (Puntambekar & Kolodner, 2005; Tabak, 2004) have referred to as distributed scaffolding systems. Distributed scaffolding interventions are comprised of multiple supports (Tabak, 2004). Yet, whether one or many, the estimated impacts of these scaffolding interventions are not available. There is no synthesis providing guidance as to which tutor actions or combinations of tutorial actions produce the largest learning outcomes nor can there be while the field lacks a definitional framework of tutor actions.

In summary, the confusion surrounding terminology has led to a gap in scaffolding literature. These language issues have led some researchers to argue that scaffolding has become too broad (Pea, 2004; Puntambekar & Hubscher, 2005) and to call for a common theoretical framework from which scaffolding can be understood and evaluated (Quintana et al., 2004). Due to confusion brought about by the first taxonomy of scaffolding functions (tutor actions vs intended effects) as well as the tremendous expansion of computer-based scaffolding, no framework or conglomeration of multiple frameworks exist to accurately and succinctly describe the types of computer-based scaffolding interventions present in existing empirical research. This lack of a taxonomy around the types of tutor actions that make up scaffolding interventions has impeded researchers from both communicating efficiently with one another as well as estimating the effects of computer-based scaffolds.

Objectives

The overall purpose of this systematic literature review is to resolve some of the language issues that have impaired consensus surrounding the theory of scaffolding.

First, I disambiguate between the tutorial actions and the intended effects of scaffolding. Then I provide a taxonomy of the types of tutorial actions (scaffolding forms) of computer-based scaffolding found in extant empirical literature. Lastly, I discuss how this new taxonomy aligns or deviates from the original terms of the scaffolding construct.

As evidenced in the computer-based scaffolding empirical STEM literature, the following research questions are addressed.

> RQ 1: What terms have researchers used to describe the tutorial actions and the intended effects in prior syntheses and seminal works on scaffolding? Is there consistency among the terms employed?
>
> RQ 2: What are the forms of computer-based scaffolding in extant experimental computer-based scaffolding literature in STEM fields?

Methods

This literature review followed a modified version of Cooper's (2015) steps of a systematic literature review. These revised steps include (a) formulating the problem, (b) searching the literature, (c) gathering the information from studies, (d) analyzing and integrating scaffolding forms, (e) interpreting the evidence, and (f) presenting the results.

A review of all scaffolding literature is beyond the scope of this paper. Following the suggestion of Collins and Fauser (2005), this systematic review avoids tackling all aspects of scaffolding and focuses on targeted questions surrounding the language that has been used to describe the forms of the scaffolding construct. To make this work feasible, this review was also constrained by including only those articles which used computer-based scaffolding to produce cognitive outcomes in Science, Technology, Engineering, and Mathematics (STEM) disciplines under the assumptions that several

STEM pedagogies are well suited to scaffolding and STEM workforce preparation is a pressing educational need.

The future world economy will be dominated by jobs in STEM (National Academies of Sciences, Engineering, and Medicine, 2016). From 2009 to 2015, STEM jobs (10.5%) grew at twice the pace of non-STEM jobs (5.2%) in the U.S. (Fayer et al., 2017). This rate looks to continue as the U.S. Bureau of Labor Statistics projects that between 2019 and 2029 STEM occupations will grow by 8% as compared to 3.7% in non-STEM occupations (Zilberman & Ice, 2021). Not only are STEM jobs growing faster, but they also pay more than non-STEM occupations. In the United States, 97% of STEM jobs pay above the national average (Fayer et al., 2017). These statistics substantiate the claim that the competitiveness of a nation in the future global economy will be contingent upon that nation's capacity to create and retain enough highly qualified STEM workers (National Science Board, 2010). However, despite STEM occupations experiencing ever-growing demand and producing better outcomes for students, the United States has consistently struggled to produce either strong learning outcomes or a sufficient amount of STEM workers.

Literature Search/Data Collection

In order to answer the research questions, the literature search included several phases and two different inclusion criteria. RQ1 required finding prior syntheses, seminal works, and experimental research on scaffolding theory. RQ2 required finding experimental literature on computer-based scaffolding. The literature search for prior syntheses, seminal papers, and experimental literature was iterative but did include the following four main phases. Table 2.3 details the phases of the literature search, the focus of each phase, and the corresponding research question.

Table 2.3

Literature Search by Phase, Focus, and Research Question

Phase	Focus	Research question
Phase 1	Database search for experimental literature.	RQ1 & RQ2
Phase 2	Ancestor search for more experimental literature, seminal works, and syntheses.	RQ1
Phase 3	Search of prior syntheses (literature reviews, meta-analyses) on scaffolding.	RQ1
Phase 4	Descendent search of Wood et al., 1976 for highest cited works in scaffolding.	RQ1

Phase 1

The literature search was designed to find each empirical study of the effectiveness of computer-based scaffolding in STEM content areas. The search for articles focused first on database searches using the Boolean phrase: “(scaffold OR scaffolding OR scaffolds) AND (intelligent tutoring systems OR computer OR computers).” The search date was constrained to any research published before 8/20/2022 which defaulted to 1993 in all searches. These searches were conducted in Education Source, ERIC, PsycINFO, Academic Search Ultimate, Scopus, and ProQuest Dissertation and Theses Global databases. The initial database search produced 4,803 search results. After a pre-pass screening of article abstracts and methods sections most were removed for not using a scaffolded intervention, using scaffolds but not in a computer-based setting, or not being empirical research. The remaining 1,401 articles were added to a spreadsheet which tracked the article, its focus, its status in the coding process (e.g., uncoded, included, excluded), and the reason for exclusion (if that was the case).

Phase 2

While reading articles found in phase 1, an ancestor search for articles was conducted. When prior experimental literature was found in the literature review sections, these studies were added to the study tracker for future review. If meta-analyses or seminal works were cited, these were added directly into separate folders in NVivo for subsequent systematic coding.

Phase 3

A search for prior meta-analyses was conducted in Education Source using the Boolean phrase (Scaffold* AND (review of literature or literature review or meta-analysis or systematic review or scoping review or synthesis))." This search yielded 192 results of which 70 were added to a tracker for closer review after a pre-pass screening that checked for a focus on scaffolding intervention and cognitive learning outcomes.

Phase 4

To ensure that all seminal works were found during the aforementioned ancestor search, a decedent search was conducted in Google Scholar. Using the "Cited by" link, a search was made of the first 900 articles that included the (Wood et al., 1976) as a citation in the article. One hundred nineteen articles were added to the tracker along with how many times the article has been cited. This list was sorted by highest citations and compared against the seminal articles already found during the decedent search.

Scaffolding articles with over 750 citations that were not already included were added to the study.

Evaluating Study Quality and Inclusion/Exclusion Criteria

The four-phase search produced experimental STEM literature focused on computer-based scaffolding, meta-analyses on computer-based scaffolding, and seminal works on scaffolding in general. The inclusion criteria varied for each type of literature included.

Experimental Literature Inclusion Criteria

The included studies had to meet the following criteria: (a) be published prior to 8/20/2022, (b) possess a control condition, (c) possess an experimental condition, (d) measure cognitive outcomes in STEM subjects, (e) engage learners in problem-solving, (f) deliver a computer-based scaffold as the independent variable, and (g) give considerable detail when explaining forms of the computer-based scaffolding intervention. After final exclusions, 236 empirical articles were included in the analysis.

Prior Syntheses Inclusion Criteria

Included meta-analyses needed to (a) be published prior to 8/20/2022, (b) require computer-based scaffolding as the coded intervention, (c) include verbiage for moderators estimating the form or functions of scaffolding, and (d) include problem-centered STEM education. After final exclusions, nine meta-analyses were included in the analysis.

Seminal Works Inclusion Criteria

Seminal works were defined as studies that referenced the Wood et al. (1976) foundational article, were cited over 1,000 times, and included scaffolding as the major focus of the article. While the number of citations is impacted by how long an article has been published, it does capture which articles are most cited by researchers referencing the scaffolding theory. After final exclusions, 26 articles were added into NVivo and included in the analysis.

Coding of Study Information/ Technological Review Tools

In order for new terms for scaffolding forms to arise from the studies, I took an inductive approach when coding each of the articles. I used the qualitative data analysis software (QDAS), NVivo, to ensure that the codes preserved the terminology and descriptions for tutor actions/scaffolding forms that were used by the original author(s). QDAS, and NVivo in particular, is becoming a popular tool for literature reviews since it allows researchers to manage large amounts of data (in this case, quotations from empirical studies) and create linkages across studies (Bandara et al., 2011; Beekhuyzen, 2007; Di Gregorio, 2000).

The NVivo QDAS software is well fitted for the task of collecting the descriptions of tutor actions (scaffolding forms) found in the empirical papers. Rather than copying scaffolding from descriptions and adding them to a spreadsheet cell, NVivo allowed me to highlight many terms and phrases used by the authors regardless of whether they were in the text, tables, and/or images throughout the paper. This method kept my codes tied to the verbatim quotations (i.e., “in-vivo” code) of the original authors (Saldaña, 2012) and avoided prematurely affixing my own labels.

Coding Process

Each article was coded systematically following a modified form of Saldana’s cycles of coding for grounded theory coding methods (Saldaña, 2012, p. 213). Grounded theory usually includes six coding methodologies: “In-vivo, Process, Initial, Focused, Axial, and Theoretical Coding” (Saldana, 2012, p. 51). The purposes of this study were to describe and synthesize the language of computer-based scaffolding researchers and not to define a process or develop a new theory. As such, the process coding step and theoretical coding step was excluded. The rest of the grounded theory steps were followed along with its guiding principles of staying nested in the language of the participants and employing constant comparative analysis when generating new codes (Charmaz, 2014). Table 2.4 provides an overview of the coding cycles, steps, and objective at each stage organized by research question.

The objective of RQ1 was to describe how researchers have referred to both the type and intent of computer-based scaffolds. For RQ1, the coding process included just two steps: in-vivo coding and descriptive coding. In-vivo coding is the process of capturing the terminology of the participant. In the case of this study, in-vivo codes were sections of text in empirical papers where scaffolding theorists enumerated the types of scaffolds. The length of in-vivo codes varied from sentences to multiple paragraphs. These sections of text were captured in the NVivo software and “preserve(d) the meaning” or language employed by the theorists themselves (Charmaz, 2014). Note that

Table 2.4

Explanation of Systematic Coding Process Organized by Research Question

Coding process RQ	Cycle	Coding step	Objective
RQ1	1st	In-vivo coding	Capture and catalog terms employed by researchers for scaffolding forms and functions.
	1st	Descriptive coding	Describe and categorize terms based upon the nouns used in author's descriptions of scaffolding types.
RQ2	1st	In-vivo coding	Capture and catalog terms employed by researchers for scaffolding forms and functions.
	1st	Descriptive coding	Describe and categorize terms based upon the nouns used in author's descriptions of scaffolding types.
	2nd	Focus coding	Compare and collapse previously generated codes into a simplified list of distinct forms of scaffolds
	2nd	Axial coding	Within each distinct form of computer-based scaffold, generate sub-categories.

throughout the rest of this manuscript in-vivo is used to refer to a specific type of code in the coding process and NVivo refers to the qualitative analysis software, which was used to capture in-vivo codes.

In-vivo coding was followed by descriptive coding. During this step a descriptive code was developed for each of the in-vivo sections of captured text. These descriptive codes were based upon the nouns used by the researchers (Saldaña, 2012). To answer RQ1, these descriptive codes were then analyzed to define what terms researchers have used to describe the tutorial actions and the intended effects in prior syntheses and seminal works on scaffolding.

For RQ2 the coding process included four steps through two cycles of coding: (1) in-vivo, (2) descriptive, (3) initial, and (4) axial. Similar to RQ1, the first cycle of coding began with in-vivo coding of the experimental literature. The author's description of the scaffold form was captured using the NVivo software and then assigned to a group based upon the noun utilized by the author (i.e., descriptive coding). For example, the following quote was captured as an in-vivo code. When describing their intelligent tutoring system agent that scaffolded the Academically Productive Talk (APT) of students, Adamson and Rosé (2013) wrote:

> If the other students do not respond with either an evaluation or a contentful follow-up, the agent prompts them to comment on the candidate statement - for example, 'What do you think about Billy's idea? Do you agree or disagree?' (p. 54).

Using NVivo, I highlighted this section and created the code "prompt." This descriptive coding process was followed for each NVivo code of each paper. As other researchers described tutor action (scaffolding form) using the term prompt, I highlighted the source and added it to the previous "prompt" code as well. Over time, these codes began to create themes or what NVivo refers to as nodes. Nodes are essentially buckets holding similar quotations/codes. Following this process, I highlighted 424 references across 236 research papers.

The second cycle of coding included two steps: focus coding and axial coding. Focus coding "follows first cycle grounded theory coding methods" (Saldaña, 2012, p. 213) and is defined as the process of selecting the most significant and most frequently used descriptive code that was generated in the first cycle of coding (Charmaz, 2014). At this stage, descriptive codes were sifted, sorted, rearranged, and relabeled depending on their similarity or differences with other descriptive codes. During the focus coding stage, the myriad descriptive codes were summarized into the "most salient categories"/codes

(Saldaña, 2012, p. 213).

The relationship of “hints” and “prompts” is a good example of the focus coding stage. When looking at the original in-vivo codes of “hints,” it became apparent the hints did not differ substantially from the “prompts” code examples regarding the scaffold’s form or function (i.e., guidance). While prompts and hints did not differ in their appearance or intent. Instead, the two descriptive codes differed in terms of how they were administered. Hints were often associated with self-selected scaffolds where students clicked a hint button when they felt they were lost. Prompts, on the other hand, were usually delivered by the CBLE program either based upon the student’s need or a certain difficult stage of the problem-solving process. Because of this similarity, I made “hints” a subcategory of prompts.

The final coding step, axial coding, started after the major groups (focus codes) of scaffolding forms had been generated. During this last step, focus codes were further refined into sub-categories within each of the major nodes. For example, the “prompt” node had two subcategories: (a) question prompts and (b) command prompts. When subcategories began to solidify, I then continued to further develop the similarities and differences between the nodes. Some of the coding nodes, while using different author terms, were indistinguishable from other nodes (e.g., modeling and worked examples). Table 2.5 shows an early hierarchy of scaffolding nodes (on the left) and the final hierarchy (on the right) after node comparisons.

Table 2.5

Comparison of 1st Cycle vs 2nd Cycle Scaffolding Forms (Tutor Actions)

1st cycle descriptive codes	2nd cycle focus codes
Structuring, model progression	Structuring
Modeling, worked examples	Modeling
Hints, command prompts, question prompts	Command prompts Question prompts
Cues, highlights	Cues
Visualization, simulation, role play	Visualization
Feedback (elaborated, immediate, delayed, correct/incorrect, knowledge of correct response, knowledge of results, uninterpreted)	Feedback

Results

> RQ 1: What terms have researchers used to describe the tutorial actions and the intended effects in prior syntheses and seminal works on scaffolding since 1976? Is there consistency among the terms employed?

There were 109 distinct articles found that employed terms for the tutorial actions and/or the intended effects of scaffolding (see Table 2.6). Scaffolding researchers have used nine different terms to refer to the action of the tutor (see left column of Table 2.6) and seven terms to refer to the intended effects of those actions on the learner (see right column of Table 2.6). There were four terms (i.e., functions, types, strategies, and mechanisms) that have been used to describe both tutor actions and intended effects of scaffolding. As mentioned previously, the terms *means* and *intentions* terms have not been widely adopted by researchers after being proposed by Van de Pol, Volman et al. (2010). This lack of adoption is clearly seen in Table 2.6 as subsequent studies continued to use other terms.

Table 2.6

Most Frequently Used Terms for Tutor Actions and Intended Effects of Scaffolding

Term for tutor actions (*n* unique articles/*n* total uses)	Term for intended effects (*n* unique articles/*n* total uses)
Form(s) (52/75)	Function(s) (23/26)
Strategies (28/45)	Types (9/9)
Features (13/14)	Strategies (5/6)
Functions (11/16)	Mechanisms (2/2)
Types (10/12)	Intervention (2/2)
Mechanisms (10/11)	Intentions (1/3)
Techniques (7/9)	Meta Principles (1/2)
Elements (6/6)	
Means (2/6)	

The systematic review of these terms reveals a few key insights. First, there exists a need to simplify the terminology employed by researchers in order reduce confusion. When four terms have been used to define two different constructs communication between researchers is frustrated. The lack of consistency of terminology has decreased the ability of researchers to discuss these constructs. Second, the majority of the papers did use two different terms for the tutor actions and intended effects of scaffolding thus giving credence to the fact that these aspects of the scaffolding construct are perceived as separate and distinct from one another by scaffolding researchers (see Table 2.6). However, Table 2.6 also displays terms (i.e., *functions*, *types*, and *mechanisms)* that have been used to describe both actions taken by the tutor as well as the intended effect of the scaffolding intervention.

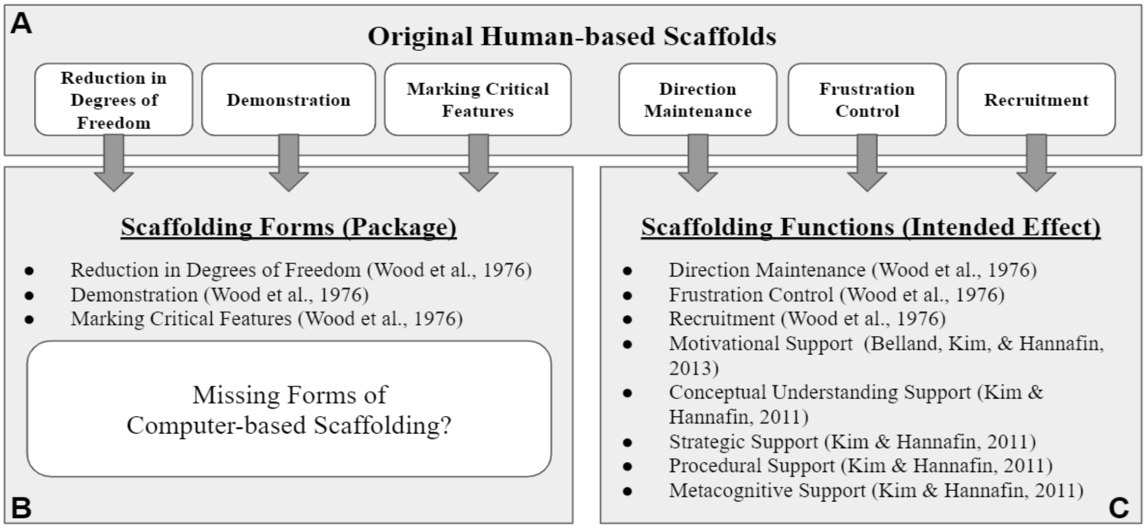
Is there Consistency Among the Terms Employed? Form and Function

Of the terms employed by scaffolding researchers (see Table 2.6), unsurprisingly *functions* show up as most frequently applied to define both the tutor's actions as well as the intended effect of the scaffold. If we use frequency as the best determinant for consensus among researchers, then *form* is the logical term to use to describe the tutor's action (appearance of the tutorial help) and *function* could be employed to describe the intended effect of the scaffold. *Type* was also used to describe both terms; however, it was less popular than form and/or function. Type also lacks the descriptive utility of *form* and *function*. When speaking about the tutor's action we are describing the form or its appearance, so scaffolding *form* is an apt term to utilize for the tutorial interactions. The descriptive utility of form has been the preferred term by researchers. When describing the intended effect of the scaffold, function has been far and wide the favorite term employed. Furthermore, there seems to be trending momentum behind using the combination of *form* and *function* based upon the most recent publications (Quintana, 2021; Suwastini et al., 2021). For example, Figure 2.1 shows the original scaffolding taxonomy from Wood et al. (1976) reinterpreted as scaffolding forms and scaffolding functions.

Box A of Figure 2.1 lists the original six scaffolding terms employed by Wood et al. (1976). Three of the original scaffolds describe in what "package" the assistance was delivered to the student (see Figure 2.1 Box B). Constraining a problem space (i.e., *reduction in degrees of freedom*) is something that a tutor/teacher does to the student. The label "*marking a critical feature"* is also a description of the tutor's act of helping the

Figure 2.1

Original Taxonomy Reinterpreted as Scaffolding Forms and Scaffolding Functions



student attend to what is necessary for the solution. Modeling effective problem-solving strategies (i.e., *demonstration*) is again a description of the help that the tutor provides to the student. These three scaffolds all describe the tutor's actions or in other words the form of the scaffold (see Figure 2.1, Box B).

However, the remaining three original scaffolds in Box A of Figure 2.1 *(direction maintenance*, *frustration control*, and *recruitment*) describe the intended impact of the scaffold on the student rather than describing the form of the scaffold. For example, *recruitment* and *direction maintenance* both describe what the scaffold is targeting to support "in the student." Or said differently, these scaffolds were labeled based upon the scaffold's intended effect on the student (i.e., students' attention is now enlisted or maintained in the desired direction). The scaffold *frustration control* describes the impact of the scaffold on the state of the student (i.e., their frustration level was managed or alleviated). However, each of these labels places less emphasis on what form the support took when it was offered to the student (e.g., a description of the actions from the tutor or design of the curriculum that leads to a reduction in frustration).

In alignment with recent syntheses (Quintana, 2021; Suwastini et al., 2021), I suggest that researchers and practitioners employ the terms of *form* and *function* to describe the scaffolding interventions more accurately. Scaffolding *form* will be used for the remainder of this article to describe the tutor's action, the intervention, or the "package" in which the tutorial assistance was delivered to the student. When referring to how the student was affected by the scaffold (intended effect), the term *function* will be employed.

> Research Question 2: What are the forms of computer-based scaffolding in extant experimental computer-based scaffolding literature in STEM fields?

Across the empirical literature, I found six distinct forms of computer-based scaffolds. These were *structuring, modeling, prompts, cues, simulation/visualization*, and *feedback*. Each of these six forms of computer-based scaffolding will be explained individually in the following sections.

Structuring

The intention of structuring scaffolds is to alleviate the cognitive load of the learner and/or guide the learner through the problem space. In contrast to other scaffolds where something is offered to the student (prompt, feedback, cues/highlights), structuring scaffolds manipulate the problem space in one of three ways: (a) constraining the problem space, (b) sequencing problem rigor in an incremental stepwise fashion, and/or

(c) walking the student lockstep through the problem-solving scenario.

Butz et al. (2006) offer a great example of structuring scaffolding that aids students by constraining the problem space. In their Interactive Multimedia Intelligent Tutoring System (IMITS), based upon the students' proficiency, the IMITS CBLE modified both the sequence of the problems as well as how much information the student received while problem solving (Butz et al., 2006). In this way, the students were not cognitively overburdened by extraneous information.

The scaffolding intervention from authors de Jong et al. (1996) offers a good example of structuring scaffolds that focused on ensuring that the rigor of sequential problems progressed in a stepwise fashion. In this paper, the authors aptly describe the benefits of their intervention as an environment that "gradually unfolds the properties of the domain to the learner" in a gentle sequence of increasing complexity (de Jong et al., 1996, p. 12). This incremental progression ensures that students do not finish one task only to be subsequently confronted by a task that is too far beyond their respective zones of proximal development (ZPD; Vygotsky, 1978). With the aid of structuring scaffolds, each problem is moderated to be within the ZPD of the student.

Last, in addition to constraining the problem space and ensuring that series of problems increased rigor in a stepwise fashion, structuring scaffolding also came frequently in the form of CBLEs which walked the students lockstep through a particular problem-solving process (Linn & Eylon, 2000; M. Liu, 2004; Zhang et al., 2004). In the study by Linn and Eylon, students were directed through a particular sequence of problem-solving activities such as writing explanations for their predictions, summarizing their experiments, and reconciling their predictions with actual results as they learned about liquid displacement. Similarly, the Alien Rescue (M. Liu, 2004) CBLE structured the learning space around a storyline which constrained the students to solve the given problem using a specific prescribed process. This ensured that the students experienced the expert problem-solving methodology and began to acquire proven problem-solving skills and strategies.

Modeling

Students confronted with unfamiliar or ill-structured problems can quickly become lost and frustrated. Modeling scaffolds alleviate this complexity for students in two ways: (a) full/partial worked example of the problem-solving process or (b) a visual of the expert model of the final solution.

Liu (2004) offered both varieties of modeling scaffolds. In addition to providing the case logs (final product), the CBLE also provided expert demonstrations of how to use interface tools and problem-solving models. In some cases, rather than providing a full expert model, studies provided students with a partial model (K. Chang et al., 2001; Laru et al., 2012). In one study, seventh-grade science students were tasked to produce various concept maps of biology topics such as cell division, sexual reproduction, and the endocrine system (K. Chang et al., 2001). Students in the experimental condition were provided with a partially completed concept map whereas students in the control condition received a blank concept map (K. Chang et al., 2001). The partially completed concept map helped reduce the complexity of the task in addition to providing a model of how concepts should look when completed.

In another case of a partial concept map (MacGregor & Lou, 2004), students were provided with a template which "provided a framework that specified how the learner was to make connections from the information they acquired with their study guide to the major relevant concepts" (MacGregor & Lou, 2004, p. 168). In addition to demonstrating what the final product should look like, students were also guided in their search and presentation design.

While the two types of modeling scaffolds differ in the extent to which they reveal the expert example, they both provide direction to the student. The difference between the variations of modeling scaffolds was due to the completeness of the model and when the model was delivered. Some scaffolding interventions started with a partial model and then moved to a full model if the student was unable to successfully complete the task (Butz et al., 2006). There were examples of the inverse as well. In one such study, students received a full model at the beginning of the intervention and then were weaned off a full model (faded) in subsequent exercises (Renkl, 2002).

There were instances where students did not receive a modeling scaffold until after they had submitted the assignment. In these situations, they were often expected to juxtapose their solution to that of an expert (Y. S. Chen et al., 2003). However, when an expert model was offered after a student submission, this was coded as feedback.

Prompts

More than any of the scaffolding forms enumerated here, prompts varied widely in how they appeared in the included empirical scaffolding literature. In some cases, prompts came in the form of imperatives/commands (Mayer et al., 2002), questions

(Roscoe et al., 2013), and hints or suggestions (Bulu & Pedersen, 2010). Regardless of whether the prompt came in the form of a command, question, or hint, the overall goal of prompts was to offer strategic guidance to the student as they navigated the problem-solving process.

Command prompts came in the form of firm directives to the student which guided them to take specific actions. A multimedia simulation game for geology, directed students to “Check all that apply: trench, ridge, basin, island seamount...” (Mayer et al., 2002, p. 172). This command prompt was not a suggestion. Students were not expected to own any part of the decision of what to do next. The command prompt firmly directed the students to take an action and students had only the choice between complying with the command or not.

Command prompts sometimes came from pedagogical agents. In one such case, the students engaged in problem-solving activities where the student interacted with a faux peer pedagogical agent as well as a faux teacher pedagogical agent (Roscoe et al., 2013). As the student submitted hypotheses to the peer pedagogical agent, the peer agent prompted the student to “explain that again" if the theory lacked satisfactory explanation (Roscoe et al., 2013, p. 287). Thus, the forceful command prompt led students to engage in more reflection and generate more substantial explanations for their solutions. Command prompts were similar in goal to other prompt types (i.e., question prompts and hints) but different in tone, force, and the amount of ownership the student had at that point of the problem-solving process.

Question prompts showed up frequently in computer-based scaffolding interventions. Similar to Roscoe et al., (2013), one experiment prompted real students to evaluate the work of a fictitious peer named Mary, such as “How well did Mary answer her question? Should Mary run another experiment to answer her question? Why or why not? ... How can Mary improve her experiment” (H. Y. Chang & Linn, 2013, p. 864). In contrast, to command prompts, question prompts were softer in tone, power, and less directive. Like command prompts, question prompts offered strategic guidance, but they expected the student to take more ownership in deciding what the next step to take in the problem-solving process.

Hints were even less forceful than command or question prompts. In contrast to command and question prompts, which were delivered by the CBLE to the student after an incorrect submission, hints were frequently initiated by the student through a hint button (Butz et al., 2006; K. Chang et al., 2001; Graesser et al., 2007; Mendicino et al., 2009; VanLehn, 2011). Rather than the scaffold contingently arising from a student evaluation, these hint buttons were often offered right before or after a submission by the student with the intent to guide the student towards a satisfactory response. During a study where students were tasked with building a concept map in a biology course, if the student was becoming frustrated, they were able to click the hint button and receive the message “partial proposition type, such as [Meiosis results in???]” (K. Chang et al., 2001, p. 23). This hint, in the form of a short sentence frame, gently directed the student toward what was missing while also jumpstarting the student towards the required information connected to meiosis.

As mentioned previously, CBLEs frequently offered more than one type of prompt to students (Bulu & Pedersen, 2010; Graesser et al., 2007). In a CBLE program called SEEK, a computer tutor helped students develop the ability to evaluate web evidence when exploring the causes of volcanic eruptions (Graesser et al., 2007). SEEK started with a hint button at the top of the search page, which when pressed by the student, would provide a prompt that suggested a possible next step or reminded the student of the initial task goal. After the first prompt was offered, the CBLE would begin a countdown. If the student was found to be directionless or unable to respond for more than 20 seconds, a window would pop up and reveal the correct answer to the student. These CBLEs which offered multiple forms of prompts often began with less powerful prompts first and then followed with stronger scaffolds when the student was unable to successfully complete the task with the lesser level of support (Graesser et al., 2007).

Cues

Similar to prompts, cues offered students guidance. However, cues differed with respect to the medium of that guidance. Cues came in the form of multisensory (i.e., sight and sound) messages embedded into the instruction that directed students' attention to salient features. In this manner, cues assisted students to avoid being inundated and overwhelmed by too much information while also helping students weigh which features were essential for solving the problem. Cue scaffolds showed up in the literature as a) animations and b) directive highlights.

In an engineering study of current and voltage (Finkelstein et al., 2005), cues came in the form of animation which signaled the student to the direction of the electron flow as well as the conservation of the current. In another paper by Nathan et al. (1992)

that measured the effectiveness of computer-based scaffolding on algebraic word problems, the experimental condition received cues that focused students on the salient features of the materials. Through cues, CBLEs ensure that students would pay attention to critical aspects of the word problem through animations and highlights.

Cues can also be seen as a type of modeling where a novice is given an example of what an expert would lend their attention to if given the same opportunity. For example, in one study graduate-level medical students in Finland were tasked with diagnosing diseases by investigating tissue samples (Nivala et al., 2012). In this study, both conditions received the same digitized slides of the tissue samples, but the experimental condition also received visual cues in their CBLE that directed the students to a general area on the slide without revealing what the abnormality in the tissue actually signified. The visual cue served as a model of what features an expert would attend to when given the task of diagnosing tissue samples.

Visualization

Both *visualization* (and simulation*)* scaffolds allowed students to move past the constraints of their senses and time, to see and experience complex phenomena. Through *visualizations*, infinitesimally small objects were enhanced and made accessible (H. Y. Chang & Linn, 2013; Magana, 2014). For example, scientific phenomena that would normally take extraordinary lengths of time such as stellar parallax could be observed in seconds through simulations (Ruzhitskaya, 2011). Ultimately, simulation and *visualization* scaffolds were collapsed into one group since they were very infrequently found separate from one another.

For example, Yoon et al. (2012) used augmented reality to project visual representations of electrons on the participants' bodies when they worked as a group to create a human circuit. When the group of participants broke the circuit the visually projected cues disappeared. This scaffold provided the participants with a large-scale *visualization* of a sub-atomic activity. However, in addition to making the normally invisible phenomenon visible, this scaffold also simulated a complex phenomenon in a very simple and interactive way.

In addition to making the inaccessible accessible, *visualizations* scaffolds provided students with engaging interactive opportunities to see how concepts interact with one another through a simulation (Nichols et al., 2013). Simulations often required students to control a number of the variables in a simulation (Swaak et al., 1998). Rather than have a teacher model the process/experiment and tell the students what to attend to at each step, simulation enlisted the attention of the students as they modified variables and saw direct changes to the outcomes of the simulations (Sharma & Hannafin, 2007).

Feedback

Feedback was a regular feature in scaffolding interventions with CBLEs. There was both immediate *feedback* and delayed *feedback*. Besides *feedback* timing, the factor that most distinguished one instance of *feedback* from the other was the robustness of *feedback* supplied to the student. Two levels of *feedback* emerged as the studies were coded: (a) correct or incorrect messages with interpretation, and (b) correct or incorrect messages without interpretations.

The most extensive cases of *feedback* were those when after submitting their solution a student was supplied with not only a response of whether they were correct or incorrect but also a full explanation of how their response deviated from the solution. For example, in the ChemProV CBLE, students were provided with what they called "dynamic feedback" (Hundhausen et al., 2011, p. 581). Students were not only alerted to their errors, but they were also provided with hints on how to fix their errors.

In contrast, other studies included interventions which supplied students with knowledge about whether their submitted work was correct or incorrect, but that was the extent of the *feedback*. Beyond a message of correct or incorrect, there was no further help offered. In one such example (Hundhausen et al., 2011), students were tasked with creating computer-aided design (CAD) engineering drawings. Once a CAD drawing was submitted, the CBLE would compare the student's drawing against an expert version of the same drawing and then deliver a message that notified the student of their errors and then allowed them to attempt the exercise again. However, there were instances when the CBLE would pair the "correct/incorrect" response with a message such as "try again and think carefully" (Ulicsak, 2004). In these instances, students were provided with the level of correctness of the response but also given motivational messages.

Discussion

The overall purpose of this systematic literature review was to resolve some of the language issues that have frustrated communication and consensus surrounding the theory of scaffolding. In particular, the intent was to disambiguate the form and function of scaffolding and enumerate the forms of computer-based scaffolding found in extant empirical literature. The implication of these results is discussed in the following sections.

Form and Function

First, aligning with the work of van de Pol et al. (2010), scaffolding researchers should avoid conflating the appearance of the scaffold with its intended outcome. While van de Pol et al. offered up two new terms (i.e., means and intentions) to distinguish between scaffolding interventions and their outcomes, these terms have not been adopted by the scaffolding research community.

A review of seminal works in scaffolding revealed that most researchers have similarly avoided using Wood et al.'s (1976) term "functions" to refer to both aspects of scaffolding interventions. However, rather than rallying around specific terms, researchers have introduced new terms for both *form* and *function*. Some consensus seems to be forming around using the term *function* to refer to only the intended effect or impact of the intervention on the student (Belland, 2014; Quintana, 2021; Rosenshine & Meister, 1992). While there is less consensus around which term(s) should be used to refer to the various types of tutor actions in scaffolding interventions, two of the most recent reviews of scaffolding have put forth the term *form*.

I align with Quintana (2021), that moving forward researchers will reduce the confusion surrounding scaffolding jargon by utilizing the terms *form* and *function* to refer to the appearance of the scaffolding intervention and its intended outcome, respectively. Disambiguating between the *form* and *function* of scaffolding is a strong step towards providing a framework of terminology that will allow for researchers to communicate scaffolding interventions more precisely and succinctly (Quintana, 2021). Beyond the confusion of *form* and *function*, there are other language issues exacerbating researchers' ability to communicate efficiently and effectively about scaffolding interventions. One such issue is the lack of a common lexicon for the forms of computer-based scaffolds present in the literature, including those that have arisen as computers have become more and more capable of delivering one-to-one tutoring.

Six Forms of Computer-Based Scaffolding and Their Alignment

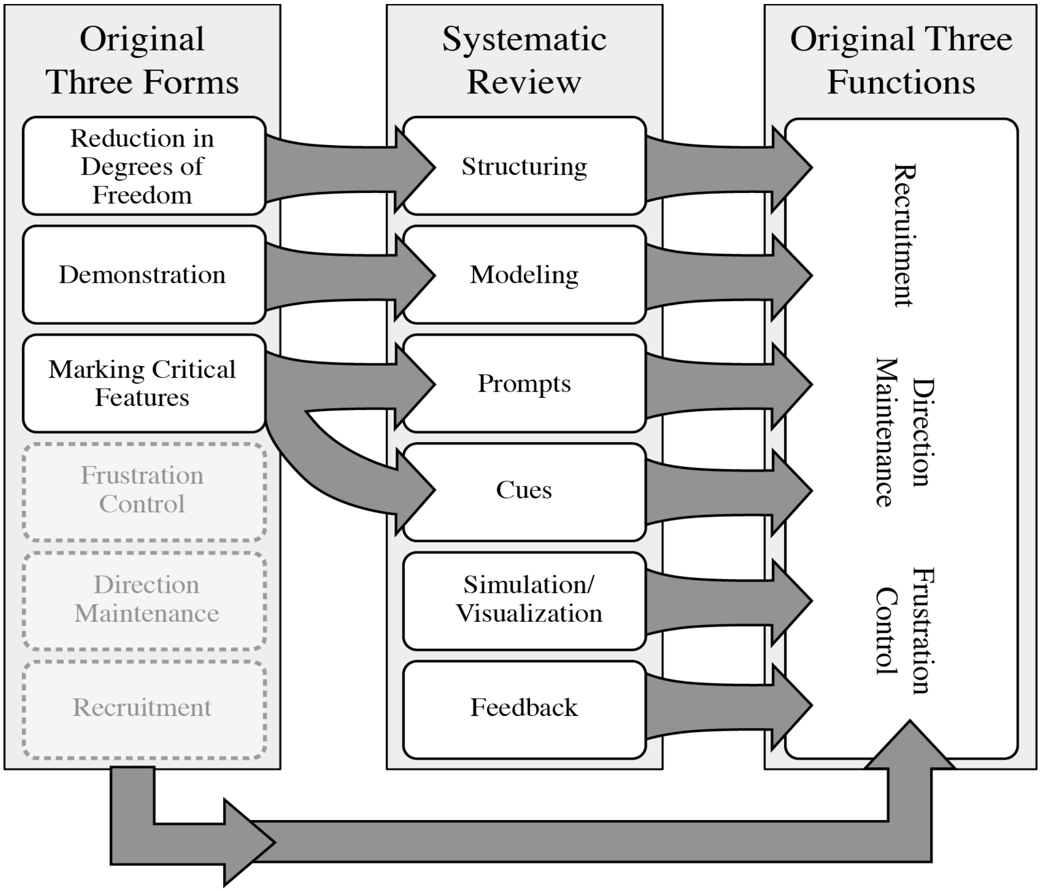
Through this analysis, I also labeled six scaffolding forms found consistently throughout the body of computer-based scaffolding literature in STEM education. These forms include: (a) *structuring*, (b) *modeling*, (c) *prompts*, (d) *cues*, (e) *visualizations*, and (f) *feedback*. A retrospective and prospective discussion of these forms of scaffolding is included below.

Retrospective: Contextualizing with Wood, Bruner, and Ross

There is both alignment and deviation between the six forms of new computer-based scaffold offered up in this article and the six original scaffolding types enumerated by Wood et al. (1976). The original six types of scaffolding were recruitment, reduction in degrees of freedom, direction maintenance, marking critical features, frustration control, and demonstration (Wood et al., 1976). As described earlier, I along with other researchers (van de Pol et al., 2010) argue that these original six scaffolding "functions" actually represent both the *form* (tutor action) and *function* (intended effect) of scaffolding. As such, three of the Wood et al. (1976) scaffolding functions *(Reductions in Degrees of Freedom, Demonstration,* and *Marking Critical Features*) align directly with four forms of computer-based scaffolding (*Structuring, Modeling, Prompts,* and *Cues*) put forth in this paper (see Figure 2.2).

Figure 2.2

Alignment of Six Scaffolding Forms with Original Scaffolding Taxonomy



The remaining three original functions of scaffolding (*direction maintenance*, *frustration control*, and *recruitment*) do not align with these new forms of scaffolding. Rather, the original scaffolding types of *direction maintenance*, *frustration control*, and *recruitment* are better described as functions, or the intended outcomes of the new scaffolding forms proposed in this paper (see Figure 2.2).

Reduction in degrees of freedom, *demonstration*, and *marking critical features* are almost a one-to-one match with new scaffolding forms other than slight modifications of the terminology (e.g., *demonstration* to *modeling*). *Structuring* scaffolds most closely align with the Wood et al. (1976, p. 98) "*Reduction in degrees of Freedom*." *Reduction in degrees of freedom* sought to simplify "the task by reducing the number of constituent acts required to reach a solution...tutor fills in the rest and lets the learner perfect the component sub-routines that he can manage" (Wood et al., 1976, p. 98).

Modeling scaffolds align with the Wood et al. (1976) "*demonstration.*" *Modeling* is more than a *demonstration*. It is an "idealization" representing the act of an expert delivering an idealized version of the problem solution (Belland, 2014). A substantial amount of research has been devoted to modeling especially with respect to cognitive load theory (CLT) researchers.

Computer-based scaffolding *prompts* and *cues* overlap with *marking critical features* and *direction maintenance* from the original scaffolding types listed in Wood et al., (1976). *Marking critical features* were originally defined as marking or accentuating "certain features of the task" to guide the student through the learning activity and provide information to the student, which highlights the discrepancy between the student's attempt and expert level work (Wood et al., 1976, p. 98).

Two forms of computer-based scaffolding included in this systematic review did not map well to the original scaffolding forms listed by Wood et al. (1976): *Visualization* and *Feedback*. Both *Visualization* and *Feedback* rely on technology that did not exist when scaffolding was first conceived. This underscores the need to review computer-based scaffolding research published after the labeling of the original forms of scaffolding.

Last, a connection between scaffolding forms proposed here and the three original scaffolds are now relabeled as scaffolding functions (i.e., *recruitment*, *direction maintenance*, and *frustration control*). Over time it became clear that many of the scaffolding forms proposed by this systematic review all served the functions of *recruitment*, *direction maintenance*, and *frustration control* (see Figure 2.2). To a greater or lesser extent, the overall goal or intended effect of each of the scaffolding forms is to help moderate frustration and keep students on the right path toward the problem solutions. This is potentially why there has been so much confusion in the scaffolding community. This is also why these original labels have resisted consensus and meta-analysis. Disambiguating the form of scaffolding from its intended function is a necessary step toward consensus and clearer communication between researchers.

Prospective: Contextualizing with Contemporaries

Since Wood et al. (1976) first coined the scaffolding term, there have been several reviews of the scaffolding construct which included lists of the forms of scaffolding. Table 2.7 shows how the forms of scaffolding enumerated in this systematic review map to the reviews offered by other researchers.

While authors used different labels and terms, Table 2.7 shows that there is clear consensus in perceiving *modeling* (worked examples, demonstration) and *prompts*

Table 2.7

Matrix of Terms for Scaffolding Forms Across Research Articles

Article	Structuring	Modeling	Prompts	Cues	Simulation/ visualization	Feedback
Wood et al., 1976	X	X	X	X		
Rosenshine & Meister, 1992	X	X	X	X		
S. Li, 2001	X	X	X	X		X
Quintana et al., 2004	X	X	X	X	X	X
Ge & Land, 2003		X	X			
Yelland & Masters, 2007		X	X		X	
Kali & Linn, 2008			X	X	X	
van de Pol et al., 2010		X	X			X
Belland, 2014	X	X	X	X		X
Chernikova, Heitzmann, Fink, et al., 2020		X	X	X	X	

(prompts, question prompts, and hints) as forms of scaffolding. There is some consensus that *cues* and *structuring* are also forms of scaffolding among contemporary researchers. *Feedback* and *Visualization* show the least consensus across these articles. A larger discussion of these two features and why they should be included in the list of scaffolding forms is detailed below.

Two New Forms

Visualization (e.g., simulation) is the form of computer-based scaffolding least aligned to the original six scaffolding types enumerated by Wood et al. (1976). This is most likely due to the advancement in technologies that were not available in the 1970s. Take for example the parents and toddlers in the Wood et al. study. Parents were able to provide feedback, hints, direction maintenance, and motivation as well as constrain how many blocks their child was handling at a given time. However, parents were not able to virtually modify the pyramidal structure. They could not decrease task rigor in the face of failure by quickly restructuring the number of blocks, the overall form, their size, or how they interlocked. They could not aid the emerging motor skills of a toddler by instantaneously modifying the block's weight, size, or texture. However, through advancements in technology, CBLEs are now able to assist students in all these ways and more.

Kali and Linn (2008) enumerated various technological strategies to support inquiry. The authors encouraged technology that supported students by enabling "three-dimensional manipulation" and "manipulation of factors in models and simulations" (Kali & Linn, 2008, pp. 153-155). The computer-based scaffolding examples coded under the form of *visualization* and *simulation* in empirical literature are very much in alignment with Kali and Linn's guidance. *Visualization* scaffolds assisted students primarily by making the inaccessible accessible (Nichols et al., 2013) either conceptually (e.g., visualization) or procedurally, (e.g., simulation).

Feedback has long been seen as having one of the largest effects on learning (Hattie & Timperley, 2007; Wisniewski et al., 2020). *Feedback* is sometimes included as a form of scaffolding (Belland, 2014; van de Pol et al., 2010) and in other cases seen as distinct from scaffolding (VanLehn, 2011). I align with the perspective of Shute (2008) which characterizes *feedback* both as a form of scaffolding as well as a part of the scaffolding process. *Feedback*, as a scaffolding form, comes after a student action and serves to “reduce the distance between the current outcome and the intended learning outcome” (Hattie & Timperley, 2007, p. 87). *Feedback*, as a part of the scaffolding process, shows up after each successive approximation of the intended behavior.

In addition to signaling how close the student was to success, *feedback* also often carries with it the next *prompt*, *cue*, etc. (Van der Kleij et al., 2015). Shute (2008) called this type of feedback, formative feedback and explained that it not only verified the correctness of the answer but also elaborated upon the correctness of the answer. By so doing, *elaborated feedback* or *formative feedback* serves to carry the next contingent scaffold to the student and essentially begin the instructional process anew (Van der Kleij et al., 2015).

Succinct and Descriptive

Using these terms will reduce the confusion that has arisen in the scaffolding literature and begin to create a consensus of language that researchers can rally around. Additionally, labels for scaffolding forms and functions can be combined to describe computer-based scaffolding interventions succinctly and accurately. For example, a CBLE titled Alien Rescue (M. Liu, 2004) tasked students with an ill-structured problem of relocating six different alien species to suitable new planets based upon their disparate needs before they die. This CBLE offered various scaffolds to the students as they acted like scientists while they engaged in a variety of problem-solving activities. Due to the number of various scaffolding supports, it is difficult to distinguish the various scaffolds from one another. However, using the language suggested in this paper can ease the burden of effectively and efficiently communicating how the students are being assisted.

The Alien Rescue CBLE program also assisted students by providing *strategic modeling scaffolds* on the problem-solving process through expert models. Additionally, the Alien Rescue CBLE provided *procedural structuring scaffolds* as it guided students through the problem-solving process and constrained them to complete specific problem-solving skills. By listing both the *form* and *function* of the scaffold, researchers can ensure that their peers and teacher practitioner can understand what the scaffold is and how it is assisting students. Scaffolding interventions, which describe both *form* and *function* elements of their intervention, will also aid researchers in efficiently coding articles for meta-analyses or in replication, either for scholars or practitioners.

Limitations and Recommendations for Future Research

To make this work feasible, large constraints had to be placed on the literature search. There were many studies excluded where the scaffolding was delivered through other sources such as teachers, peers, or paper-based textual supports. Likewise, studies outside of STEM content areas were excluded. This meant that non-STEM content areas such as language arts with their rich histories of scaffolding research were omitted. However, it is important to note that even within STEM content areas there were further exclusions. Only cognitive outcomes in STEM content areas were included. As such, studies that focused on generalizable skills (i.e., language acquisition, argumentation, search strategies, etc. or affective outcomes like satisfaction) were excluded from the review. This constrained lens of computer-based scaffolding effects on cognitive learning outcomes within STEM content areas does not provide comprehensive coverage of all computer-based scaffolding literature. Additional reviews should be conducted which include content areas outside of science, technology, engineering, and mathematics. Additionally, there is a need to review computer-based scaffolding research investigating non-cognitive outcomes such as meta-cognition and motivation.

Furthermore, one of the other major criticisms of scaffolding, in addition to the obfuscation of terminology, is the theoretical drift from foundational principles of scaffolding such as fading, contingency, and transfer of responsibility (Pea, 2004; Puntambekar & Hubscher, 2005). A critical evaluation of whether the forms of computer-based scaffolding offered up in this article align or deviate from foundational principles of scaffolding is the next logical step for review. For example, are each of these forms of computer-based scaffolding contingently added or faded in CBLEs? Is there a relationship between the forms of scaffolding and transfer of responsibility? Meta-analyses on scaffolding should seek to code how these forms of scaffolding fade their support(s). These efforts, and their subsequent insights, would provide powerful recommendations for the design of future computer-based scaffolding interventions.

Lastly, there is also a substantive amount of research measuring the effects of computer-based scaffolds on student learning outcomes (Belland, Walker, Kim, & Lefler, 2017; N. J. Kim et al., 2018). Many of these studies include interventions with multiple forms of computer-based scaffolds each intending to help the student in a different way. In agreement with Quintana (2021) a full meta-analysis should be conducted to attempt to quantify which forms of computer-based scaffolds (or combinations of forms) produce the greatest effects on student learning.

Conclusion

Over 40 years have passed since the scaffolding term was first introduced. Since then, the scaffolding construct has expanded beyond its original specific context of children building block towers to include new types of tutorial relationships, age groups, and content areas. Computer-based scaffolding first emulated what parents and teachers were doing to support children. But since then, the scaffolding construct has gone beyond the constraints of human delivered scaffolding (Soloway et al., 1994) to include other sources of scaffolding such as visualizations and simulations.

Advances in computing have allowed for the rise of computer-based scaffolding which can both do more and less than human tutors. While the definition of scaffolding, to temporarily assist students to help them succeed at a task beyond their unassisted capability, has remained the same over time, other aspects of scaffolding have become muddled and sometimes left out. There has been no consensus of terminology about how to characterize the various forms of scaffolds nor how new computer-based scaffolds abide by the constraints of the original theory. In the absence of consensus, scholars contend the scaffolding construct has been at a crucial precipice between preservation or death by dilution (Puntambekar & Hubscher, 2005).

This call for a common language is not unique (Bostwick et al., 2014) and frustrates progress in scaffolding research. The lack of consistent and comprehensive language impedes researchers from comparing the effects of different types of scaffolds as well as making it difficult for researchers to communicate effectively. The application of scaffolding in each of these paradigmatic silos is on one hand very valuable as it leads to a robustness of literature that would otherwise be lost. However, on the other hand, consistently expanding without consensus or synthesis of the terminology, will only lead to further ambiguities. A lack of universally accepted theory and terminology could very well lead to inefficiency as researchers talk past each other and even possibly duplicate the same work.

The goal of this research was to preserve the scaffolding construct by creating an initial set of concise terms to describe the various forms of scaffolds and discuss how computer-based scaffolding has aligned or deviated from the original six labels for scaffolds by Wood et al. (1976). First, I recommend that researchers begin using the term *form* to describe the tutor's actions or "package of delivery" and to use the term *function* to describe the "intended effect" of the scaffold. Second, after synthesizing empirical research in computer-based scaffolding, I listed six forms of scaffolding: (a) structuring, (b) modeling, (c) prompts, (d) cues, (e) visualizations/simulations, and (f) feedback. Using these terms will reduce the confusion that has arisen in the scaffolding literature and begin to create a consensus of language that researchers and practitioners can rally around. Subsequent design, practitioner usage, research, and review work, and their subsequent insights, may provide powerful recommendations for the use of computer-based scaffolding interventions.

CHAPTER 3

ESTIMATING THE EFFECTS OF COMPUTER-BASED SCAFFOLDING FORMS IN ENGINEERING EDUCATION: A META-ANALYSIS

Abstract

Computer-based scaffolding assists students as they develop solutions to complex problems. Several meta-analyses have shown that computer-based scaffolding is effective at increasing the cognitive outcomes of STEM problem solvers. However, very few moderator analyses have provided insight into which aspect of scaffolding interventions produce systematically larger effects. More specifically, there is a dearth of literature focused on estimating the effects of the various forms of computer-based scaffolding interventions in order to prescribe which combinations of computer-based scaffolding forms produce the highest learning gains in engineering students. This review synthesizes twenty-seven outcomes from thirteen experimental engineering education research studies. This random effect meta-analysis demonstrates that computer-based scaffolding in engineering education has a positive effect ($g = 0.53$) on cognitive outcomes.

Keywords: engineering education, scaffolding, meta-analysis, problem-centered instruction

Introduction

Scaffolding is the temporary aid offered to students which enables them to complete tasks that would have otherwise been outside of their capabilities (Wood et al., 1976). From its origin in the study of children building block towers in 1976, the theoretical construct of scaffolding has expanded to other content areas, age groups, and sources (Belland, Walker, & Kim, 2017; van de Pol et al., 2010). For the past few decades, there have been hundreds of studies investigating the capacity of computer-based scaffolding to produce learning gains in students engaged in problem-centered STEM education (Belland, Walker, & Kim, 2017; Belland, Walker, Kim, & Lefler 2017).

Several meta-analyses have estimated the overall impact of computer-based scaffolding on STEM learning gains (Belland et al., 2015; Belland, Walker, & Kim, 2017; Belland, Walker, Kim, & Lefler, 2017; Cai et al., 2022; Chernikova, Heitzmann, Fink, et al., 2020; Chernikova, Heitzmann, Stadler, et al., 2020; Doo et al., 2020; N. J. Kim et al., 2018, 2020). All meta-analyses conducted on computer-based scaffolding have shown scaffolding to have a positive effect on STEM learning outcomes. However, these studies have found few statistically significant moderators to explain the range of effect size estimation of STEM learning outcomes. In addition to overall effect size estimations, these meta-analyses also conducted additional analyses to investigate whether specific characteristics (i.e., variables) can help explain the range of included outcomes.

Typically, moderator analyses investigate the impact of various study, participant, and intervention characteristics on observed outcomes. However, the form of the scaffold itself has been almost entirely absent from meta-analyses investigating the effects of computer-based scaffolding on learning (Belland et al., 2015; Belland, Walker, Kim, & Lefler, 2017; Doo et al., 2020). In part, that absence is due to a lack of common vocabulary for scaffolding (Quintana et al., 2004), which would enable the coding of scaffolding forms. Through this meta-analysis, we address this research gap by estimating the impact of computer-based scaffolding forms on collegiate engineering learning outcomes.

Background and Context

The future world economy will be dominated by jobs in Science, Technology, Engineering, and Mathematics (STEM; National Academies of Sciences, Engineering, and Medicine, 2016). From 2009 to 2015, STEM jobs grew at twice the pace (10.5%) of non-STEM jobs (5.2%) in the U.S. (Fayer et al., 2017). These statistics substantiate the claim that the competitiveness of a nation in the future global economy will be contingent upon that nation’s capacity to create and retain enough highly qualified STEM workers (National Science Board, 2010). However, some STEM programs in academia recruit many students but retain few, putting both the student’s and the nation's economic prosperity at risk.

Engineering programs are among the most popular declared majors in college (Snyder et al., 2019) but many undergraduate engineering students do not make it to graduation. Dropout across all years of engineering programs is estimated to be as high as 40-70% depending on the program (Hartman & Hartman, 2006). Increasing engineering student retention rates has been a major focus of college engineering administrators and educational researchers (Hartman & Hartman, 2006; Q. Li et al., 2009). While many factors have been found to contribute to engineering dropout, some researchers have suggested that cognitive factors may have the greatest impact on reducing dropout since academic success has been shown to not only boost retention but to also impact affective outcomes positively in students (Q. Li et al., 2009).

Wicked Problems and Poor Support

Many first- and second-year engineering students struggle with the rigorous demands of the engineering program curriculum and courses that are often overcrowded, competitive, and low on student-teacher interaction (Geisinger & Raman, 2013; National Academies of Sciences, Engineering, and Medicine, 2016). Engineering dropout research has shown that one-to-one tutoring and strong teacher-student relationships help students find early success in courses (Besterfield-Sacre et al., 1997). However, in early engineering gateway courses student-teacher interaction and remediation are often hard to find (Hundhausen et al., 2011). To make matters worse, engineering programs are purposefully designed to include ill-structured problem-solving tasks (Jonassen et al., 2006). Ill-structured problems are open-ended, authentic, and simulate real-world complex problems which often lack a single right answer/solution (Eris et al., 2010; Ge & Land, 2003).

In order to prepare prospective engineers for their future work life, engineering students need to be prepared to use new technologies to solve complex problems with interdisciplinary teams composed of individuals from around the world (Johri & Olds, 2011). Over time engineering curricula has shifted from well-structured problems (i.e., single solution) solved by individual students applying rote algorithms, towards problem-based learning (PBL) models that center around groups of students solving complex, ill-structured problems (Jonassen et al., 2006; Savery, 2015). These so-called “wicked problems” often cause frustration if engineering students aren’t sufficiently supported (Lönngren et al., 2019).

A 4-year longitudinal study revealed that engineering students begin their college experience confident in their ability to tackle open-ended problem-solving tasks but then steadily decline until their junior and senior years where they regain their confidence (Eris et al., 2010). Poor grades and self-confidence are interrelated and contribute to dropout during this dip. It has been found that engineering students require almost constant attention and tutoring from instructors in order to successfully solve rigorous complex-problem solving exercises (J. Chen et al., 2021). However, increasing one-to-one tutoring or mentoring is difficult when faced with the unbalanced teacher student ratios that plague large introductory gateway courses (Besterfield-Sacre et al., 1997). If complex-problem solving is imperative to engineering student preparation, engineering programs need ways to increase support and guidance during open-ended problem-solving tasks at scale.

Computer-Based Scaffolding

Scaffolding has been effectively implemented with engineering students to aid them in successfully confronting complex, problem solving tasks (Hmelo-Silver et al., 2007; Jonassen et al., 2006; Lönngren et al., 2019; Lönngren & van Poeck, 2021). Scaffolding was originally researched among human tutors (Pea, 2004; Stone, 1998; Wood et al., 1976) but for the past few decades researchers have begun to examine whether scaffolding could be delivered effectively by computers and thus provide customized support to large numbers of learners (Belland, Walker, Kim, & Lefler, 2017;

N. J. Kim et al., 2018).

Computer-based scaffolding has the potential to ensure engineering curriculum is within reach of each student as well as substantially boost teacher-student interaction. Often these scaffolds are delivered to engineering students through computer-based learning environments (CBLEs) which provide students with more engaging, interactive, and supportive learning (Parchman et al., 2000). In these CBLEs, students are able to engage in problem-solving tasks and use engineering tools such as simulations while also receiving computer-based scaffolding support (Chernikova, Heitzmann, Fink, et al., 2020; Johri & Olds, 2011). Computer-based scaffolding has been shown to have a strong effect on helping students successfully engage in complex-problem solving environments in STEM fields (Belland, Walker, Kim, & Lefler, 2017).

Over the past few decades, engineering research has measured the impact of new forms of computer-based scaffolds such as structuring scaffolds (Adair & Jaeger, 2014; Aydin & Cagiltay, 2012), modeling scaffolds (Butz et al., 2006; Parchman et al., 2000), prompts (Kumar et al., 2007), cues (Hundhausen et al., 2011), and visualizations/ simulations (Finkelstein et al., 2005; Philpot et al., 2005). Among this research of new computer-based scaffolding interventions, there is considerable variation between both the quantity and type of supports offered by these CBLEs. For example, some research investigates the impact of computer-based learning environments that offer one form of scaffold (MacGregor & Lou, 2004; Mayer et al., 2002) where other interventions offer many (Aydin & Cagiltay, 2012; Finkelstein et al., 2005). These interventions which offer many supports have been referred to as distributed scaffolding (Puntambekar &

Kolodner, 2005; Quintana, 2021; Tabak, 2004).

Gap in the Research

As illustrated in Chapter 1, there have been at least nine meta-analyses estimating the effects of computer-based scaffolding on learning outcomes (Belland et al., 2015; Belland, Walker, & Kim, 2017; Belland, Walker, & Kim, & 2017; Belland, Walker, Kim, & Lefler, 2017; Cai et al., 2022; Chernikova, Heitzmann, Fink, et al., 2020; Chernikova, Heitzmann, Stadler, et al., 2020; Doo et al., 2020; N. J. Kim et al., 2018, 2020). The mean effect size estimations of computer-based scaffolding were all found to be positive ranging from (*g* = 0.39; Chernikova, Heitzmann, Stadler, et al., 2020) to (g = 0.88; Chernikova, Heitzmann, Fink, et al., 2020) (see Table 3.1). Effect size estimates of this size are considered medium to high within the context of educational (Kraft, 2020).

These meta-analytic researchers also analyzed which moderators (e.g., study characteristics, population characteristics, and intervention characteristics) have a statistically significant impact on learning outcomes. Prior knowledge, fading/adding schedules and validity reporting have been found to have a statistically significant impact on learning outcomes (Belland et al., 2015; Belland, Walker, & Kim, 2017; Cai et al., 2022; Chernikova, Heitzmann, Fink, et al., 2020; Chernikova, Heitzmann, Stadler, et al., 2020; Doo et al., 2020; N. J. Kim et al., 2020). Other moderators such as publication region, discipline, scaffolding function, assessment level, and publication year, despite being included in multiple meta-analyses, have largely been shown to not impact effect size estimates of computer-based scaffolding interventions (Belland et al., 2015; Belland, Walker, & Kim, 2017; Cai et al., 2022; Chernikova, Heitzmann, Fink, et al., 2020;

Table 3.1

Effect Size Estimates of Previous Meta-Analyses on Computer-Based Scaffolding

Short citation	Content focus	Analysis type	Context of use	# of studies/ outcomes	Mean effect size estimate
Cai et al., 2022	Learning outcomes in all content areas	Meta-analysis	Digital game-based learning	49/154	(g = 0.43)
Chernikova, Heitzmann, Fink, et al., 2020	Learning outcomes medical & teacher education	Meta-analysis	Problem solving	145/409	(g = 0.88)
N. J. Kim et al., 2020	STEM learning outcomes	Meta-analysis	Group problem solving in CBLEs	145/333	(g = 0.46)
Doo et al., 2020	Learning Outcomes In All Content Areas	Meta-analysis	Online learning	18/64	(g = 0.87)
N. J. Kim et al., 2018	STEM learning outcomes	Bayesian network meta-analysis	PBL various	21/47	(g = 0.39)
Chernikova, Heitzmann, Stadler, et al., 2020	Learning Outcomes Medical & Teacher Education	Meta-analysis	Problem solving	29/35	(g = 0.39)
Belland, Walker, Kim, & Lefler, 2017	STEM learning outcomes	Meta-analysis	Problem solving in CBLEs	144/333	(g = 0.46)
Belland, Walker, & Kim, 2017	STEM learning outcomes	Bayesian network	Problem solving in CBLEs	56/218	(g = .74)
Belland et al., 2015	STEM learning outcomes	Meta-analysis	Problem solving in CBLEs	7/17	(g = 0.53)

Note. Kim et. Al. (2018) and Belland et al. (2017) are Bayesian network meta-analyses and model population statistics rather than employ inferential statistics. They are also based on mean differences within groups (pre-post gains) rather than between groups (treatment vs control conditions).

Chernikova, Heitzmann, Stadler, et al., 2020; Doo et al., 2020; N. J. Kim et al., 2020).

Despite having primary research that shows a positive effect of various types of scaffolding (i.e., modeling, prompts, highlights, and simulations) there has been very few meta-analyses which have investigated how single forms of scaffolding or combinations of computer-based scaffolding forms (distributed scaffolding interventions) moderate cognitive learning gains. Scaffolding forms showed up in only two of the seven traditional meta-analyses on computer-based scaffolding (see Table 3.2). In some instances, it was shown to be significant and in others, non-significant. For example, Table 3.2 outlines which of the seven prior meta-analyses have investigated (a) single forms of computer-based scaffolding, (b) multiple forms of computer-based scaffolding, and (c) whether the forms/combinations of form produced statistically significant outcomes.

Table 3.2

Results of Computer-based Scaffolding Moderator Analyses from Previous Meta-Analyses

Short citation	Investigated single forms? (Y/N)	Significant differences for forms? (Y/N)	Investigated multiple forms? (Y/N)	Multiple forms differences? (Y/N)
Cai et al., 2022	Yes	Yes	Yes	Yes
Chernikova, Heitzmann, Fink, et al., 2020	Yes	Yes	Yes	Yes
N. J. Kim et al., 2020	No	No	No	No
Doo et al., 2020	No	No	No	No
Chernikova, Heitzmann, Stadler, et al., 2020	Yes	Yes	No	No
Belland, Walker, Kim, & Lefler, 2017	No	No	No	No
Belland et al., 2015	No	No	No	No

Note. Previously included Bayesian network meta-analyses (Kim et. al., 2018 and Belland, Walker, & Kim, 2017) were excluded from this review

Table 3.2 illustrates that of the seven prior meta-analysis on computer-based scaffolding, only three of the studies investigated single forms of scaffolding. Additionally, only two of the seven meta-analyses addressed combinations of scaffolding forms into moderator analyses. Furthermore, Table 3.2 also shows that of the few instances where the form of the scaffold was included, statistically significant differences were found. However, in the three instances where scaffolding forms were included, these studies did not include all forms of computer-based scaffolds, nor did they include all potential combinations of scaffolding forms in their analyses.

While Cai et al. (2022) included scaffolding form(s) as a moderator and found significance, there were limitations to these findings. First, the authors included reflection, feedback, hints, exposition, collaboration, mixed, and others as the scaffolding type moderators. This list did not include single scaffolding forms such as question prompts, modeling, and structuring that have always been considered essential types of scaffolds (van de Pol et al., 2010; Wood et al., 1976). In addition to not coding for widely accepted forms of scaffolding, the researchers (Cai et al., 2022) fell short of providing details into which combinations were statistically significant. Both the "mixed" and "others" scaffolding form moderators were "catch all" coding groups. If a combination was found between scaffolding forms included in the study, it was coded as mixed. For instances "when scaffolding could not be classified into any of the above categories, it was coded as 'others'" (Cai et al., 2022, p. 542). Despite finding statistical significance for the "mixed" and "others" scaffolding type moderators the coding scheme is not orthogonal. As a result, we are left without guidance as two which scaffolding combinations might provide the largest impact on learning.

Similar to Cai et al. (2022) study above, the meta-analysis on simulation and scaffolding based interventions (Chernikova, Heitzmann, Stadler, et al., 2020) only included three types of scaffolding forms (i.e., expert examples, refection, and prompts). Broadly accepted scaffolding forms such as visualizations, explanatory feedback, and structuring were excluded from the analysis. Because of this constrained coding framework, it calls into question whether the statistically significant difference, found between the included scaffolding forms, represents the full breadth of interventions.

The remaining meta-analysis (Chernikova, Heitzmann, Fink, et al., 2020) similarly included a short list of scaffolding forms. These were role-taking, prompts, and reflection phases and were all found to be statistically significant forms of scaffolding. In addition to representing a reduced set of scaffolding forms, this coding scheme intermingles scaffolding processes (reflection phases) with scaffolding forms (role-taking and prompts).

A broad look at prior meta-analyses reveals their important contributions to the literature, including preliminary evidence for the important role of scaffolding forms. They also reveal the need for additional work to meet the needs of researchers and instructional designers who would like to develop the most efficacious scaffolding interventions in CBLEs. First, few meta-analyses include scaffolding forms as moderators. Second, the few studies that do include scaffolding forms as moderators include substantially reduced, and at times, non-orthogonal sets of forms. Third, the moderator analyses applied across studies are coding for different forms of scaffolding which impedes researchers from gaining insights through meta-analyses. Last, important moderators such as rich descriptions of the control population and study quality have also been largely absent from these meta-analyses.

Hearkening attention to these gaps in the literature, many researchers have called for future meta-analyses to more precisely measure contributions of individual forms of scaffolds, as well as combinations of scaffolding forms found in distributed scaffolding interventions (Azevedo & Hadwin, 2005; Belland, 2014; Doo et al., 2020; Kermani, 2017; Kern & Crippen, 2017; N. J. Kim et al., 2018; Pea, 2004; Quintana, 2021; Quintana et al., 2004; Shin et al., 2020; Thomas, 2011; van de Pol et al., 2010). Gaining insight into which forms of scaffolding produce the largest learning outcomes is critical for practitioners and researchers, especially with regard to problem solving in engineering.

Research Questions

The goal of this meta-analysis is to take the first steps toward estimating the extent to which the full range of individual scaffolding forms, as well as a separate analysis of orthogonal combinations of scaffolding forms, moderate learning outcomes. This analysis will be directly targeted where it can most advance STEM education by examining collegiate level engineering studies through the following research questions.

1. What is the overall contribution of computer-based scaffolding on engineering learning gains and how much variability is present in the findings?
2. To what extent do single computer-based scaffolding forms make individual contributions to collegiate student engineering learning gains?
3. Which combinations of computer-based scaffolding forms, as observed in individual studies, make contributions to collegiate student engineering learning gains?

Methods

Table 3.3 details each research question and the analysis used to answer each included research question.

Table 3.3

Research Questions and Corresponding Analyses

Research question	Analysis
Supporting Analyses (publication bias, outlier detection, test assumption of outcome/study independence, quality analysis)	Funnel plot, Egger's test, *Z* score for outlier detection, Robust Variance Estimation, examination of internal/external threats via meta-regression and funnel plot
RQ1 - What is the overall contribution of computer-based scaffolding on engineering learning gains and how much variability is present in the findings?	Random effects meta-analysis and forest plot of outcomes
RQ2 - To what extent do single computer-based scaffolding forms make individual contributions to collegiate student engineering learning gains?	Random effects meta-analysis of scaffolding forms (present/absent) Pairwise Z tests between scaffolding forms
RQ3 - Which combinations of computer-based scaffolding forms, as observed in individual studies, make contributions to collegiate student engineering learning gains?	Random effects meta-analysis and forest plot of outcomes grouped by scaffolding form combinations; Pairwise Z tests between scaffolding form combinations

Note. All analyses were conducted on the same 27 outcomes.

Literature Search Procedure

The literature search process included three phases: database searches, hand searches, and referral searches. First, we used various combinations of the search terms: *scaffold*, computer*, tutor*, intelligent tutoring system*, cognitive tutor** to search the following databases: Education Source, PsychINFO, Eric, CiteSeer, Proquest, PubMed, Academic Search Premier, IEEE, and Google Scholar between 1/01/1993 and 8/22/2022. Next, we conducted hand searches of individual engineering journals: *Computer Applications in Engineering Education* and the *Journal of Professional Issues in Engineering Education and Practice.* Finally, during the coding process we searched the literature reviews of included studies for additional relevant studies (Belland, Walker, &

Kim, 2017; Belland, Walker, Kim, & Lefler, 2017; Botelho et al., 2016; Devolder et al., 2012; Jumaat & Tasir, 2014; Yasin & Yunus, 2014).

Inclusion Criteria

Included studies were required to possess the following: (a) an experimental condition with ample description of a scaffolding intervention, (b) a control condition, (c) cognitive learning outcome(s) as the dependent variable, (d) sufficient details for calculating effect size(s), and (e) a population of college level engineering students.

Literature Search Results

The database search resulted in 4,809 potential articles. During initial screening of article abstracts and methodology sections, 3,430 articles were excluded from literature search due to qualitative study design, content area outside of engineering education, absence of learning outcomes, and no scaffolding. The remaining articles were read more deeply in order to ensure that they met all inclusion criteria (see Figure 3.1). After exclusions, 14 articles were included in the study and subsequently coded.

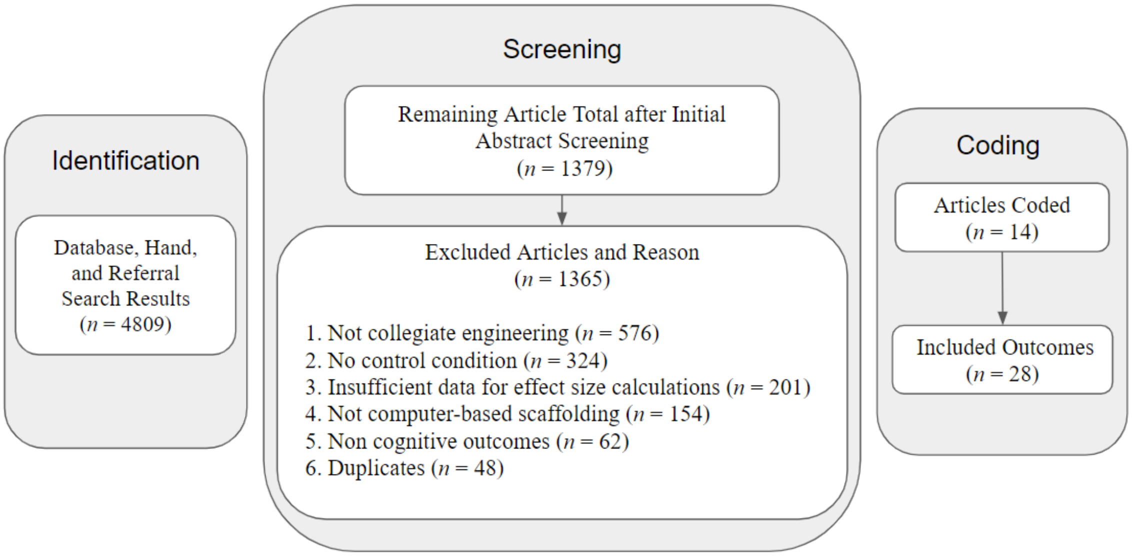
Coding Process

Using a Coding Guide

Each article was first coded independently by two researchers with expertise in scaffolding and meta-analysis. After each article was coded independently, the two researchers met to synthesize the independent codes into a single consensus row for each outcome.

Figure 3.1

Literature Search Stages and Outcomes



Coding

Included studies were coded with regards to both study characteristics (Control Condition, Internal Threats, and External Threats to Validity) and intervention characteristics (Scaffolding Forms, Feedback Type, and Effect Size).

Study Feature Coding

Control condition description. There were three distinct types of control conditions included in the studies. All the intervention conditions included scaffolding from a CBLE while students engaged in STEM problem solving. The control conditions all received lecture and then varied with respect to lab activity and engagement with CBLE technology. Some (*n* = 8) outcomes were comparisons of scaffolding interventions in a CBLE vs a true lecture only control. The majority (*n* = 12) included control conditions engaged in lecture and lab activities outside of a CBLE (lecture+lab). Last, there were some instances (*n* = 8) where the control population did experience the CBLE but without the scaffolding (lecture+lab+technology). Including each variation of control condition, allowed us to look at whether the proximity of the control and intervention conditions played a systematic role in effect size estimates.

Threats to validity. Each outcome was coded on a 4-point Likert scale for threats to validity. A “0” meant that the researcher felt there was no threat to the study’s validity. A “1” signified that the researcher felt there was a presence of a minor threat to validity. If a threat was coded as “2” that meant that the researcher deemed this threat to be a plausible alternative explanation for the observed results. Last, a “3” signified that the researcher felt that the threat could explain most, if not all, of the differences between treatment and control groups. The following table includes the internal and external threats, their definition, and the coding framework (see Table 3.4).

Intervention Characteristics Coding

Structuring. Progression scaffolds alleviate the cognitive load of the problem solver by structuring the problem-solving space for the student. This can be done by (a) sequencing the consecutive problems incrementally in terms of rigor, (b) constraining the problem space (Butz et al., 2006), and (c) lock stepping the students through the problem-solving process.

Modeling. Modeling scaffolds assist students by demonstrating the product or process of an expert (Belland, 2014). This support aligns with “demonstration” from Wood et al. (1976). Modeling can come in the form of a full or partial expert model in

Table 3.4

Definitions for Internal and External Threats to Validity

Type	Definition
Internal threats	
History	An event outside of the research study (such as COVID-19) was experienced differentially by the treatment and control groups.
Maturation	Physiological changes of participants during the time of the study or differences between the development of treatment and control groups led to performance differences.
Testing	Participants scores were improved by frequent exposure to test items (i.e., identical pre-posttest taken in close proximity)
Instrumentation	Participant performance could be explained by a variation in the assessment.
Statistical regression	Differences in performance can be partially explained not as a true gain but as a regression in prior performance to the overall mean.
Experimental mortality	Differential attrition between the control and treatment groups.
Differential selection	The samples of the treatment and control group were systematically different (such as use of intact classrooms with the treatment as an early morning class).
External threats	
limited description	The description of the experiment is poor and lacks full study characteristic details.
multiple treatment	Participants are exposed to alternative treatments (e.g., experimental condition receives more instructional time than control condition) that could explain the change in performance.
experimenter effect	The change in performance could be explained by the vested interest of the experimenter, especially in a way that would be challenging to replicate.

order to offer the right amount of scaffolding support for the individual student (K. Chang et al., 2001; Laru et al., 2012).

Prompts/hints. Prompts scaffold student learning by marking critical features or providing just in time strategic guidance to struggling students. Prompts come in a range of directness. At one extreme, learners are told what steps to follow. On the other end of the spectrum, are recommendations such as suggesting content knowledge for novice learners to consider during a problem-solving task (Bulu & Pedersen, 2010).

Question prompts. Similar to prompts/hints, question prompts sometimes come in the form of assistive messages phrased as questions and are often meta-cognitive in nature (Ge & Land, 2003). For example, in Roscoe (2013) students are asked if they can explain a principle again so that they can “reflect on their knowledge and produce better explanations” (p. 287).

Cues/highlights. Cue scaffolds align with “marking critical features” and “direction maintenance” from Wood et al. (1976). Similar to question prompts and prompts/hints the intention is to guide the student. Whereas prompts/hints and question prompts are verbal, cues/highlights are visual or auditory messages that both reduce complexity and guide the student’s attention to salient features necessary for problem solving success.

Visualization. Simulation and visualization scaffolds make the inaccessible accessible (Nichols et al., 2013). These scaffolds assist students to move past the constraints of their senses. Small representations like electrons can be enhanced and made accessible to the students so that they are able to interact and experience them at scale (Yoon et al., 2012). These scaffolds also help students move beyond the constraints of time. Scientific phenomena that usually take long lengths of time transpire in seconds and give students the opportunity to simulate the impact of different variable setups.

Effect size calculations. Effect sizes for each included study were calculated using an open online tool linked to the Campbell Collaboration called the "Practical Meta-Analysis Effect Size Calculator" (Wilson, 2022). Included studies had to include enough information to calculate a mean difference between a treatment and control group. The preferred and most common statistic was a pooled estimate of the population standard deviation to arrive at Cohen's *d*. If additional information was available, such as pre-test scores to account for pre-existing differences we included it. Where less information was available, we used *t* or *F* statistic and sample size. In a single case we derived the effect size from a specific *p* value and sample size (Lipsey & Wilson, 2000) rather the exclude important data. Table 3.5 details the coding of the key variables for all included articles. A full coding guide is included in the Appendix.

Meta-Analytic Procedures/Statistical Analyses

STATA 14 software was utilized for the analyses. Due to the wide range of scaffolding intervention forms, analyses were conducted using a random effects model (Borenstein et al., 2021). Prior to conducting the meta-analysis, we also conducted several supporting analyses to test assumptions, and look for systematic explanations (such as publication bias, study quality, and outliers) that could potentially explain effect size differences.

Outlier Detection

To detect potential outliers, we z scored the Hedges' *g* point estimates and found a single outcome at 3.57. This suggests a single positive outlier warranting closer examination and potential removal. After determining there were no systematic patterns

Table 3.5

Key Variable

Study	Outcome names	Control condition	Structuring	Modeling	Prompts/ hints	Question prompts	Cues/ highlights	Visualization/ stimulation	Feedback type	Internal threats combined	External threats combined	*ES*
Hundhausen et al., 2011	solution acc	lecture + lab	Y	Y	Y	N	N	Y	EF	0	0	-0.21
Parchman et al., 2000	game vs /app	lecture	Y	N	N	N	N	Y	NIF	0	3	0.00
Parchman et al., 2000	game vs /con	lecture	Y	N	N	N	N	Y	NIF	0	3	0.04
Adair & Jaeger, 2014	principles (3&4)	lecture + lab	Y	N	N	Y	N	Y	SR	1	2	0.13
Parchman et al., 2000	CBPD vs /app	lecture	Y	N	Y	Y	N	N	EF	0	3	0.13
Chen & Levinson, 2006	exam	lecture + lab	N	Y	N	Y	Y	N	SR	3	1	0.17
Finkelstein et al., 2010	Lab	lecture + lab	N	N	N	N	N	Y	SR	3	0	0.24
Parchman et al., 2000	ECBI vs /con	lecture	Y	Y	N	N	N	Y	EF	0	3	0.27
Parchman et al., 2000	ECBI vs /app	lecture	Y	Y	N	N	N	Y	EF	0	3	0.30
Finkelstein et al., 201	exam	lecture + lab	N	Y	N	Y	Y	N	SR	3	0	0.43
Parchman et al., 2000	CBPD vs /con	lecture	Y	Y	N	N	N	Y	EF	0	3	0.48
Westerfield et al., 2015	errors	lecture + lab + technology	Y	Y	Y	N	Y	Y	EF	2	2	0.51

(*table continues*)

Study	Outcome names	Control condition	Structuring	Modeling	Prompts/ hints	Question prompts	Cues/ highlights	Visualization/ stimulation	Feedback type	Internal threats combined	External threats combined	*ES*
Gokhale, 1996	drill & practice	lecture + lab	N	N	N	N	N	Y	KR	2	3	0.53
Weusijana et al., 2004	posttest gains	lecture + lab + technology	N	Y	Y	Y	N	Y	KR	3	1	0.54
Kumar et al., 2007	conceptual test	lecture + lab + technology	Y	N	N	N	N	N	KCR	3	1	0.59
Rodriguez et al., 2006	Y.3 simple	lecture + lab + technology	Y	N	N	N	N	Y	SR	6	3	0.61
Philpot et al., 2005	centroid quiz	lecture	Y	N	N	N	N	Y	EF	2	1	0.63
Adair & Jaeger, 2014	concept (J.2)	lecture + lab	Y	N	Y	N	Y	Y	SR	1	2	0.67
Philpot et al., 2005	inertia quiz	lecture	Y	N	N	N	N	Y	EF	2	1	0.79
Rodriguez et al., 2006	Y.4 complex	lecture + lab + technology	Y	Y	Y	N	Y	Y	SR	6	3	0.84
Butz et al., 2006	lab	lecture + lab	Y	Y	N	Y	Y	Y	EF	4	3	0.95
Gokhale, 1996	test problems	lecture + lab	Y	Y	Y	N	N	Y	KR	2	3	1.00
Rodriguez et al., 2006	Y.2 knowledge	lecture + lab + technology	Y	N	N	N	N	Y	SR	6	3	1.00
Westerfield et al., 2015	gain	lecture + lab + technology	Y	Y	Y	N	Y	Y	EF	2	2	1.04
Butz et al., 2006	IMITS	lecture + lab	Y	Y	N	Y	Y	Y	EF	4	3	1.28
Westerfield et al., 2015	time	lecture + lab + technology	N	Y	Y	Y	N	Y	EF	2	2	1.37
Aydin & Cagiltay, 2012	lab	lecture + lab	Y	N	N	Y	N	Y	KR	1	1	1.42
AlNajdi et al., 2018	exam (outlier)	lecture + lab	Y	N	Y	N	Y	Y	SR	1	1	2.88

with this outcome and other outcomes, we decided to remove this outlier (AlNajdi et al., 2020) and its single outcome to avoid over-estimates of the contribution of scaffolding to learning. Thus, all subsequent analyses used a slightly lower final number of studies (k = 13) and outcomes (n = 27).

Publication Bias

The tendency of a journal to publish a study based upon the studies' positive and statistically significant results, as opposed to the overall quality, is called publication bias. In meta-analyses, publication bias may lead to an inflation of effect size estimates of a particular intervention since it increases the likelihood of including studies with positive results (Egger et al., 1997; Peters et al., 2006). In order to test whether our analyses were at risk of publication bias, we conducted an Egger's Regression and a visual inspection of a funnel plot. The Egger's test found no relationship between standard error and effect size $t(26) = 1.14$, $p = 0.27$, which suggests there was no publication bias among the included articles in this meta-analysis (see Table 3.6). Importantly, there was no statistically significant publication bias without the outlier as shown below or with the outlier kept in. We also visually inspected funnel plots which showed important variables such as the control condition, feedback type, and threats to validity. The latter is described in more detail below.

Visual inspection of the funnel plot (see Figure 3.2), with Egger's regression line (shown in yellow), clearly shows a lack of publication bias which aligns with the regression-based significance test above. Note that in Figure 3.2 the single outlier has already been removed.

Table 3.6

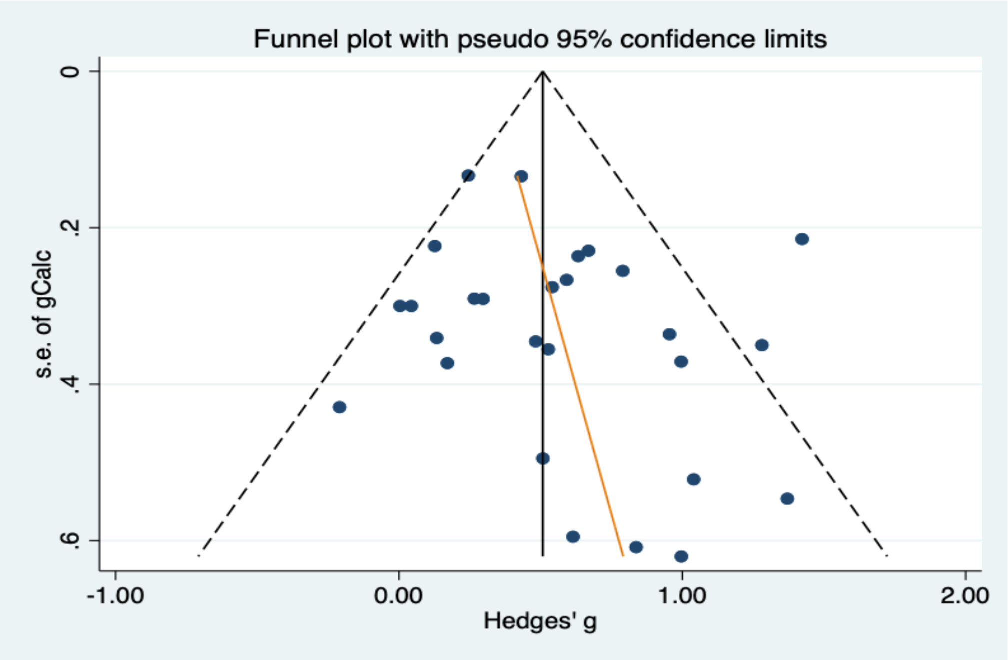
Results of Egger's Regression Analysis for Publication Bias

					95% CI	
Coefficient	Standard error	*n*	*t*	*p*	Lower	Upper
0.77	0.68	27	1.14	.798	-0.62	2.16

Note: n refers to the number of included outcomes; CI = confidence interval.

Figure 3.2

Funnel Plot with Pseudo 95% Confidence Limits



Effect Size Dependency

After the exclusion of one study/outcome outlier (AlNajdi et al., 2020), twenty-seven outcomes from thirteen studies were included in this meta-analysis. Five of the included studies had a single outcome (Aydin & Cagiltay, 2012; W. Chen & Levinson, 2006; Hundhausen et al., 2011; Kumar et al., 2007; Weusijana et al., 2004) and the other eight studies had more than one included outcome. Of the eight studies with multiple outcomes, five contributed two outcomes (Adair & Jaeger, 2014; Butz et al., 2006; Finkelstein et al., 2005; Gokhale, 1996; Philpot et al., 2005), two studies had three outcomes (Rodriguez et al., 2006; Westerfield et al., 2015), and one study had six outcomes (Parchman et al., 2000). All five studies with multiple included outcomes violate the independence assumptions of the subsequent analyses. Rather than drop all or some of this data, especially given the interest in individual and combinations of scaffolding forms, we decided to check for effect size interdependence through robust variance estimation (RVE). Using RVE, we simulated results to test a range of assumptions for intra-class correlation between studies and outcomes. They range from outcomes having a strong relationship (Rho = 0.99) to the study of origin or outcomes as completely independent of the study of origin (Rho = 0.00). We found that there was no difference to four significant digits in simulated effect sizes, suggesting the nesting of the data can be ignored (Hedges et al., 2010). As a result, all outcomes were included in the analyses.

Study Quality

To determine if study quality contributed to effect size differences, we ran a meta-regression of two combined predictors (internal threats and external threats to validity) on Hedges' *g*. The model accounts for relatively little variation ($R^2 = .047$) in effect size estimates and is not statistically significant $F(2, 24) = 2.26$, $p = 0.13$. As a result, a determination was made to keep all of the outcomes in the study.

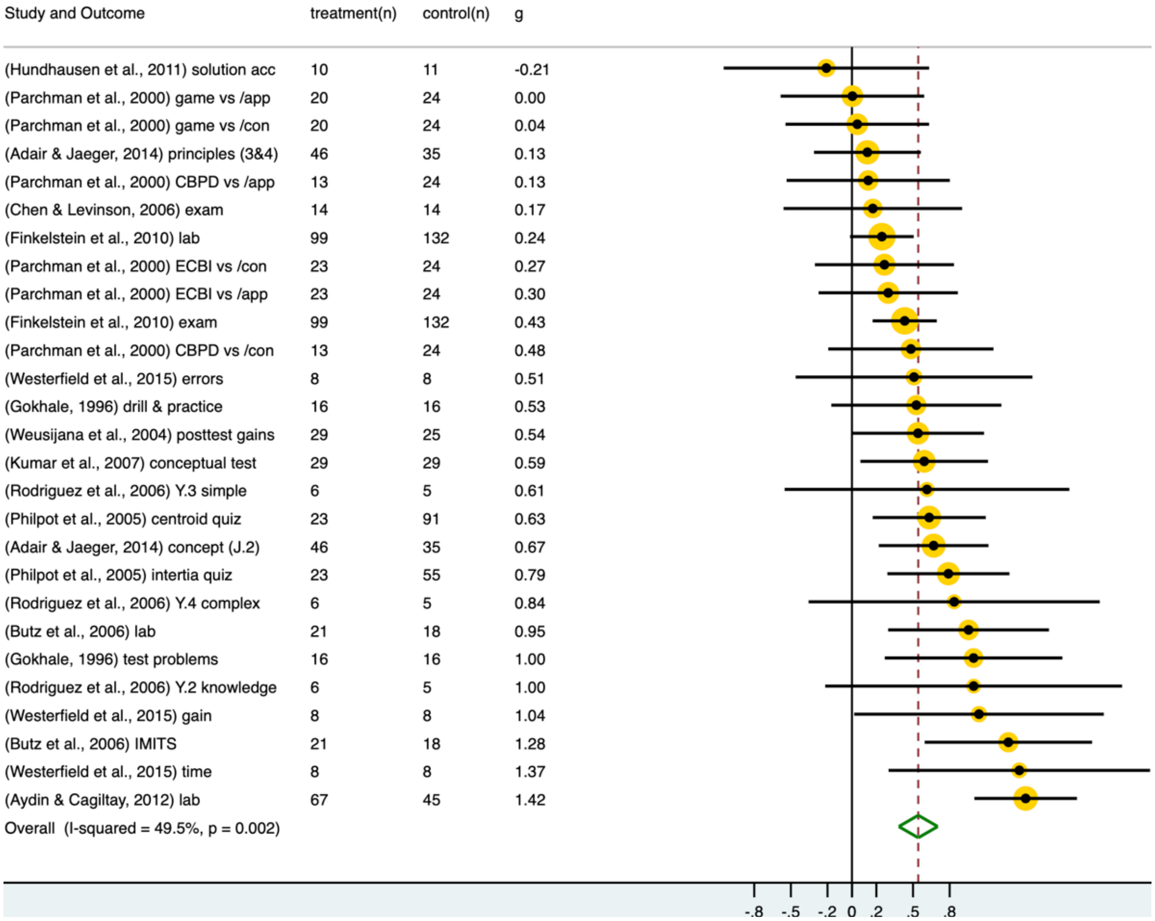
Results

RQ1 - What is the overall contribution of computer-based scaffolding on engineering learning gains and how much variability is present in the findings?

Figure 3.3 includes individual point estimates for each outcome, the overall effect size estimate, and 95% confidence intervals across all estimations. There is a considerable range among the effect size estimates. The mean effect size for all outcomes was *g* = 0.54 which would be considered a medium effect size according to Cohen

Figure 3.3

Forrest Plot of All Outcomes



Study and Outcome	treatment(n)	control(n)	g
(Hundhausen et al., 2011) solution acc	10	11	-0.21
(Parchman et al., 2000) game vs /app	20	24	0.00
(Parchman et al., 2000) game vs /con	20	24	0.04
(Adair & Jaeger, 2014) principles (3&4)	46	35	0.13
(Parchman et al., 2000) CBPD vs /app	13	24	0.13
(Chen & Levinson, 2006) exam	14	14	0.17
(Finkelstein et al., 2010) lab	99	132	0.24
(Parchman et al., 2000) ECBI vs /con	23	24	0.27
(Parchman et al., 2000) ECBI vs /app	23	24	0.30
(Finkelstein et al., 2010) exam	99	132	0.43
(Parchman et al., 2000) CBPD vs /con	13	24	0.48
(Westerfield et al., 2015) errors	8	8	0.51
(Gokhale, 1996) drill & practice	16	16	0.53
(Weusijana et al., 2004) posttest gains	29	25	0.54
(Kumar et al., 2007) conceptual test	29	29	0.59
(Rodriguez et al., 2006) Y.3 simple	6	5	0.61
(Philpot et al., 2005) centroid quiz	23	91	0.63
(Adair & Jaeger, 2014) concept (J.2)	46	35	0.67
(Philpot et al., 2005) intertia quiz	23	55	0.79
(Rodriguez et al., 2006) Y.4 complex	6	5	0.84
(Butz et al., 2006) lab	21	18	0.95
(Gokhale, 1996) test problems	16	16	1.00
(Rodriguez et al., 2006) Y.2 knowledge	6	5	1.00
(Westerfield et al., 2015) gain	8	8	1.04
(Butz et al., 2006) IMITS	21	18	1.28
(Westerfield et al., 2015) time	8	8	1.37
(Aydin & Cagiltay, 2012) lab	67	45	1.42
Overall (I-squared = 49.5%, p = 0.002)			

(1988). To offer some perspective, an effect of this size would mean that roughly 33% of the experimental condition population distribution would exceed the control condition on the same measured outcomes. As suggested by Fritz et al. (2012), it is imperative that effect sizes are interpreted within the context of the field of research in which they are found. For example, in the medical field where life is on the line, very small effect sizes are of considerable value (Fritz et al., 2012). Within the context of educational research, an effect size of 0.54 is on the larger side according to Kraft (2020). This effect size is in alignment with effect size estimates from previous meta-analyses (Belland, Walker, Kim, & Lefler, 2017; Doo et al., 2020; N. J. Kim et al., 2018; Kulik & Fletcher, 2015) on computer-based scaffolding which ranges from (g = .39) (N. J. Kim et al., 2018) to (g = .89) (Chernikova, Heitzmann, Fink, et al., 2020) and further supports the idea that computer-based scaffolding is an effective intervention for boosting the learning outcomes. This overall effect size has further substantiated the value of computer-based scaffolding. More importantly, the variability ($I^2 = 49.5\%$) in both effect size estimates and precisions of those estimates across outcomes suggests additional factors are at play which warrant subsequent analysis. Gaining insights into which computer-based scaffolding forms or combinations of scaffolding forms produce the largest learning gains is clearly warranted.

RQ2 - To what extent do single computer-based scaffolding forms make individual contributions to collegiate student engineering learning gains?

We ran a series of pairwise comparisons for each of the scaffolding forms to determine if their presence or absence was associated with variations in student learning outcomes (see Table 3.7). Whether present or not, computer-based scaffolding is consistently associated with improvements in student learning when compared to regular classroom instruction and laboratory experiences. None of the scaffolding forms showed significant differences ($\alpha = 0.05$) when a single form was present or not in an outcome. Pairwise comparison results between the presence of any two scaffolding forms also did not contain any statistically significant differences.

Table 3.7

Presence/Absence of Scaffolding Forms

Scaffolding Feature (*n* = yes)	Yes *g*(*se*)	No *g*(*se*)
Cues Highlights (8)	0.37(0.13)	0.53(0.06)
Question Prompts (10)	0.44(0.10)	0.54(0.06)
Modeling (14)	0.54(0.09)	0.49(0.06)
Visualizations (23)	0.51(0.06)	0.47(0.15)
Prompts/Hints (9)	0.60(0.11)	0.48(0.06)
Structuring (21)	0.56(0.07)	0.42(0.08)

Note. No statistically significant difference between presence (yes) and absence (no) of the scaffolding feature.

It is important to note that among included studies, control groups were in the same courses as the experimental scaffolding conditions. None of the included outcomes were from experiments with control populations that did not receive instruction or participate in instructional tasks. Despite the fact that the control students participated in the same courses, received the same lectures, and in almost a third of the cases (*n* = 8) conducted similar labs while using the same technology but without scaffolds (Adair & Jaeger, 2014), further accentuates the power of scaffolding to produce statistically significant learning outcomes in engineering tasks. It also potentially explains why there was a lack of differentiation between individual scaffolding feature outcomes (see Table 3.7). Another likely explanation for the lack of significant pairwise comparisons between computer-based scaffolding forms is that the forms were rarely used in isolation.

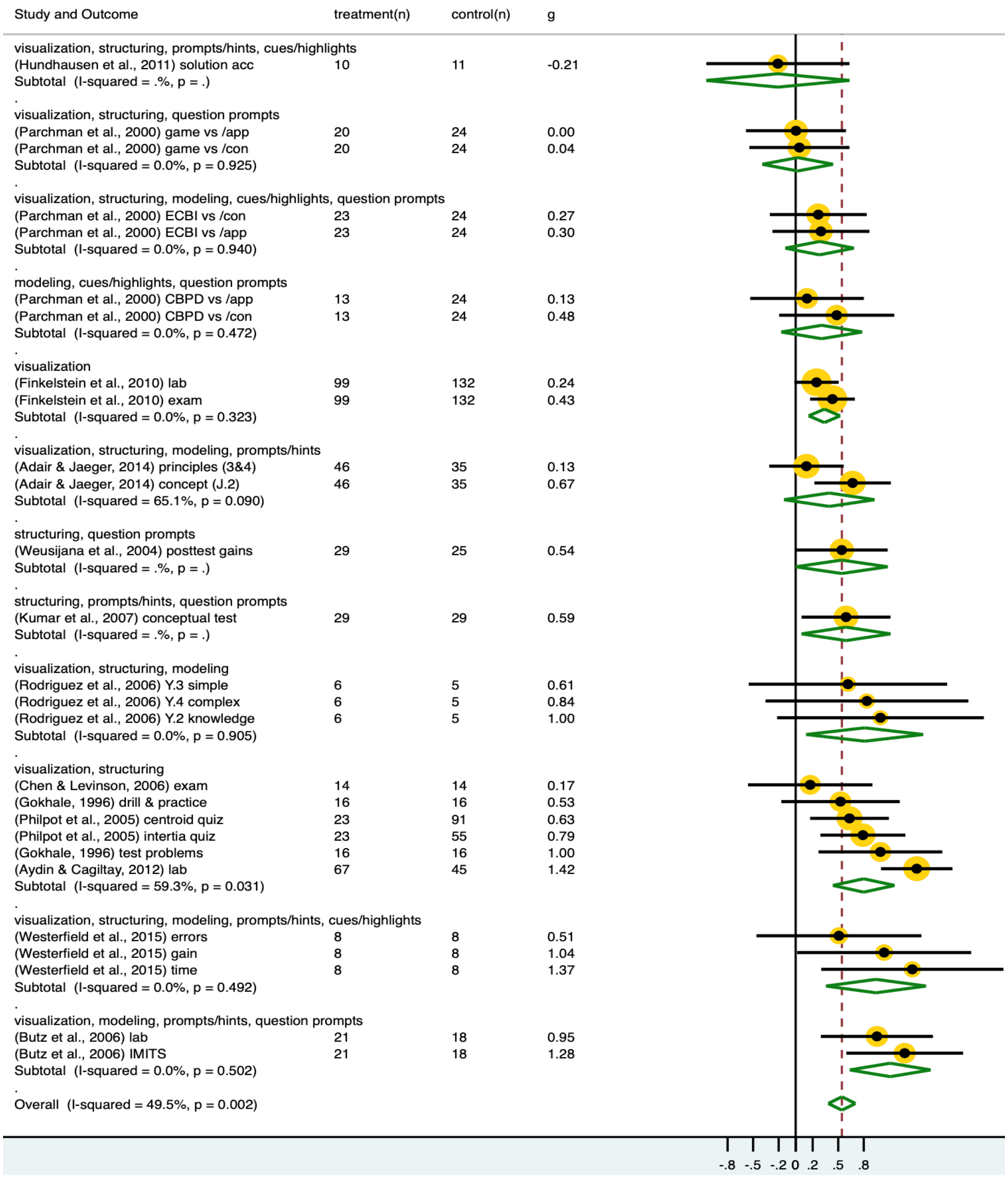
> RQ3 - Which combinations of computer-based scaffolding forms, as observed in individual studies, make contributions to collegiate student engineering learning gains?

Across the thirteen included studies, we observed 12 different combinations of scaffolding forms (see Figure 3.4). There was almost a one-to-one match between the number of included studies and the number of different scaffolding combinations. Out of the 12 different scaffolding combinations, visualization (9/12) and structuring (7/12) were the most frequently present forms. Prompts/hints (4/12) and cues/highlights (3/12) were least frequent forms included in scaffolding combinations. The only scaffolding feature combinations that showed up across more than one study was "structuring+ visualizations," which showed up in four included studies (Aydin & Cagiltay, 2012; W. Chen & Levinson, 2006; Gokhale, 1996; Philpot et al., 2005).

We conducted pairwise comparisons between the various combinations of computer-based scaffolding interventions. The Hedge's $\bar{g}$ estimates from the different scaffolding feature combinations ranged from $\bar{g} = -0.21$ to $\bar{g} = 1.11$ (see Table 3.8). All scaffolding combinations were positively correlated with engineering student learning outcomes except for one condition "structuring+prompts/hints+cues/highlights+ visualization" (Hundhausen et al., 2011). The largest effect size ($\bar{g} = 1.11$, $p = .01$) resulted from experimental conditions with "modeling+prompts/hints+question prompts+visualization" (Butz et al., 2006).

Figure 3.4

Graphic Summaries for Overall Effects of Computer-Based Scaffolding Combinations



Study and Outcome	treatment(n)	control(n)	g
visualization, structuring, prompts/hints, cues/highlights			
(Hundhausen et al., 2011) solution acc	10	11	-0.21
Subtotal (I-squared = .%, p = .)			
.			
visualization, structuring, question prompts			
(Parchman et al., 2000) game vs /app	20	24	0.00
(Parchman et al., 2000) game vs /con	20	24	0.04
Subtotal (I-squared = 0.0%, p = 0.925)			
.			
visualization, structuring, modeling, cues/highlights, question prompts			
(Parchman et al., 2000) ECBI vs /con	23	24	0.27
(Parchman et al., 2000) ECBI vs /app	23	24	0.30
Subtotal (I-squared = 0.0%, p = 0.940)			
.			
modeling, cues/highlights, question prompts			
(Parchman et al., 2000) CBPD vs /app	13	24	0.13
(Parchman et al., 2000) CBPD vs /con	13	24	0.48
Subtotal (I-squared = 0.0%, p = 0.472)			
.			
visualization			
(Finkelstein et al., 2010) lab	99	132	0.24
(Finkelstein et al., 2010) exam	99	132	0.43
Subtotal (I-squared = 0.0%, p = 0.323)			
.			
visualization, structuring, modeling, prompts/hints			
(Adair & Jaeger, 2014) principles (3&4)	46	35	0.13
(Adair & Jaeger, 2014) concept (J.2)	46	35	0.67
Subtotal (I-squared = 65.1%, p = 0.090)			
.			
structuring, question prompts			
(Weusijana et al., 2004) posttest gains	29	25	0.54
Subtotal (I-squared = .%, p = .)			
.			
structuring, prompts/hints, question prompts			
(Kumar et al., 2007) conceptual test	29	29	0.59
Subtotal (I-squared = .%, p = .)			
.			
visualization, structuring, modeling			
(Rodriguez et al., 2006) Y.3 simple	6	5	0.61
(Rodriguez et al., 2006) Y.4 complex	6	5	0.84
(Rodriguez et al., 2006) Y.2 knowledge	6	5	1.00
Subtotal (I-squared = 0.0%, p = 0.905)			
.			
visualization, structuring			
(Chen & Levinson, 2006) exam	14	14	0.17
(Gokhale, 1996) drill & practice	16	16	0.53
(Philpot et al., 2005) centroid quiz	23	91	0.63
(Philpot et al., 2005) intertia quiz	23	55	0.79
(Gokhale, 1996) test problems	16	16	1.00
(Aydin & Cagiltay, 2012) lab	67	45	1.42
Subtotal (I-squared = 59.3%, p = 0.031)			
.			
visualization, structuring, modeling, prompts/hints, cues/highlights			
(Westerfield et al., 2015) errors	8	8	0.51
(Westerfield et al., 2015) gain	8	8	1.04
(Westerfield et al., 2015) time	8	8	1.37
Subtotal (I-squared = 0.0%, p = 0.492)			
.			
visualization, modeling, prompts/hints, question prompts			
(Butz et al., 2006) lab	21	18	0.95
(Butz et al., 2006) IMITS	21	18	1.28
Subtotal (I-squared = 0.0%, p = 0.502)			
.			
Overall (I-squared = 49.5%, p = 0.002)			

Table 3.8

Results for Scaffolding Feature Combinations

Scaffolding feature (number of significantly different forms)	*n*	*g*	*SE*
visualization, structuring, prompts/hints, cues/highlights* (3 higher)	1	-0.21	0.43
visualization, structuring, question prompts* (4 higher)	2	0.02	0.21
visualization, structuring, modeling, cues/highlights, question prompts* (2 higher)	2	0.28	0.21
modeling cues/highlights, question prompts* (1 higher)	2	0.31	0.24
visualization* (3 higher)	2	0.34	0.09
visualization, structuring, modeling, prompts/hints* (2 higher)	2	0.39	0.16
structuring, question prompts	1	0.54	0.28
structuring, prompts/hints, question prompts	1	0.59	0.27
visualization, structuring, modeling** (1 lower)	3	0.81	0.35
visualization, structuring** (5 lower)	6	0.87	0.11
visualization, structuring, modeling, prompts/hints, cues/highlights** (3 lower)	3	0.94	0.30
visualization, modeling, prompts/hints, question prompts** (6 lower)	2	1.11	0.24

*Significantly lower ($p < .05$) learning than (*n* higher) other combinations of scaffolding forms.
**Significantly higher ($p < .05$) learning than (*n* lower) other combinations of scaffolding forms.

Only two outcomes, both coming from the same article (Finkelstein et al., 2005), used a single feature (visualization). While one combination “structuring+prompts/hints, cues/highlights+visualization” had a negative effect size estimate. None of the combinations were worse than no scaffolding at a statistically significant level. Starting with visualization alone ($g = 0.34$) the rest of the scaffolding combinations were a significant improvement over control groups that completed alternative educational experiences and problem-solving tasks without scaffolding support.

The two most frequently occurring scaffolding forms: structuring ($n = 21$) and visualization (*n* = 23) had among the highest effect sizes when analyzed in isolation (see Table 3.7) but are paired with the full range of scaffolding feature combinations (see Table 3.8). These complex relationships underscore the need to examine not just isolated forms, but the combinations of forms as they exist in the literature.

With a total of 66 unique pairwise comparisons, reporting is challenging. The range of learning outcomes between the various computer-based scaffolding interventions is quite large (*g* = -0.21 to *g* = 1.11) suggesting that the combination of scaffolding forms may play a large role in outcomes. Table 3.8 shows the six scaffolding feature combinations from “visualization+structuring+prompts/hints+cues/ highlights” (*g* = -0.21) to “visualization+structuring+modeling+prompts/hints” (*g* = 0.39) with significantly lower learning gains over control when compared to at least one other combination of scaffolding forms. By contrast the top four combinations from “visualization+structuring+modeling” (g = 0.81) to “visualization+modeling+prompts/ hints+question prompts” (*g* = 1.11) exhibited better learning gains than at least one other combination of scaffolding forms. Though there are several detectable differences, there are three single outcome combinations and only three combinations that have three or more outcomes, suggesting a need for additional research.

Limitations

Hedges et al. (2010) suggest that RVE is a reliable tool for measuring effect size dependency in meta-analyses that included as few as 20-40 studies and possibly less. However, this study only included thirteen studies. We suggest that a larger meta-analysis should be conducted to see if the RVE matches these results. Of note, we did consider alternative approaches such as combining outcomes or dropping multiple outcomes (Cooper et al., 2009) and did not want to omit data, especially given the risk of obscuring or skewing results.

One of the major limitations of meta-analyses is that they neither include all relevant empirical research nor do they account for (code) all relevant intervention forms (Cooper et al., 2009). This study only included computer-based scaffolding interventions at the collegiate level. Results showed that computer-based scaffolding interventions were consistently statistically positive and effective at raising cognitive learning outcomes. However, the intent of this study was to cast light on which types of scaffolds (as well as combinations of scaffolds) led to the greatest cognitive gains. Computer-based scaffolding has been used as an intervention in collegiate engineering courses. Researchers have evaluated the effects of scaffolding supports such as prompts/hints, modeling, structuring, cues/highlights as well as visualizations, on engineering cognitive outcomes. The results of this meta-analysis indicate that computer-based scaffolding interventions are highly effective (*g* = .53) at raising cognitive outcomes in collegiate level engineering courses.

Discussion

The overall effect size estimate from this study (*g* = .53) is consistent from other meta-analyses on computer-based scaffolding and cognitive outcomes. This effect size estimate is slightly higher than a random effects meta-analysis (*g* = .46) on computer-based scaffolding impact on cognitive outcomes in STEM education broadly (Belland, Walker, Kim, & Lefler, 2017). These results are also higher than a Bayesian meta-analysis on computer-based scaffolding interventions (*g* = .39) during complex problem solving in STEM content areas (N. J. Kim et al., 2018). However, other meta-analyses of intelligent tutoring systems (*g* = .66) (Kulik & Fletcher, 2015) and scaffolding interventions with higher education online learners have shown higher effect sizes (*g* = .89) (Chernikova, Heitzmann, Fink, et al., 2020). It is becoming increasingly clear that computer-based scaffolding interventions create large learning gains in even the most difficult problem-solving tasks.

Where this study departs from other recent analyses is its attempt to tease out the effects of single forms and combinations of scaffolding forms. While previous computer-based scaffolding meta-analyses (Belland et al., 2015; Belland, Walker, & Kim, 2017; Belland, Walker, Kim, & Lefler, 2017; Cai et al., 2022; Chernikova, Heitzmann, Fink, et al., 2020; Chernikova, Heitzmann, Stadler, et al., 2020; Doo et al., 2020; N. J. Kim et al., 2018, 2020) have shown computer-based scaffolding to be effective at producing positive learning gains, these studies mostly treated interventions globally rather than attempting to look at how individual scaffolds, or combinations of scaffolds, contributed to learning outcomes.

Results indicate that *visualization* and *structuring* scaffolds are frequently used in collegiate engineering programs. These results are substantiated by several recent meta-analyses that have investigated the intersection of *visualization* (sometimes referred to as simulation or modeling), CBLEs, and scaffolding (Chernikova, Heitzmann, Fink, et al., 2020; Lei et al., 2016). As an isolated inclusion criterion, these prior meta-analyses resulted in large effect size estimates associated with STEM learning (*g* = .82; *g* = 1.45). It is also clear that including a wider range of scaffolding forms with a narrow focus on engineering education dramatically changes that picture. In this study, *visualization* and *structuring* are part of a scaffolding form combination that actually favors control students (*g* = -0.21) and a combination that favors scaffolded students at a level that is so large (*g* = 1.11) that it is significantly greater than six other scaffolding combinations of scaffolding forms.

Our results, finding no statistically significant gains for the individual presence of any one scaffolding form, departs from other meta-analyses of scaffolded STEM learning. This prior research found significant improvements in learning associated with *modeling*, *visualizations* (Cai et al., 2022; Chernikova, Heitzmann, Fink, et al., 2020) and *prompts/hints* (Cai et al., 2022; Chernikova, Heitzmann, Fink, et al., 2020; Chernikova, Heitzmann, Stadler, et al., 2020). Across all of these meta-analyses only a single non-significant test was reported for *modeling* (Chernikova, Heitzmann, Stadler, et al., 2020) which may well reflect a similar publication bias as that of primary research. Additional research is needed to further explore these differences in findings.

Research across engineering research, as well as scaffolding research, points to the student's current expertise as the moderator of whether a scaffolding feature is a benefit or detriment to the learning process. For example, post-graduate students have been shown to benefit more from *modeling* scaffolds (i.e., worked examples) than undergraduates and graduate students when engaging simulation problem solving exercises (Chernikova, Heitzmann, Fink, et al., 2020) . Likewise, *prompts* have been found to be more beneficial for low education level students than those with higher levels of education (Chernikova, Heitzmann, Fink, et al., 2020). These varied results depend upon student competency and point towards the original principles of scaffolding (i.e., contingency and fading) as well as to cognitive load theory principles such as the expertise reversal effect (van Merriënboer & Sweller, 2005). Research on the expertise reversal effect has shown that instructional methods may work well for novices but not for experts and vice versa (Kalyuga & Singh, 2016; Renkl, 2002; Yeh et al., 2010).

Conclusion

These results suggest that combinations of scaffolding forms impact learning outcomes. We found 12 different combinations across thirteen studies. While it is clear that more work needs to be done it is noteworthy that researchers in this field are already gravitating, based on the number of outcomes, towards feature combinations associated with the highest learning gains. This natural trend towards what seems to work best for students, suggest that researchers may have additional insights about the complex relationships among scaffolding forms and how the interact with learner needs. *Structuring* and *visualization* showed up most frequently in the distributed scaffolding interventions. However, more research is needed to elucidate why specific scaffolding forms are present in scaffolding combinations that produced both the highest and lowest effect sizes. Further research is warranted to discover what nuances in these scaffolding interventions produce such dramatically different cognitive outcomes for engineering students. While additional research progresses, these results are a clear call for primary research and practice that intentionally engages in multiple scaffolding interventions (Quintana, 2021; Tabak, 2004).

CHAPTER 4

COMPUTER-BASED SCAFFOLDING: WHAT WE HAVE LEARNED AND WHAT WORK REMAINS

Purpose of Multiple Paper Dissertation

For over four decades, researchers, instructional designers, and practitioners have developed computer-based scaffolding interventions in order to help students achieve learning gains in problem-centered STEM activities. Various meta-analyses have estimated the effects of computer-based scaffolding interventions on raising learning outcomes in STEM subjects (Belland et al., 2015; Belland, Walker, & Kim, 2017; Belland, Walker, Kim, & Lefler 2017; Chernikova, Heitzmann, Fink, et al., 2020; Chernikova, Heitzmann, Stadler, et al., 2020; Doo et al., 2020; N. J. Kim et al., 2018, 2020). These meta-analyses have consistently reported the positive effects of computer-based scaffolding on learning outcomes. Effect size estimations have ranged from *g* = 0.39 (Chernikova, Heitzmann, Stadler, et al., 2020; N. J. Kim et al., 2018) to *g* = 0.88 (Chernikova, Heitzmann, Fink, et al., 2020; Doo et al., 2020).

Moderator analyses of study characteristics, participant characteristics, and intervention characteristics have been included in these same studies in an attempt to explain the wide distribution of effect sizes (Belland et al., 2015; Belland, Walker, & Kim, 2017; Belland, Walker, Kim, & Lefler, 2017; Cai et al., 2022; Chernikova, Heitzmann, Fink, et al., 2020; Chernikova, Heitzmann, Stadler, et al., 2020; Doo et al., 2020; N. J. Kim et al., 2018, 2020). Some study characteristics (i.e., validity reporting) and participant characteristics (i.e., prior knowledge) were consistently statistically significant moderators across meta-analyses (Belland et al., 2015; Belland, Walker, & Kim, 2017; Belland, Walker, Kim, & Lefler, 2017; Chernikova, Heitzmann, Stadler, et al., 2020). Among intervention characteristics, meta-analytic results found statistically significant results for fading (Belland et al., 2015; Belland, Walker, Kim, et al., 2017) and consistently nonstatistically significant results for functions of scaffolding (Belland et al., 2015; Belland, Walker, Kim, & Lefler, 2017; N. J. Kim et al., 2018, 2020).

Among the statistically significant moderators from intervention characteristics, individual forms of scaffolding have also shown promise (Cai et al., 2022; Chernikova, Heitzmann, Fink, et al., 2020; Chernikova, Heitzmann, Stadler, et al., 2020). However, despite showing statistical significance, only three meta-analyses have begun investigating and coding for scaffolding forms (Cai et al., 2022; Chernikova, Heitzmann, Fink, et al., 2020; Chernikova, Heitzmann, Stadler, et al., 2020). Only two meta-analyses have attempted to estimate the effects of combinations of scaffolding forms on learning outcomes (Cai et al., 2022; Chernikova, Heitzmann, Fink, et al., 2020). Without knowledge of which individual scaffolds or combinations of computer-based scaffolding forms produce the largest learning gains, researchers, instructional designers, and practitioners do not have the information they need to design and implement the most effective computer-based scaffolding interventions in STEM education.

One of the major reasons for this literature gap has been the language used to describe scaffolding. The popularity of the theory, the influx of scaffolding research, the expansion of scaffolding to new content areas/age groups, and the development of new computer-based scaffolds have brought the theoretical construct to a place where its overgrowth of jargon is impeding progress (Pea, 2004). In particular, researchers have criticized the initial six functions of scaffolding claiming that they represent both the form of the scaffold as well as its intended impact on the learner (van de Pol et al., 2010). Consequently, there have been calls for a simple taxonomy of scaffolding forms descriptive enough to account for the types of scaffolding found in current literature (Belland, Walker, & Kim, 2017; Lajoie, 2005; Quintana, 2021; Tabak, 2004).

The overall purpose of this research was to take a few steps toward discovering which individual scaffolds, or combinations of scaffolding forms, produce the largest learning gains in STEM education. This was accomplished through two papers. The first paper illustrated the language issues that have thwarted previous moderator analyses. Through a systematic review of extant research literature, a new lexicon of scaffolding forms was generated. The second paper applied this new lexicon as a moderator in a meta-analysis of computer-based scaffolding intervention effects on collegiate engineering learning. The results, key insights, and limitations of these two studies will be discussed in the following sections.

Discussion

The first paper sought to answer (a) What terms have researchers used to describe the tutorial actions and the intended effects in prior syntheses and seminal works on scaffolding, (b) Is there consistency among the terms employed, and (c) What are the forms of computer-based scaffolding in extant experimental computer-based scaffolding literature in STEM fields?

Similar to other educational theories that have experienced dramatic expansion and overgrowth of theory jargon, these research questions were answered through a systematic review of scaffolding literature (Alexander et al., 1991; Dinsmore, 2017, 2017; Dinsmore et al., 2008; Loughlin & Alexander, 2012).

Systematic Review to Disambiguate Scaffolding Form and Scaffolding Function

The vocabulary employed by researchers to characterize the tutorial actions (appearance of the scaffold) and intended outcome of computer-based scaffolds were analyzed through a two-step coding process (Charmaz, 2014; Saldaña, 2012). Paying close attention to nouns, sixteen terms were found, categorized by what they defined (tutorial action or intended effect), and then sorted in terms of frequency.

This systematic review of scaffolding terminology for Chapter 2 - RQ1 resulted in three key insights. First, scaffolding researchers perceive the form and function of scaffolding as two separate constructs as evidenced by researchers frequently employing separate terms within the same articles (Quintana, 2021; Sharma & Hannafin, 2007; Zheng, 2016). Second, there is a lack of consistency among this terminology usage. Polysemy, the use of a single term to have multiple meanings, exists with respect to the terms researchers have used for the form (tutorial assistance) and function (intended effect) of scaffolding. For example, four terms (functions, types, strategies, and mechanisms) were used by researchers to refer to both the tutorial action as well as to its intended outcome. Last, a ranking of term frequency showed that researchers are coalescing around two terms for the scaffolding characteristics: scaffolding form and scaffolding function. Scaffolding form describes the tutorial action of the teacher. In other words, the form is the appearance (or package) that the tutorial assistance takes as it is delivered to the students. Scaffolding function was the term most used by researchers to refer to the intent of the scaffolding support (e.g., metacognitive, motivational, strategic, etc.) on the student.

This polysemy has been criticized by researchers for decades and likely began with the Wood et al. (1976) original list of "functions," which did not distinguish between the appearance of the tutorial help and the scaffold's intended outcome on the student. Researchers have used the terms interchangeably to describe both the form and function of a scaffold. This has caused confusion and inhibited the ability of researchers to communicate clearly with one another.

Systematic Review of Scaffolding Forms– Building a Taxonomy

With the form and function disambiguated, the next objective of this research was to develop a simple taxonomy of scaffolding forms that was powerful enough to characterize the forms of computer-based scaffolding found in extant STEM literature. Despite calls from scaffolding theorists (Belland, 2014; Chernikova, Heitzmann, Fink, et al., 2020; Tabak, 2004; van de Pol et al., 2010; Zheng, 2016), the majority of previous meta-analyses have not included the form of the scaffold as a moderator (Belland et al., 2015; Belland, Walker, Kim, & Lefler, 2017). The few meta-analyses that have included scaffolding form as a moderator (Cai et al., 2022), struggled to distinguish between the various forms found in included empirical literature. Instead of coding each form of scaffold separately, researchers employed catch-all coding categories for anything outside their coding framework (i.e., “mixed” and “others”; Cai et al., 2022, p. 556).

Specifically, Chapter 2 – RQ2 sought to answer, “What are the forms of computer-based scaffolding in extant experimental computer-based scaffolding literature in STEM fields”? To answer this research question, a taxonomy of scaffolding forms was generated through a systematic literature review of empirical STEM research. Rather than add even more language to the construct, the intent of this analysis was to have experimental literature in STEM education reveal the forms of computer-based scaffolding that have been evaluated for the past four decades. Through a four-stage systematic coding process that started with in-vivo coding and ended with axial coding, six forms of computer-based scaffolding were identified (Charmaz, 2014; Saldaña, 2012). These were (a) *structuring*, (b) *modeling*, (c) *prompts*, (d) *cues/highlights*, *visualization*, and (e) *formative feedback*.

Structuring

Of the scaffolds found through this systematic review, structuring might be one of the most distinct forms of scaffolding. The other scaffolding forms are added to the problem space in the form of a *hint*, *prompt*, *cue*, *model*, etc. However, instead of being offered to the student as a help, *structuring* scaffolds manipulate the problem itself by narrowing the focus of the problem (Linn & Eylon, 2000; M. Liu, 2004; Zhang et al., 2004), offloading tasks from the student (Butz et al., 2006), or strategically increasing the complexity of problems over time in order to ensure success (de Jong et al., 1996).

Modeling

Another form of scaffolding found in literature was modeling. Whether it was a full expert solution of the final product (de Jong et al., 1996; Devolder et al., 2012) or a partially worked example (Laru et al., 2012), modeling guided STEM learners toward the solution. Modeling is highly aligned to one of the original scaffolds enumerated by Wood et al. (1976) titled “demonstration” (p. 98). A potential issue facing the term *modeling*, is that it refers to two different activities within the realm of education. For language arts researchers, modeling refers to the activity of a teacher providing an example (Palincsar & Brown, 1984). However, for certain content areas such as STEM subjects, modeling is a student activity where systems are simulated (Dori et al., 2003; Finkelstein et al., 2005; Gijlers & Jong, 2013). For the sake of simplicity, it may behoove researchers to substitute *expert examples* or *worked examples* as the chosen term for modeling in order to avoid future confusion.

Prompts

Prompts are verbal messages, often delivered via text, that provide directional and supportive guidance to students. In this systematic review, prompts were the most frequently coded type of scaffolding form in extant research. Prompts varied in tone and delivery, ranging from directive command prompts (Mayer et al., 2002; Roscoe et al., 2013), to question prompts (H. Y. Chang & Linn, 2013), to the most open-ended type of prompts known as hints which were also usually self-selected by the students (Butz et al., 2006; Graesser et al., 2007; Mendicino et al., 2009; VanLehn, 2011).

Cues/Highlights

Originally referred to as “marking critical features,” cues/highlights are another scaffolding form that is highly aligned to the original work of Wood et al. (1976, p. 98). The intention of *cues/highlights* was to direct the attention of the learner towards salient features necessary to the solution of the problem. For example, highlights were placed in strategic areas on tissue sample images to assist students diagnose diseases (Nivala et al., 2012). *Cues/highlights* were similar to *prompts* in intention but were different in terms of medium as they showed up as visual or auditory messages instead of written text (Nivala et al., 2012).

Visualizations/Simulations

Visualization scaffolds were found ubiquitously among science and engineering literature. These scaffolds assisted students by making previously inaccessible content, accessible (Nichols et al., 2013). For example, these scaffolds employed technology to see and experience phenomena beyond space, time, and the constraints of the student’s senses (Yoon et al., 2012). *Visualizations* included a subgroup form called simulations. In these cases, *simulations* compressed phenomena that would normally take extraordinary amounts of time into just a few seconds such as observing a stellar parallax (Ruzhitskaya, 2011). Visualization scaffolds also gave students power to control and visualize the impact of variables on complex systems such as an ecosystem (Basu et al., 2015). Of the forms found in Chapter 2, *visualization* was the newest scaffold brought about by advancements in technology (Quintana, 2021; Soloway et al., 1994).

Formative Feedback

As found in literature, f*eedback* varied as to whether it was immediately provided to students (AlNajdi et al., 2020; Gokhale, 1996; Philpot et al., 2005) or delayed (Afriyie-Adams, 2020; Corbett & Anderson, 2001; Gweon et al., 2007). *Feedback* also varied in how much support was provided to the student. *Feedback* came in several varieties such as (a) providing results without an indication of correctness and leaving interpretation up to the student (Ulicsak, 2004), (b) providing a correct/incorrect message with no interpretation/indication of what was wrong (Van der Kleij et al., 2015), (c) providing a correct/incorrect message with an explanation of what was incorrect (Pareto et al., 2011), and (d) providing a correct/incorrect response, explanation, and an additional scaffold to help the student try again and find success (Hundhausen et al., 2011). Finally, *feedback* can be paired with scaffolding forms. For instance, a simulation visualization might be used to provide *feedback* for a problem solution attempt.

Key Insights

This systematic review of scaffolding terminology for RQ2 resulted in five key insights. First, there are generally six forms of computer-based scaffolds found in literature. These are *structuring*, *modeling*, *prompts*, *cues/highlights*, *visualizations/ simulations*, and *formative feedback*. Second, three of the forms found here (*structuring*, *modeling*, and *cues/highlights*) map directly back to the original scaffolds enumerated by Wood et al. (1976; i.e., reduction in degrees of freedom, demonstration, and marking critical features). Third, in alignment with scaffolding theorists (Quintana, 2021; Soloway et al., 1994), advances in technology have brought about new forms of computer-based scaffolding such as visualizations and simulations. Fourth, *feedback* is both a part of the scaffolding process as well as a scaffolding form. Fifth, there is considerable depth to each type of scaffolding. For example, *prompts* ended up having at least three types of sub-forms which differed with regards to their delivery and power.

Meta-Analysis of Scaffolding Forms on Collegiate Engineering Learning Outcomes

The second research study (Chapter 3) sought to answer (a) What is the overall contribution of computer-based scaffolding on engineering learning gains and how much variability is present in the findings, (b) To what extent do single computer-based scaffolding forms make individual contributions to collegiate student engineering learning gains, and (c) Which combinations of computer-based scaffolding forms, as observed in individual studies, make contributions to collegiate student engineering learning gains? These questions were addressed through a random effect meta-analysis of 27 outcomes from 13 studies that measured the effects of computer-based scaffolding on collegiate learning outcomes.

The Overall Contribution of Computer-Based Scaffolding

After the exclusion of an outlier, Chapter 3 – RQ1 sought to quantify and visualize the mean effect ($g = 0.54$) and variability of computer-based scaffolding. This is considered a medium (J. Cohen, 1988) or large effect depending on interpretation (Kraft, 2020). The $g = 0.54$ effect size is right in the middle of effect size estimations for computer-based scaffolding across varied content areas (Belland et al., 2015; Belland, Walker, & Kim, 2017; Belland, Walker, Kim, & Lefler, 2017; Cai et al., 2022; Chernikova, Heitzmann, Stadler, et al., 2020, 2020; Doo et al., 2020). Notably, it is slightly higher than the majority mean effect sizes from previous STEM education focused meta-analyses (Belland et al., 2015 ($g = 0.53$); Belland, Walker, Kim, & Lefler, 2017 ($g = 0.46$); N. J. Kim et al., 2018 ($g = 0.39$), 2020 ($g = 0.46$)). Furthermore, it provides further evidence that scaffolding may produce larger outcomes in engineering fields which was also reported by Kim et al., (2018). Individual point estimates have a wide range ($g = 0.21$ to 1.42) even after outlier removal. Point estimate outcomes in conjunction with a large degree of heterogeneity ($I^2 = 49.5\%$), warrants further moderator analyses to look for systematic sources of variation between scaffolding combinations.

Estimating the Effects of Individual Scaffolding Forms

Next, the new taxonomy of scaffolding forms developed in Chapter 2 was applied as a moderator in a traditional meta-analysis of collegiate engineering education in Chapter 3. For Chapter 3 – RQ2, Individual scaffolding forms were analyzed to see if any of the moderators had a statistically significant impact on effect size estimations. While there were point estimate variations between the presence and absence of individual scaffolding forms, none of the differences were statistically significant. There were also not significant differences between any scaffolding form pairs when they were present. *Prompts/hints*, *visualization*, and *modeling* had higher if nonsignificant effect size estimates when present, which parallels the findings of other meta-analysis (Cai et al., 2022; Chernikova, Heitzmann, Fink, et al., 2020; Chernikova, Heitzmann, Stadler, et al.,

2020) showing promise for these scaffolding forms. *Structuring* (*g* = 0.56 when present and *g* = 0.42 when absence) had the largest mean difference and both *question prompts* and *cues/highlights* showed lower effect sizes when present. Again, none of these pairwise comparisons were statistically significant.

Estimating the Effects of Combinations of Scaffolding Forms

Finally, the impact of scaffolding combinations on collegiate engineering learning outcomes was investigated in Chapter 3 – RQ3. Twelve different scaffolding combinations were found among included articles. Results of pairwise comparisons found a total of 15 significant differences between scaffolding form combinations. Those combinations exhibited a large range of estimates from *g* = -0.21 (Hundhausen et al., 2011) to *g* = 1.11 (Butz et al., 2006). Among the 12 different combinations of scaffolding forms found in research, no single scaffolding form was systematically associated with more or less effective scaffolding combinations. In fact, the same forms of scaffolding (i.e., *visualization*, *modeling*, *prompts/hints*) were present in treatment conditions with the largest and smallest effect sizes.

Despite the lack attribution to and single form of scaffolding, the fifteen cases of significant differences as well as the broad distribution of effect size estimations among interventions suggests that the combinations do indeed matter. Furthermore, researchers appear to be naturally coalescing around the combinations of forms that are the most effective. The third most effective scaffolding combination (visualization+structuring) also happened to be the scaffolding combination most prevalent in the literature included in this study (Aydin & Cagiltay, 2012; W. Chen & Levinson, 2006; Gokhale, 1996; Philpot et al., 2005). From the limited perspective of included studies, this may suggest that practitioners, researchers, and designers are choosing the most efficacious combinations of scaffolding.

Key Outcomes

Three main insights were found through the meta-analysis of computer-based scaffolding. First, similar to other meta-analyses, computer-based scaffolding continues to produce medium/large effects on engineering learning gains. Second, in contrast to other meta-analyses, no statistically significant effects were found for a more comprehensive set of individual scaffolding forms in isolation. Third, while no statistically significant results were found for scaffolding combinations. Effect size estimations ranged from *g* = -0.21 (Hundhausen et al., 2011) to 1.11 (Butz et al., 2006). This broad distribution of effect size estimates suggests that further analyses of combinations of scaffolding forms is strongly warranted, perhaps with a larger sample of studies.

Limitations and Suggestions for Future Research

Decisions were made that limit the ability of this study to be generalized. This study (a) included only STEM research and STEM education outcomes for the meta-analysis, (b) investigated only the impact of scaffolding on learning, (c) constrained its view to scaffolding forms and their combinations, and (d) did not code for all essential aspects of the scaffolding theory. The following sections provide explanations for each of these limitations and the corresponding solution to be applied in future research.

Dependent Variable Constraints

Both the systematic review (Chapter 2) and meta-analysis (Chapter 3) included experimental research that focused on the impact of computer-based scaffolding on learning outcomes. There were many excluded studies that estimated the effects on scaffolding on non-cognitive outcomes (e.g., self-regulation, self-efficacy, motivation, interest). Future systematic reviews should investigate the possibility of other forms of computer-based scaffolding that have been developed to bolster other dependent variables. Analyses of this type may lead to new understanding of how forms of computer-based scaffolding make differential contributions to the experiences of learners.

Content Area Constraints

The systematic review of computer-based scaffolding forms in Chapter 2 was constrained to STEM content areas. The meta-analysis in Chapter 3 was constrained even further to include only collegiate engineering outcomes. Previous meta-analyses on computer-based scaffolding have included more science, mathematics, and medical outcomes than engineering (Belland et al., 2015; Belland, Walker, & Kim, 2017; Belland, Walker, Kim, & Lefler, 2017; Cai et al., 2022; Chernikova, Heitzmann, Fink, et al., 2020; Chernikova, Heitzmann, Stadler, et al., 2020; N. J. Kim et al., 2018, 2020). In addition to applying these results to other STEM subjects beyond engineering, a systematic review of computer-based scaffolding outside of STEM content areas may reveal new types of scaffolding forms. Likewise, the results of Chapter 3 will be bolstered by future meta-analyses which are expanded to include other disciplines inside or outside of STEM.

Investigate Interplay of Scaffolding and Feedback

A glaring disconnect between Chapter 2 and Chapter 3 is the presence and then absence of feedback as a scaffolding form. This disconnect was purposeful. During the systematic literature review in Chapter 2, it was found that feedback acted as both a form as well as an integral part of the scaffolding process. Four different variations of *feedback* were found in Chapter 2. During the article coding phase of Chapter 3, it became clear that tackling the complex relationship between other scaffolding forms and *feedback* was beyond the scope of this paper. This was primarily due to a conflation between certain *feedback* types with other forms of scaffolding. For example, the *feedback* provided by simulations was coded both as NIF (no intentional feedback) and as the *visualization* scaffolding form. NIF was coded when students received uninterpreted results of their simulation/visualization exercises. An example of this double coding happened when students were engaged in simulating circuits in Parchman et al. (2000). In this intervention, students received the *visualization* scaffolding form as well as NIF *feedback* from the simulation (Parchman et al., 2000). In other instances, EF (elaborated feedback) overlapped with other computer-based scaffolding forms. In Westerfield et al. (2015), students were supplied with *feedback* after each motherboard assembly attempt. However, this *feedback* came in the form of “detailed feedback hints” (Westerfield et al., 2015, p. 164) which would have required the same feature to be coded under two separate scaffolding forms. These instances, where *feedback* and scaffolding forms merged, have been referred to as formative feedback (Shute, 2008; Van der Kleij et al., 2015). Given the focus on scaffolding forms, a decision was made to not add these non-orthogonal and highly dependent *feedback* variations to the analysis, especially given the small degrees of freedom. Future research should focus on describing this relationship and estimating its effects on learning.

Reductionist Nature of Meta-analysis Coding

One of the consistent criticisms of meta-analyses is the reductionist nature of the coding process. Depending on the focus of the research, meta-analytic researchers choose which characteristics of the scaffolding intervention they will investigate. In many cases, this results in an oversimplification of the original study's characteristics.

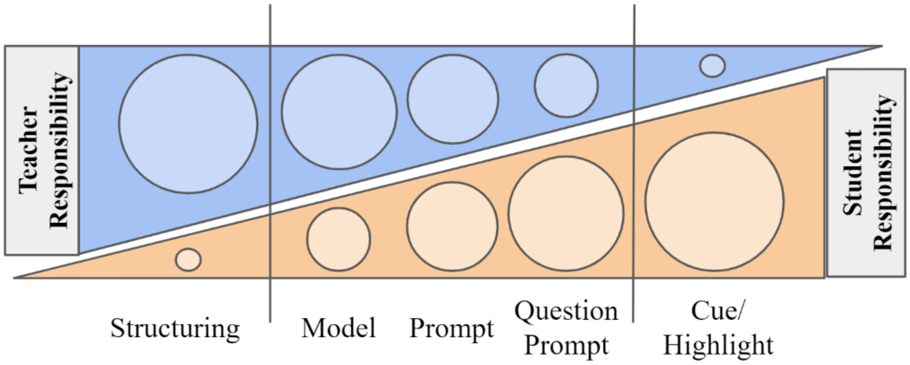
The most powerful contribution of this dissertation was its attempt to dramatically expand the coding structure for scaffolding interventions. Previous meta-analyses have focused on other moderators other than scaffolding form or only coded a single form. In contrast, this research attempted to code all of the scaffolding forms found in computer-based scaffolding interventions. However, coding an expanded set of scaffolding forms is still a gross oversimplification of what is happening in scaffolding interventions. Each form of scaffold has nuances of how it is added/faded from the learning environment, how many times it is used, or even how long it is available to students. Future research estimating the effect of scaffolding forms should also include these critical details especially considering that previous meta-analyses have found statistically significant differences for how the scaffold is added/faded (Belland et al., 2015; Belland, Walker, Kim, & Lefler, 2017). Now that knowledge of scaffolding forms has been expanded, revisiting the relationships of forms and how each scaffold is customized over time can be accomplished.

A Theory for Scaffolding Forms

The systematic literature review of scaffolding forms followed a four-step coding process of grounded theory but stopped short of providing an overarching theory for how the forms relate with one another or their relationship to the overall theory of scaffolding. When looking at the forms from the context of transfer of responsibility, a picture starts to form for how each form relates to one another and the scaffolding theory. Each scaffold varies in two ways: how much support it provides and how much responsibility the teacher or student has over the scaffold. A structuring scaffold often rests entirely under the responsibility of the teacher and exercises a tremendous amount of influence over the learning environment. Conversely, a self-selected hint is less impactful and within the control of a student. When placed on a continuum from full teacher responsibility to full student responsibility, the form of the scaffold itself becomes a step in the process of gradual release/transfer of responsibility (see Figure 4.1).

Figure 4.1

Scaffolding Forms as a Transfer of Responsibility



Scaffolding is a process whereby skills and knowledge are transferred from the teacher to the student until the student has internalized the knowledge and taken full responsibility over the task completion. When multiple forms are mapped onto *transfer of responsibility* in order of their strength of support, an interrelated picture begins to emerge between scaffolding form, transfer of responsibility, and fading. Several examples of this emerged during the review of included studies. In one study, in which students learned about sorting algorithms, the CBLE provided students a "fading mode" where the system reduced both the form (hints, visualizations, teacher explanations, and feedback) as well as the frequency of scaffold until the students were able to solve the problems independently (Yin et al., 2013). In some cases, transfer was realized through multiple forms of the same type of scaffold. In these cases, the same scaffold varied in terms of strength. For example, in one study worked examples of mathematical steps were delivered to students. Students started with a complete model and then slowly faded to models that demonstrated just a few steps towards the solution (Renkl et al., 2004). In this study, the various forms of the modelling scaffold became the fading function. Future research should focus on the interrelationship between the various individual form of scaffolding as well as the relationship of the scaffolding form to the foundational principles of scaffolding (i.e., contingency, transfer of responsibility, and fading).

Forms versus Tools

CBLEs offer a mixture of support to students. In addition to delivering computer-based scaffolding, CBLEs provide tools such as calculators, information databases, and virtual laboratories to students as they solve STEM problems (H. Y. Chang & Linn, 2013). These tools cannot be internalized or faded over time, and as such, should not be considered as scaffolding. Technological tools were not included as a scaffolding form or moderator in Chapter 3. However, the effect of these tools on learning should be included in future meta-analyses.

Recommendations for Researchers

In addition to the research mentioned above, there are several keyways in which researchers can aid future meta-analytic work. This research came about mainly due to language issues facing the theoretical construct of scaffolding. Progress towards finding out which forms or combinations of scaffolding forms produce the greatest outcomes in learners will be highly dependent on the language researchers employ in future scaffolding research. I offer the following suggestions.

Adopt a Simplified Language for Scaffolding

Scaffolding researchers have called for a common language (Pea, 2004; Quintana, 2021). Utilizing the constructs of scaffolding form and function accurately and consistently will help clear up confusion. Additionally, researchers will assist the theory by adopting and adapting the six forms of scaffolding found in this research to new experimental research and meta-analyses. This will ensure that researchers clearly articulate the essential characteristics of their scaffolding interventions. It will also ensure that meta-analysts can code the interventions in future syntheses. Last, a common taxonomy of scaffolding forms will allow researchers to compare results between meta-analyses.

Include Robust Descriptions of Scaffolds

Devolder et al. (2012) conducted a systematic review of scaffolding for self-regulated learning in CBLEs. The authors expressed a criticism of scaffolding literature stating that "in most studies, no attention was paid to the design characteristics of scaffolds, which are of relevance in reaching conclusions about the research data" (Devolder et al., 2012, p. 565). After conducting the systematic review and meta-analysis included in this dissertation, I echo these sentiments. The most frequent threat to validity in the included meta-analysis was the inadequate descriptions of the scaffolding interventions. The capacity of a meta-analysis to accurately estimate the effects of an intervention are dependent on robust descriptions of the intervention. Research of scaffolding should include an ample description of each scaffold's form, function, duration of use, frequency of use, and how it is added/faded. Better experimental research will allow for better meta-analyses.

Conclusion

The results of this research show that the form and function of scaffolding have been conflated. Through this research, six distinct forms of computer-based scaffolding in STEM education were developed. These results add to previous meta-analytic research showing that computer-based scaffolding consistently provides a positive impact on STEM learning gains. This research also provided insights into which individual scaffolds or combinations of computer-based scaffolds may produce the largest learning gains. While no statistically significant outcomes were found, the range of outcomes strongly suggests that individual scaffolds, as well as combinations of computer-based scaffolds, do impact engineering learning outcomes differently.

This research also sheds light on areas within scaffolding literature where more attention is needed. The forms of computer-based scaffolding listed here should be applied to computer-based scaffolding literature that include non-cognitive outcomes, different age groups, and different content areas outside of STEM. Additionally, now that a taxonomy of computer-based scaffolding forms exists, more work is needed to investigate the relationships between forms of scaffolding as well as the relationship of scaffolding form to the essential principles of the scaffolding theory such as contingency, fading, and transfer of responsibility.

REFERENCES

Adair, D., & Jaeger, M. (2014). Integration of computational fluid dynamics into a fluid mechanics curriculum. *Computer Applications in Engineering Education*, *22*(1), 131–141. https://doi.org/10.1002/cae.20539

Adamson, D., & Rosé, C. P. (2013). Academically productive talk: One size does not fit all. *AIED 2013 Workshops Proceedings*, 51-60.

Afriyie-Adams, M. (2020). *MathConceptz: An experimental design to improve math performance* [Doctoral dissertation, Rutgers The State University of New Jersey]. https://www.proquest.com/docview/2433253961/abstract/919E8622924038PQ/1

Alexander, P. A., Schallert, D. L., & Hare, V. C. (1991). Coming to terms: How researchers in learning and literacy talk about knowledge. *Review of Educational Research*, *61*(3), 315–343. https://doi.org/10.3102/00346543061003315

AlNajdi, S. M., Alrashidi, M. Q., & Almohamadi, K. S. (2020). The effectiveness of using augmented reality (AR) on assembling and exploring educational mobile robot in pedagogical virtual machine (PVM). *Interactive Learning Environments*, *28*(8), 964–990. https://doi.org/10.1080/10494820.2018.1552873

Austin, D., Gilkison, A., & Clemons, J. (2020). Turning reflection into learning: A practice development tool for midwifery students. *Reflective Practice*, *21*(3), 301–315. https://doi.org/10.1080/14623943.2020.1738370

Aydin, E., & Cagiltay, N. (2012). A new RF and microwave engineering course enriched with advanced technologies. *Computer Applications in Engineering Education*, *20*(4), 634–645.

Azevedo, R., & Hadwin, A. F. (2005). Scaffolding self-regulated learning and metacognition–Implications for the design of computer-based scaffolds. *Instructional Science*, *33*(5), 367–379.

Azevedo, R., & Jacobson, M. J. (2008). Advances in scaffolding learning with hypertext and hypermedia: A summary and critical analysis. *Educational Technology Research and Development*, *56*(1), 93–100.

Bandara, W., Miskon, S., & Fielt, E. (2011). A systematic, tool-supported method for conducting literature reviews in information systems. *ECIS 2011 Proceedings [19th European Conference on Information Systems]:* 1–13.

Basu, S., Sengupta, P., & Biswas, G. (2015). A scaffolding framework to support learning of emergent phenomena using multi-agent-based simulation environments. *Research in Science Education*, *45*(2), 293–324.

Beekhuyzen, J. (2007). Putting the pieces of the puzzle together: Using Nvivo for a literature review. *Proceedings of QualIT2007: Qualitative Research, From the Margins to the Mainstream, Wellington, New Zealand, Victoria University of Wellington*, 18–20.

Belland, B. R. (2014). Scaffolding: Definition, current debates, and future directions. In J. M. Spector, M. D. Merrill, J. Elen, & M. J. Bishop (Eds.), *Handbook of research on educational communications and technology* (pp. 505–518). Springer. http://link.springer.com/chapter/10.1007/978-1-4614-3185-5_39

Belland, B. R., Kim, C. M., & Hannafin, M. J. (2013). A framework for designing scaffolds that improve motivation and cognition. *Educational Psychologist*, *48*(4), 243–270. https://doi.org/10.1080/00461520.2013.838920

Belland, B. R., Walker, A. E., & Kim, N. J. (2017). A Bayesian network meta-analysis to synthesize the influence of contexts of scaffolding use on cognitive outcomes in STEM education. *Review of Educational Research*, *87*(6), 1042–1081. https://doi.org/10.3102/0034654317723009

Belland, B. R., Walker, A. E., Kim, N. J., & Lefler, M. (2017). Synthesizing results from empirical research on computer-based scaffolding in STEM education: A meta-analysis. *Review of Educational Research*, *87*(2), 309–344. https://doi.org/10.3102/0034654316670999

Belland, B. R., Walker, A. E., Olsen, M. W., & Leary, H. (2015). A pilot meta-analysis of computer-based scaffolding in STEM education. *Journal of Educational Technology & Society*, *18*(1), 183–197.

Besterfield-Sacre, M., Atman, C. J., & Shuman, L. J. (1997). Characteristics of freshman engineering students: Models for determining student attrition in engineering. *Journal of Engineering Education*, *86*(2), 139–149. https://doi.org/10.1002/j.2168-9830.1997.tb00277.x

Bloom, B. S. (1984). The 2-sigma problem: The search for methods of group instruction as effective as one-to-one tutoring. *Educational Researcher*, 4–16.

Borenstein, M., Hedges, L. V., Higgins, J. P. T., & Rothstein, H. R. (2021). *Introduction to meta-analysis*. John Wiley & Sons.

Bostwick, J. A., Calvert, I. W., Francis, J., Hawkley, M., Henrie, C. R., Hyatt, F. R., Juncker, J., & Gibbons, A. S. (2014). A process for the critical analysis of instructional theory. *Educational Technology Research and Development*, *62*(5), 571–582. https://doi.org/10.1007/s11423-014-9346-5

Botelho, W. T., Marietto, M. das G. B., Ferreira, J. C. da M., & Pimentel, E. P. (2016). Kolb's experiential learning theory and Belhot's learning cycle guiding the use of computer simulation in engineering education: A pedagogical proposal to shift toward an experiential pedagogy. *Computer Applications in Engineering Education*, *24*(1), 79–88. https://doi.org/10.1002/cae.21674

Collins, A., Brown, J. S., and Newman, S. E. (1989). Cognitive apprenticeship: Teaching the crafts of reading, writing, and mathematics. In L. B. Resnick (Ed.), *Knowing, learning, and instruction: Essays in honor of Robert Glaser* (pp. 453-494). Erlbaum.

Bulu, S. T., & Pedersen, S. (2010). Scaffolding middle school students' content knowledge and ill-structured problem solving in a problem-based hypermedia learning environment. *Educational Technology Research & Development*, *58*(5), 507–529. https://doi.org/10.1007/s11423-010-9150-9

Butz, B. P., Duarte, M., & Miller, S. M. (2006). An intelligent tutoring system for circuit analysis. *IEEE Transactions on Education*, *49*(2), 216–223. https://doi.org/10.1109/TE.2006.872407

Cai, Z., Mao, P., Wang, D., He, J., Chen, X., & Fan, X. (2022). Effects of scaffolding in digital game-based learning on student's achievement: A three-level meta-analysis. *Educational Psychology Review*, 34, 537-574.

Chang, H. Y., & Linn, M. (2013). Scaffolding learning from molecular visualizations. *Journal of Research in Science Teaching*, *50*(7), 858–886. https://doi.org/10.1002/tea.21089

Chang, K., Sung, Y., & Chen, S. (2001). Learning through computer-based concept mapping with scaffolding aid. *Journal of Computer Assisted Learning*, *17*(1), 21–33. https://doi.org/10.1046/j.1365-2729.2001.00156.x

Charmaz, K. (2014). *Constructing grounded theory*. SAGE.

Chen, J., Kolmos, A., & Du, X. (2021). Forms of implementation and challenges of PBL in engineering education: A review of literature. *European Journal of Engineering Education*, *46*(1), 90–115. https://doi.org/10.1080/03043797.2020.1718615

Chen, W., & Levinson, D. M. (2006). Effectiveness of learning transportation network growth through simulation. *Journal of Professional Issues in Engineering Education and Practice*, *132*(1), 29–41. https://doi.org/10.1061/(ASCE)1052-3928(2006)132:1(29)

Chen, Y. S., Kao, T. C., & Sheu, J. P. (2003). A mobile learning system for scaffolding bird watching learning. *Journal of Computer Assisted Learning*, *19*, 347–359. https://doi.org/10.1046/j.0266-4909.2003.00036.x

Chernikova, O., Heitzmann, N., Fink, M. C., Timothy, V., Seidel, T., Fischer, F., & DFG Research group COSIMA. (2020). Facilitating diagnostic competences in higher education—A meta-analysis in medical and teacher education. *Educational Psychology Review*, *32*(1), 157–196. https://doi.org/10.1007/s10648-019-09492-2

Chernikova, O., Heitzmann, N., Stadler, M., Holzberger, D., Seidel, T., & Fischer, F. (2020). Simulation-based learning in higher education: A meta-analysis. *Review of Educational Research*, *90*(4), 499–541. https://doi.org/10.3102/0034654320933544

Chi, M. T., Siler, S. A., Jeong, H., Yamauchi, T., & Hausmann, R. G. (2001). Learning from human tutoring. *Cognitive Science*, *25*(4), 471–533. https://doi.org/10.1207/s15516709cog2504_1

Chinn, C. A., & Duncan, R. G. (2021). Inquiry and learning. In R. G. Duncan & C. A. Chinn (Eds.), *International Handbook of Inquiry and Learning* (pp. 1-14). Routledge.

Cho, K., & Schunn, C. D. (2007). Scaffolded writing and rewriting in the discipline: A web-based reciprocal peer review system. *Computers & Education*, *48*(3), 409–426. https://doi.org/10.1016/j.compedu.2005.02.004

Cohen, A., & Scardamalia, M. (1998). Discourse about ideas: Monitoring and regulation in face-to-face and computer-mediated environments. *Interactive Learning Environments*, *6*(1–2), 93–113. https://doi.org/10.1076/ilee.6.1.93.3610

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Erlbaum.

Cohen, L., Manion, L., & Morrison, K. (2011). *Research methods in education* (7th ed.). Routledge. https://doi.org/10.4324/9780203720967

Collins, J., & Fauser, B. (2005). Balancing the strengths of systematic and narrative reviews. *Human Reproduction Update*, *11*(2), 103–104. https://doi.org/10.1093/humupd/dmh058

Cooper, H. (2015). *Research synthesis and meta-analysis: A step-by-step approach*. SAGE.

Cooper, H., Hedges, L. V., & Valentine, J. C. (2009). *The handbook of research synthesis and meta-analysis*. Russell Sage Foundation.

Corbett, A. T., & Anderson, J. R. (2001). Locus of feedback control in computer-based tutoring: Impact on learning rate, achievement and attitudes. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 245–252. https://doi.org/10.1145/365024.365111

de Jong, T., Härtel, H., Swaak, J., & vanJoolingen, W. (1996). Support for simulation-based learning: The effect of assignments in learning about transmission lines. In A. D. de I. Sánchez & I. F. de Castro (Eds.), *Computer aided learning and instruction in science and engineering* (pp. 9–26). Springer.

Devolder, A., van Braak, J., & Tondeur, J. (2012). Supporting self-regulated learning in computer-based learning environments: Systematic review of effects of scaffolding in the domain of science education. *Journal of Computer Assisted Learning*, *28*(6), 557–573.

Di Gregorio, S. (2000, September 29-30). *Using Nvivo for your literature review* [Paper presentation]. Meeting of the Strategies in Qualitative Research: Issues and Results from the Analysis Using QSR NVivo and NUD*IST. Conference at the Institute of Education, London.

Dinsmore, D. L. (2017). Toward a dynamic, multidimensional research framework for strategic processing. *Educational Psychology Review*, *29*(2), 235–268. https://doi.org/10.1007/s10648-017-9407-5

Dinsmore, D. L., Alexander, P. A., & Loughlin, S. M. (2008). Focusing the conceptual lens on metacognition, self-regulation, and self-regulated learning. *Educational Psychology Review*, *20*(4), 391–409. https://doi.org/10.1007/s10648-008-9083-6

Doo, M. Y., Bonk, C., & Heo, H. (2020). A meta-analysis of scaffolding effects in online learning in higher education. *International Review of Research in Open and Distributed Learning*, *21*(3), 60–80. https://doi.org/10.19173/irrodl.v21i3.4638

Dori, Y. J., Barak, M., & Adir, N. (2003). A web-based chemistry course as a means to foster freshmen learning. *Journal of Chemical Education*, *80*, 1084–1092. https://doi.org/10.1021/ed080p1084

Egger, M., Smith, G., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *BMJ*, *315*(7109), 629–634. https://doi.org/10.1136/bmj.315.7109.629

Eris, O., Chachra, D., Chen, H. L., Sheppard, S., Ludlow, L., Rosca, C., Bailey, T., & Toye, G. (2010). Outcomes of a longitudinal administration of the persistence in engineering survey. *Journal of Engineering Education*, *99*(4), 371–395. https://doi.org/10.1002/j.2168-9830.2010.tb01069.x

Fayer, S., Lacey, A., & Watson, A. (2017). *BLS spotlight on statistics: STEM occupations - past, present, and future*. https://ecommons.cornell.edu/handle/1813/79240

Finkelstein, N. D., Adams, W. K., Keller, C. J., Kohl, P. B., Perkins, K. K., Podolefsky, N. S., Reid, S., & LeMaster, R. (2005). When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment. *Physical Review Special Topics - Physics Education Research*, *1*(1), 010103. https://doi.org/10.1103/PhysRevSTPER.1.010103

Fritz, C. O., Morris, P. E., & Richler, J. J. (2012). Effect size estimates: Current use, calculations, and interpretation. *Journal of Experimental Psychology: General*, *141*(1), 30–30. https://doi.org/10.1037/a0026092

Ge, X., & Land, S. M. (2003). Scaffolding students' problem-solving processes in an ill-structured task using question prompts and peer interactions. *Educational Technology Research and Development*, *51*(1), 21–38. https://doi.org/10.1007/BF02504515

Geisinger, B. N., & Raman, D. R. (2013). Why they leave: Understanding student attrition from engineering majors. *International Journal of Engineering Education*, *29*(4), 914.

Gijlers, H., & Jong, T. de. (2013). Using concept maps to facilitate collaborative simulation-based inquiry learning. *Journal of the Learning Sciences*, *22*, 340–374. https://doi.org/10.1080/10508406.2012.748664

Gokhale, A. A. (1996). Effectiveness of computer simulation for enhancing higher order thinking. *Journal of Industrial Teacher Education*, *33*(4), 36-46.

Graesser, A. C., Wiley, J., Goldman, S. R., O'Reilly, T., Jeon, M., & McDaniel, B. (2007). SEEK web tutor: Fostering a critical stance while exploring the causes of volcanic eruption. *Metacognition & Learning*, *2*(2/3), 89–105. https://doi.org/10.1007/s11409-007-9013-x

Grossnickle, E. M. (2016). Disentangling curiosity: Dimensionality, definitions, and distinctions from interest in educational contexts. *Educational Psychology Review*, *28*(1), 23–60. https://doi.org/10.1007/s10648-014-9294-y

Guzdial, M. (1994). Software-realized scaffolding to facilitate programming for science learning. *Interactive Learning Environments*, *4*(1), 001–044. https://doi.org/10.1080/1049482940040101

Gweon, G., Rose, C., & Albright, E. (2007). *Evaluating the effect of feedback from a CSCL problem solving environment on learning, interaction, and perceived interdependence*. https://repository.isls.org//handle/1/3341

Hadwin, A. F., & Winne, P. H. (2001). CoNoteS2: A software tool for promoting self-regulation. *Educational Research and Evaluation*, *7*(2–3), 313–334. https://doi.org/10.1076/edre.7.2.313.3868

Hannafin, M., Land, S., & Oliver, K. (1999). Open-ended learning environments: Foundations, methods, and models. In C. M. Reigeluth (Ed.), *Instructional-design theories and models: Volume II: A new paradigm of instructional theory* (pp. 115–140). Lawrence Erlbaum Associates.

Haro, A. V., Noroozi, O., Biemans, H., & Mulder, M. (2019). First- and second-order scaffolding of argumentation competence and domain-specific knowledge acquisition: A systematic review. *Technology, Pedagogy and Education*, *28*(3), 329–345. https://doi.org/10.1080/1475939X.2019.1612772

Hartman, H., & Hartman, M. (2006). Leaving engineering: Lessons from Rowan University's college of engineering. *Journal of Engineering Education*, *95*(1), 49–61. https://doi.org/10.1002/j.2168-9830.2006.tb00877.x

Hattie, J., & Timperley, H. (2007). The power of feedback. *Review of Educational Research*, *77*(1), 81–112. https://doi.org/10.3102/003465430298487

Hedges, L. V., Tipton, E., & Johnson, M. C. (2010). Robust variance estimation in meta-regression with dependent effect size estimates. *Research Synthesis Methods*, *1*(1), 39–65. https://doi.org/10.1002/jrsm.5

Hill, J. R., & Hannafin, M. J. (2001). Teaching and learning in digital environments: The resurgence of resource-based learning. *Educational Technology Research and Development*, *49*(3), 37–52.

Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn? *Educational Psychology Review*, *16*, 235–266. https://doi.org/10.1023/B:EDPR.0000034022.16470.f3

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark. *Educational Psychologist*, *42*(2), 99–107. https://doi.org/10.1080/00461520701263368

Hundhausen, C., Agarwal, P., Zollars, R., & Carter, A. (2011). The design and experimental evaluation of a scaffolded software environment to improve engineering students' disciplinary problem-solving skills. *Journal of Engineering Education*, *100*, 574–603. https://doi.org/10.1002/j.2168-9830.2011.tb00027.x

Jackson, S. L., Krajcik, J., & Soloway, E. (1998). The design of guided learner-adaptable scaffolding in interactive learning environments. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 187–194. http://dl.acm.org/citation.cfm?id=274672

Johri, A., & Olds, B. M. (2011). Situated engineering learning: Bridging engineering education research and the learning sciences. *Journal of Engineering Education*, *100*(1), 151–185. https://doi.org/10.1002/j.2168-9830.2011.tb00007.x

Jonassen, D., Strobel, J., & Lee, C. B. (2006). Everyday problem solving in engineering: Lessons for engineering educators. *Journal of Engineering Education*, *95*(2), 139–151. https://doi.org/10.1002/j.2168-9830.2006.tb00885.x

Jumaat, N. F., & Tasir, Z. (2014). Instructional scaffolding in online learning environment: A meta-analysis. *2014 International Conference on Teaching and Learning in Computing and Engineering*, 74–77. https://doi.org/10.1109/LaTiCE.2014.22

Kali, Y., & Linn, M. C. (2008). Technology-enhanced support strategies for inquiry learning. In *Handbook of research on educational communications and technology* (pp. 145-161). Routledge.

Kalyuga, S. (2007). Expertise reversal effect and its implications for learner-tailored instruction. *Educational Psychology Review*, *19*(4), 509–539. https://doi.org/10.1007/s10648-007-9054-3

Kalyuga, S., & Singh, A.-M. (2016). Rethinking the boundaries of cognitive load theory in complex learning. *Educational Psychology Review*, *28*(4), 831–852. https://doi.org/10.1007/s10648-015-9352-0

Kermani, H. (2017). Computer mathematics games and conditions for enhancing young children's learning of number sense. *Malaysian Journal of Learning and Instruction*, *14*(2), Article 2. https://doi.org/10.32890/mjli2017.14.2.2

Kern, C. L., & Crippen, K. J. (2017). The effect of scaffolding strategies for inscriptions and argumentation in a science cyberlearning environment. *Journal of Science Education and Technology*, *26*(1), 33–43. https://doi.org/10.1007/s10956-016-9649-x

Kim, M. C., & Hannafin, M. J. (2011). Scaffolding problem solving in technology-enhanced learning environments (TELEs): Bridging research and theory with practice. *Computers & Education*, *56*(2), 403–417. https://doi.org/10.1016/j.compedu.2010.08.024

Kim, N. J., Belland, B. R., Lefler, M., Andreasen, L., Walker, A., & Axelrod, D. (2020). Computer-based scaffolding targeting individual versus groups in problem-centered instruction for STEM education: Meta-analysis. *Educational Psychology Review*, *32*(2), 415–461. https://doi.org/10.1007/s10648-019-09502-3

Kim, N. J., Belland, B. R., & Walker, A. (2018). Effectiveness of computer-based scaffolding in the context of problem-based learning for STEM education: Bayesian meta-analysis. *Educational Psychology Review*, *30*(2), 397–429. https://doi.org/10.1007/s10648-017-9419-1

Kirschner, P., & Hendrick, C. (2020). *How learning happens: Seminal works in educational psychology and what they mean in practice*. Routledge. https://doi.org/10.4324/9780429061523

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist*, *41*(2), 75–86. https://doi.org/10.1207/s15326985ep4102_1

Kraft, M. A. (2020). Interpreting effect sizes of education interventions. *Educational Researcher*, *49*(4), 241–253. https://doi.org/10.3102/0013189X20912798

Kulik, J. A., & Fletcher, J. D. (2015). Effectiveness of intelligent tutoring systems A meta-analytic review. *Review of Educational Research*, *86*(1), 42-78. https://doi.org/10.3102/0034654315581420

Kumar, R., Rosé, C. P., Wang, Y. C., Joshi, M., & Robinson, A. (2007). Tutorial dialogue as adaptive collaborative learning support. In R. Luckin & K. R. Koedinger (Eds.), *Proceedings of artificial intelligence in education* (Vol. 158, pp. 383–390). IOS Press.

Lai, M., & Law, N. (2006). Peer scaffolding of knowledge building through collaborative groups with differential learning experiences. *Journal of Educational Computing Research*, *35*(2), 123–144. https://doi.org/10.2190/GW42-575W-Q301-1765

Lajoie, S. P. (2005). Extending the scaffolding metaphor. *Instructional Science*, *33*(5–6), 541–557. https://doi.org/10.1007/s11251-005-1279-2

Lantolf, J. P. (2000). Introducing sociocultural theory. *Sociocultural Theory and Second Language Learning*, *1*, 1–26.

Laru, J., Järvelä, S., & Clariana, R. B. (2012). Supporting collaborative inquiry during a biology field trip with mobile peer-to-peer tools for learning: A case study with K-12 learners. *Interactive Learning Environments*, *20*(2), 103–117. https://doi.org/10.1080/10494821003771350

Lave, J. (1991). Situating learning in communities of practice. In L. B. Resnick, J. M. Levine, & S. D. Teasley (Eds.), Perspectives on socially shared cognition (pp. 63–82). American Psychological Association. https://doi.org/10.1037/10096-003

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge University Press.

Lei, J., Luo, P. H., Wang, Q., Shen, J., Lee, S., & Chen, Y. (2016). Using technology to facilitate modeling-based science education: Lessons learned from a meta-analysis of empirical research. *Journal of Educational Technology Development and Exchange*, *9*(2), 53-83.

Li, Q., Swaminathan, H., & Tang, J. (2009). Development of a classification system for engineering student characteristics affecting college enrollment and retention. *Journal of Engineering Education*, *98*(4), 361–376. https://doi.org/10.1002/j.2168-9830.2009.tb01033.x

Li, S. (2001). *Contingent scaffolding strategies in computer-based learning environments* (Publication Number 3024299) [Doctoral dissertation, Indiana University]. ProQuest Dissertations & Theses Full Text. http://search.proquest.com.dist.lib.usu.edu/pqdtft/docview/275805702/abstract/141E720FCD61979F6DC/28?accountid=14761

Lin, Y. N., Hsia, L. H., & Hwang, G. J. (2021). Promoting pre-class guidance and in-class reflection: A SQIRC-based mobile flipped learning approach to promoting students' billiards skills, strategies, motivation and self-efficacy. *Computers & Education*, *160*, 104035. https://doi.org/10.1016/j.compedu.2020.104035

Linn, M. C., & Eylon, B. S. (2000). Knowledge integration and displaced volume. *Journal of Science Education and Technology*, *9*, 287–310. https://doi.org/10.1023/A:1009451808539

Lipsey, M., & Wilson, D. (2000). *Practical meta-analysis (applied social research methods)*. Sage Publications.

Liu, C. C., & Chen, I. J. (2010). Evolution of constructivism. *Contemporary Issues in Education Research*, *3*(4), 63–66. https://doi.org/10.19030/cier.v3i4.199

Liu, M. (2004). Examining the performance and attitudes of sixth graders during their use of a problem-based hypermedia learning environment. *Computers in Human Behavior*, *20*, 357–379. https://doi.org/10.1016/S0747-5632(03)00052-9

Lönngren, J., Adawi, T., & Svanström, M. (2019). Scaffolding strategies in a rubric-based intervention to promote engineering students' ability to address wicked problems. *European Journal of Engineering Education*, *44*(1–2), 196–221.

https://doi.org/10.1080/03043797.2017.1404010

Lönngren, J., & van Poeck, K. (2021). Wicked problems: A mapping review of the literature. *International Journal of Sustainable Development & World Ecology*, *28*(6), 481–502. https://doi.org/10.1080/13504509.2020.1859415

Loughlin, S. M., & Alexander, P. A. (2012). Explicating and exemplifying empiricist and cognitivist paradigms in the study of human learning. In L. L'Abate (Ed.), *Paradigms in theory construction* (pp. 273–296). Springer. https://doi.org/10.1007/978-1-4614-0914-4_15

MacGregor, S. K., & Lou, Y. (2004). Web-based learning: How task scaffolding and web site design support knowledge acquisition. *Journal of Research on Technology in Education*, *37*, 161–175.

Magana, A. J. (2014). Learning strategies and multimedia techniques for scaffolding size and scale cognition. *Computers & Education*, *72*, 367–377. https://doi.org/10.1016/j.compedu.2013.11.012

Mayer, R. E., Mautone, P., & Prothero, W. (2002). Pictorial aids for learning by doing in a multimedia geology simulation game. *Journal of Educational Psychology*, *94*(1), 171–185. https://doi.org/10.1037/0022-0663.94.1.171

Mendicino, M., Razzaq, L., & Heffernan, N. T. (2009). A comparison of traditional homework to computer-supported homework. *Journal of Research on Technology in Education*, *41*, 331–359. https://doi.org/10.1080/15391523.2009.10782534

Nathan, M. J., Kintsch, W., & Young, E. (1992). A theory of algebra-word-problem comprehension and its implications for the design of learning environments. *Cognition and Instruction*, *9*(4), 329–389. https://doi.org/10.1207/s1532690xci0904_2

National Academies of Sciences, Engineering, and Medicine. (2016). *Developing a national STEM workforce strategy: A workshop summary*. https://doi.org/10.17226/21900

National Academies of Sciences & Medicine. (2022). *Imagining the future of undergraduate STEM education: Proceedings of a virtual symposium*. The National Academies Press. https://nap.nationalacademies.org/catalog/26314/imagining-the-future-of-undergraduate-stem-education-proceedings-of-a

National Governors Association Center for Best Practices, & Council of Chief State School Officers. (2010). *Common core state standards*. http://www.corestandards.org/the-standards

National Science Board. (2010). *Preparing the next generation of STEM innovators: Identifying and developing our nation's human capital* (NSB-10-33). National Science Foundation; National Science Board Report.

Nichols, K., Hanan, J., & Ranasinghe, M. (2013). Transforming the social practices of learning with representations: A study of disciplinary discourse. *Research in Science Education*, *43*(1), 179–208. https://doi.org/10.1007/s11165-011-9263-0

Nivala, M., Säljö, R., Rystedt, H., Kronqvist, P., & Lehtinen, E. (2012). Using virtual microscopy to scaffold learning of pathology: A naturalistic experiment on the role of visual and conceptual cues. *Instructional Science*, *40*(5), 799–811. https://doi.org/10.1007/s11251-012-9215-8

Palincsar, A. S. (1998). Keeping the metaphor of scaffolding fresh—A response to C. Addison Stone's "The metaphor of scaffolding: Its utility for the field of learning disabilities." *Journal of Learning Disabilities*, *31*, 370–373. https://doi.org/10.1177/002221949803100406

Palincsar, A. S., & Brown, A. L. (1984). Reciprocal teaching of comprehension-fostering and comprehension-monitoring activities. *Cognition and Instruction*, *1*, 117–175. https://doi.org/10.1207/s1532690xci0102_1

Parchman, S. W., Ellis, J. A., Christinaz, D., & Vogel, M. (2000). An evaluation of three computer-based instructional strategies in basic electricity and electronics training. *Military Psychology*, *12*, 73–87. https://doi.org/10.1207/S15327876MP1201_4

Pareto, L., Arvemo, T., Dahl, Y., Haake, M., & Gulz, A. (2011). A teachable-agent arithmetic game's effects on mathematics understanding, attitude and self-efficacy. In G. Biswas, S. Bull, J. Kay, & A. Mitrovic (Eds.), *Artificial intelligence in education* (pp. 247–255). Springer Berlin Heidelberg. http://link.springer.com/chapter/10.1007/978-3-642-21869-9_33

Pea, R. D. (2004). The social and technological dimensions of scaffolding and related theoretical concepts for learning, education, and human activity. *Journal of the Learning Sciences*, *13*(3), 423–451. https://doi.org/10.1207/s15327809jls1303_6

Pearson, P. D., & Gallagher, M. C. (1983). The instruction of reading comprehension. *Contemporary Educational Psychology*, *8*(3), 317–344.

Peters, J. L., Sutton, A. J., Jones, D. R., Abrams, K. R., & Rushton, L. (2006). Comparison of two methods to detect publication bias in meta-analysis. *Journal of the American Medical Association*, *295*(6), 676–680. https://doi.org/10.1001/jama.295.6.676

Philpot, T. A., Hall, R. H., Hubing, N., & Flori, R. E. (2005). Using games to teach statics calculation procedures: Application and assessment. *Computer Applications in Engineering Education*, *13*, 222–232. https://doi.org/10.1002/cae.20043

Pifarre, M., & Cobos, R. (2010). Promoting metacognitive skills through peer scaffolding in a CSCL environment. *International Journal of Computer-Supported Collaborative Learning*, *5*, 237–253. https://doi.org/10.1007/s11412-010-9084-6

Puntambekar, S., & Hubscher, R. (2005). Tools for scaffolding students in a complex learning environment: What have we gained and what have we missed? *Educational Psychologist*, *40*(1), 1–12. https://doi.org/10.1207/s15326985ep4001_1

Puntambekar, S., & Kolodner, J. L. (2005). Toward implementing distributed scaffolding: Helping students learn science from design. *Journal of Research in Science Teaching*, *42*(2), 185–217. https://doi.org/10.1002/tea.20048

Puntambekar, S., Stylianou, A., & Hübscher, R. (2003). Improving navigation and learning in hypertext environments with navigable concept maps. *Human-Computer Interaction*, *18*(4), 395–428. https://doi.org/10.1207/S15327051HCI1804_3

Quintana, C. (2021). Scaffolding inquiry: Reviewing and expanding on the function and form of scaffolding in inquiry learning. In R. G. Duncan & C. A. Chinn (Eds.), *International handbook of inquiry and learning* (pp. 174-188). Routledge.

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., Kyza, E., Edelson, D., & Soloway, E. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences*, *13*(3), 337–386. https://doi.org/10.1207/s15327809jls1303_4

Reiser, B. J. (2004). Scaffolding complex learning: The mechanisms of structuring and problematizing student work. *Journal of the Learning Sciences*, *13*(3), 273–304. https://doi.org/10.1207/s15327809jls1303_2

Renkl, A. (2002). Worked-out examples: Instructional explanations support learning by self-explanations. *Learning and Instruction*, *12*, 529–556. https://doi.org/10.1016/S0959-4752(01)00030-5

Renkl, A., Atkinson, R. K., & Große, C. S. (2004). How fading worked solution steps works – A cognitive load perspective. *Instructional Science*, *32*(1), 59–82. https://doi.org/10.1023/B:TRUC.0000021815.74806.f6

Rico, R., & Ertmer, P. A. (2015). Examining the role of the instructor in problem-centered instruction. *TechTrends*, *59*(4), 96–103. https://doi.org/10.1007/s11528-015-0876-4

Rodriguez, D., Sicilia, M. A., Cuadrado-Gallego, J. J., & Pfahl, D. (2006). e-Learning in project management using simulation models: A case study based on the replication of an experiment. *IEEE Transactions on Education*, *49*, 451–463. https://doi.org/10.1109/TE.2006.882367

Rogoff, B., Baker-Sennett, J., Lacasa, P., & Goldsmith, D. (1995). Development through participation in sociocultural activity. *New Directions for Child and Adolescent Development*, *1995*(67), 45–65. https://doi.org/10.1002/cd.23219956707

Roscoe, R. D., Segedy, J. R., Sulcer, B., Jeong, H., & Biswas, G. (2013). Shallow strategy development in a teachable agent environment designed to support self-regulated learning. *Computers & Education*, *62*, 286–297. https://doi.org/10.1016/j.compedu.2012.11.008

Rosenshine, B., & Meister, C. (1992). The use of scaffolds for teaching higher-level cognitive strategies. *Educational Leadership*, *49*(7), 26–33.

Ross, S. M. (2020). Technology infusion in K-12 classrooms: A retrospective look at three decades of challenges and advancements in research and practice. *Educational Technology Research and Development*, *68*(5), 2003–2020. https://doi.org/10.1007/s11423-020-09756-7

Ruzhitskaya, L. (2011). *The effects of computer-supported inquiry-based learning methods and peer interaction on learning stellar parallax* [Master's thesis, University of Missouri–Columbia]. https://mospace.umsystem.edu/xmlui/handle/10355/14226

Saldaña, J. (2012). *The coding manual for qualitative researchers*. Sage

Saye, J. W., & Brush, T. (2002). Scaffolding critical reasoning about history and social issues in multimedia-supported learning environments. *Educational Technology Research and Development*, *50*(3), 77–96. https://doi.org/10.1007/BF02505026

Savery, J. R. (2015). Overview of problem-based learning: Definitions and distinctions. *Essential Readings in Problem-Based Learning: Exploring and Extending the Legacy of Howard S. Barrows*, *9*(2), 5–15.

Sharma, P., & Hannafin, M. J. (2007). Scaffolding in technology-enhanced learning environments. *Interactive Learning Environments*, *15*(1), 27–46. https://doi.org/10.1080/10494820600996972

Sherin, B., Reiser, B. J., & Edelson, D. (2004). Scaffolding analysis: Extending the scaffolding metaphor to learning artifacts. *Journal of the Learning Sciences*, *13*(3), 387–421. https://doi.org/10.1207/s15327809jls1303_5

Shin, Y., Kim, D., & Song, D. (2020). Types and timing of scaffolding to promote meaningful peer interaction and increase learning performance in computer-supported collaborative learning environments. *Journal of Educational Computing Research*, *58*(3), 640–661. https://doi.org/10.1177/0735633119877134

Shute, V. J. (2008). Focus on formative feedback. *Review of Educational Research*, *78*(1), 153–189. https://doi.org/10.3102/0034654307313795

Snyder, T. D., de Brey, C., & Dillow, S. A. (2019). *Digest of education statistics 2018* (NCES Publication, 2020-009). U.S. Department of Education. National Center for Education Statistics, Institute of Education Sciences.

Soloway, E., Guzdial, M., & Hay, K. E. (1994). Learner-centered design: The challenge for HCI in the 21st century. *Interactions*, *1*(2), 36–48. https://doi.org/10.1145/174809.174813

Stone, C. A. (1998). The metaphor of scaffolding its utility for the field of learning disabilities. *Journal of Learning Disabilities*, *31*, 344–364. https://doi.org/10.1177/002221949803100404

Suwastini, N. K. A., Ersani, N. P. D., Padmadewi, N. N., & Artini, L. P. (2021). Schemes of scaffolding in online education. *RETORIKA: Jurnal Ilmu Bahasa*, *7*(1), Article 1. https://doi.org/10.22225/jr.7.1.2941.10-18

Swaak, J., van Joolingen, W. R., & de Jong, T. (1998). Supporting simulation-based learning; the effects of model progression and assignments on definitional and intuitive knowledge. *Learning and Instruction*, *8*(3), 235–252. https://doi.org/10.1016/S0959-4752(98)00018-8

Tabak, I. (2004). Synergy: A complement to emerging patterns of distributed scaffolding. *Journal of the Learning Sciences*, *13*(3), 305–335. https://doi.org/10.1207/s15327809jls1303_3

Thomas, J. M. (2011). *Automated scaffolding of task-based learning in non-linear game environments* (Publication No. 3463833) [Doctoral dissertation, North Carolina State University]. ProQuest Dissertations & Theses Full Text. http://search.proquest.com/pqdtft/docview/881294845/abstract/1426C9ABC3E41B17717/159?accountid=14761

Ulicsak, M. H. (2004). 'How did it know we weren't talking?': An investigation into the impact of self-assessments and feedback in a group activity. *Journal of Computer Assisted Learning*, *20*(3), 205–211. https://doi.org/10.1111/j.1365-2729.2004.00083.x

van de Pol, J., Volman, M., & Beishuizen, J. (2010). Scaffolding in teacher–student interaction: A decade of research. *Educational Psychology Review*, *22*, 271–296. https://doi.org/10.1007/s10648-010-9127-6

van de Pol, J., Volman, M., & Beishuizen, J. (2011). Patterns of contingent teaching in teacher–student interaction. *Learning and Instruction*, *21*(1), 46–57. https://doi.org/10.1016/j.learninstruc.2009.10.004

Van der Kleij, F. M., Feskens, R. C., & Eggen, T. J. (2015). Effects of feedback in a computer-based learning environment on students' learning outcomes: A meta-analysis. *Review of Educational Research*, *85*(4), 475–511. https://doi.org/10.3102/0034654314564881

van Merriënboer, J., & Sweller, J. (2005). Cognitive load theory and complex learning: Recent developments and future directions. *Educational Psychology Review*, *17*(2), 147–177. https://doi.org/10.1007/s10648-005-3951-0

VanLehn, K. (2011). The relative effectiveness of human tutoring, intelligent tutoring systems, and other tutoring systems. *Educational Psychologist*, *46*(4), 197–221. https://doi.org/10.1080/00461520.2011.611369

Vygotsky, L. S. (1978). *Mind in society*. Harvard University Press.

Westerfield, G., Mitrovic, A., & Billinghurst, M. (2015). Intelligent augmented reality training for motherboard assembly. *International Journal of Artificial Intelligence in Education*, *25*(1), 157–172. https://doi.org/10.1007/s40593-014-0032-x

Weusijana, B. K. A., Riesbeck, C. K., & Walsh, J. T., Jr. (2004). Fostering reflection with Socratic tutoring software: Results of using inquiry teaching strategies with web-based HCI techniques. *Proceedings of the 6th International Conference on Learning Sciences*, 561–567. http://dl.acm.org/citation.cfm?id=1149126.1149195

Wilson, D. B. (2022, October 3). *Practical meta-analysis effect size calculator*. CampbellCollaboration.Org. https://www.campbellcollaboration.org/escalc/html/EffectSizeCalculator-SMD-main.php

Winkler, R., Büchi, C., & Söllner, M. (2019, December 15-18). *Improving problem-solving skills with smart personal assistants: Insights from a quasi field experiment*. ICIS International Conference on Information Systems, Munich, Germany. https://www.alexandria.unisg.ch/258543/

Winters, F., Greene, J., & Costich, C. (2008). Self-regulation of learning within computer-based learning environments: A critical analysis. *Educational Psychology Review*, *20*(4), 429–444. https://doi.org/10.1007/s10648-008-9080-9

Wisniewski, B., Zierer, K., & Hattie, J. (2020). The power of feedback revisited: A meta-analysis of educational feedback research. *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.03087

Wood, D., Bruner, J. S., & Ross, G. (1976). The role of tutoring in problem solving. *Journal of Child Psychology and Psychiatry*, *17*(2), 89–100. https://doi.org/10.1111/j.1469-7610.1976.tb00381.x

Yasin, R. M., & Yunus, N. S. (2014). A meta-analysis study on the effectiveness of creativity approaches in technology and engineering education. *Asian Social Science*, *10*(3), 242–252.

Yeh, Y. F., Chen, M. C., Hung, P. H., & Hwang, G. J. (2010). Optimal self-explanation prompt design in dynamic multi-representational learning environments. *Computers & Education*, *54*(4), 1089–1100. https://doi.org/10.1016/j.compedu.2009.10.013

Yelland, N., & Masters, J. (2007). Rethinking scaffolding in the information age. *Computers & Education*, *48*(3), 362–382. https://doi.org/10.1016/j.compedu.2005.01.010

Yin, C., Song, Y., Tabata, Y., Ogata, H., & Hwang, G.-J. (2013). Developing and implementing a framework of participatory simulation for mobile learning using scaffolding. *Journal of Educational Technology & Society*, *16*(2), 137–150.

Yoon, S. A., Elinich, K., Wang, J., Steinmeier, C., & Tucker, S. (2012). Using augmented reality and knowledge-building scaffolds to improve learning in a science museum. *International Journal of Computer-Supported Collaborative Learning*, *7*(4), 519–541. https://doi.org/10.1007/s11412-012-9156-x

Zhang, J., Chen, Q., Sun, Y., & Reid, D. J. (2004). Triple scheme of learning support design for scientific discovery learning based on computer simulation: Experimental research. *Journal of Computer Assisted Learning*, *20*(4), 269–282. https://doi.org/10.1111/j.1365-2729.2004.00062.x

Zheng, L. (2016). The effectiveness of self-regulated learning scaffolds on academic performance in computer-based learning environments: A meta-analysis. *Asia Pacific Education Review*, *17*(2), 187–202. https://doi.org/10.1007/s12564-016-9426-9

Zilberman, A., & Ice, L. (2021). Why computer occupations are behind strong STEM employment growth in the 2019–29 decade. *Computer*, *4*(5,164.6), 11–15.

APPENDIX

CODING GUIDE FOR CHAPTER 3 META-ANALYSIS

Coding Guide for Chapter 3 Meta-analysis

Variable	Definition & Levels	
UID	Six Digits (4-digit article number + 2-digit coder number).	
Study Name	Short APA citation for study.	
Effect Name	Short from for what the authors characterized as the outcome.	
Treatment Name	Name to describe treatment condition.	
Control Name	Name to describe control condition.	
Control Description	Open description of control intervention.	
Control Intervention	A coded description of the control intervention based upon exposure to lecture, lab, and technology.	
	Lecture	Control experienced only lecture without lab or technology.
	Lecture+Lab	Control experienced lecture with lab activities based outside of technology (e.g., physical labs).
	Lecture+Lab+Technology	Control experienced lecture with lab activities inside the same CBLE as treatment students, but without scaffolds.
Scaffolding Forms	Temporary tutorial support provided to the student. Presence or absence of each scaffold coded as Y/N.	
	Structuring	Instructional environment manipulated by tutor in order to manage cognitive load by offloading task or to strategically manage rigor of task in a stepwise fashion. (Y/N)
	Modeling	A full/partial expert example of the correct action/final solution delivered to the student. (Y/N)
	Prompts/Hints	Verbal text delivered to the student in the form of a command or suggestion. (Y/N)
	Question Prompts	Verbal text delivered to the student in the form of a question. (Y/N)
	Cues/Highlights	Multisensory messages that direct students in what to attend to during problem solving activity (i.e., salient features). (Y/N)
	Visualization	Static or dynamic visual depiction of a phenomenon to make content accessible in terms of vision or duration. (Y/N)
Feedback Forms	A message supplied to the student as a response their submission.	
	No intentional Feedback (NIF)	Student receives results of their activity but without an indication of correctness.
	Knowledge of Results (KR)	student receives feedback on whether their response was correct or not. However, in the event that it was incorrect, the program did not reveal the correct answer.
	Knowledge of Correct Response (KCR)	student receives feedback on their response as well as the correct answer.
	Elaborated Feedback (EF)	student receives feedback on their answer, the correct answer, and additional explanation of the correct response.

Internal Threats	Evaluation of potential bias in study design, research conduct, and analyses	(0=no evidence of threat, 1=minor evidence of threat, 2=major evidence of threat that is a plausible alternative explanation for results).
	History	An event outside of the research study (such as COVID-19) was experienced differentially by the treatment and control groups. (0-2)
	Maturation	Physiological changes of participants during the time of the study or differences between the development of treatment and control groups led to performance differences. (0-2)
	Testing	Participants scores were improved by frequent exposure to test items (i.e., identical pre-posttest taken in close proximity). (0-2)
	Instrumentation	Participant performance could be explained by a variation in the assessment. (0-2)
	Statistical Regression	Differences in performance can be partially explained not as a true gain but as a regression in prior performance to the overall mean. (0-2)
	Experimental Mortality	Differential attrition between the control and treatment groups. (0-2)
	Differential Selection	The samples of the treatment and control group were systematically different (such as use of intact classrooms with the treatment as an early morning class). (0-2)
External Threats	Evaluation of study findings ability to be generalized.	(0=no evidence of threat, 1=minor evidence of threat, 2=major evidence of threat that is a plausible alternative explanation for results)
	Limited Description	The description of the experiment is poor and lacks full study characteristic details. (0-2)
	Multiple Treatment	Participants are exposed to alternative treatments (e.g., experimental condition receives more instructional time than control condition) that could explain the change in performance. (0-2)
	Experimenter Effect	The change in performance could be explained by the vested interest of the experimenter, especially in a way that would be challenging to replicate. (0-2)
Internal Threats Combined	Sum total of all internal threat ratings for a single outcome.	
External Threats Combined	Sum total of all external threat ratings for a single outcome.	

CURRICULUM VITAE

MASON REED LEFLER

EDUCATION

Utah State University, Logan, UT
Ph.D. in Instructional Technology and Learning Sciences **Fall 2022**
Dissertation: Computer-Based Scaffolding

Utah State University, Logan, UT
M.Ed. in Instructional Leadership **2016**

Arizona State University, Tempe, AZ
M.Ed. in Secondary Education **2012**

Brigham Young University, Provo, UT
B.S. in Psychology **2008**

INSTRUCTIONAL LEADERSHIP EXPERIENCE

Bridgerland Technical College, Logan, UT
Associate Vice President for Educational Innovation **2019 - Current**

Bridgerland Technical College, Logan, UT
Director of Technology Enhanced Instruction **2018 - 2019**

Bridgerland Technical College, Logan, UT
Senior Instructional Designer **2016 - 2018**

Logan City School District, Logan, UT
Leadership Intern – Wilson Elementary **Spring 2016**

Designed and led two school-wide professional development meetings aligned to the new Superintendent's district-wide initiatives on professional learning communities (PLCs) response to intervention (RTI), and data-driven-decision making (DDDM) ♦ Generated and implemented shared data spaces to facilitate weekly PLC data meetings ♦ Worked in-depth with grade-level teams to train teachers on the PLC/RTI process and to change views about common formative assessments ♦ Troubleshot ways to redesign assessment technology (MasteryConnect) to simultaneously reduce teacher workload, facilitate the PLC process, and lead to better student intervention and enrichment ♦ Generated new student learning growth data sheets to illuminate teacher pedagogical issues ♦ Evaluated direct instruction across two grade levels and provided targeted teacher feedback (modeling) ♦ Co-wrote Wilson Elementary's 2016-2017 school improvement plan based upon actionable student learning data.

TEACHING EXPERIENCE

Utah State University, Logan, UT
Adjunct Instructor – ITLS 5205/6205
"Computer Applications for Teaching and Learning " **Spring 2016**

Modified and added upon an existing project-centered curriculum to allow for more self-direction and flexibility for student interest and proficiency level ♦ Led 33 on-campus and distance students from disparate backgrounds and career trajectories through a rigorously paced learning management system ♦ Redesigned formative assessments and rubrics to enable a greater level of feedback and tutoring.

Utah State University, Logan, UT
Curriculum Designer – ITLS 6540 "Learning Theory" **Fall 2015**

Collaborated with Professor to redesign class for increased data (formative assessment), relevance, and engagement ♦ Designed and led a class on cognitive apprenticeship and socio-cultural theory.

Utah State University, Logan, UT
Teaching Assistant – ITLS 6540 "Learning Theory" **Fall 2014**

Led two classes, planned curriculum, maintained LMS course site, and graded assignments ♦ Created and implemented new student-led reciprocal review engagement strategies.

Creighton School District, Phoenix, AZ
8th/7th Grade Teacher – Reading, Mathematics, & Writing **2012 - 2013**

Piloted the districts largest one-to-one Apple i@chieve technology grant initiative with Gateway's entire 8th grade ♦ Leveraged the power of technology to simultaneously reduce teacher load and facilitate a proficiency-based (flipped mastery model) in-class instruction using standards-based reporting, standards-based formative assessment, and shared teacher-student data dashboards ♦ Designed and implemented new procedures for technology integration, increased student accountability, and maintenance of technology ♦ Collaborated with three other teachers to design and implement two new cross-curricular project-based learning units ♦ As part of the district mathematics curriculum team, generated new mathematic units for the Common Core standards ♦ Achieved double-digit growth on Arizona state's standardized summative test in Reading and Math.

Creighton School District, Phoenix, AZ

7th/8th Grade Teacher – Mathematics & Reading Interventionist **2011 - 2012**

Designed new student middle school schedule which revolved around intervention to overcome teaching licensure issues and growing lack of mathematic achievement ♦ Took full responsibility for all Reading and Mathematics intervention (reteach & enrichment) classes for 7th and 8th-grade levels ♦ Designed, implemented, and researched a yearlong, cross-curricular academic vocabulary intervention to bridge the achievement gap for our large percentage of English language learners ♦ Brought to bear a three-day "agentic" intervention to inculcate a greater sense of self-efficacy with our middle school students and to reduce apathy ♦ Participated in creating a new district-wide curriculum guides for the transition of English language arts ♦ Led an initiative for school-wide shared procedures and interventions as part of the school behavior committee ♦ Achieved double-digit growth on Arizona state's standardized summative test in Math.

Creighton School District, Phoenix, AZ

7th Grade Teacher – Reading, Writing, Reading Intervention **2010 - 2011**

Designed a new 7th grade English and Reading curriculum ♦ Invited to participate in the district's Summer Curriculum Committee to write and align district common formative assessment items to state standards and reading proficiency levels (Lexile) ♦ Achieved double-digit growth on Arizona state's standardized summative test in Reading.

Jordan School District, Sandy, UT

Continuing Education Teacher/Tutor – Spanish **2005 - 2006**

Designed a Spanish curriculum (syllabus, course, workbook, structure) for an after-school continuing education made up of students from 8 to 60+ years of age ♦ Due to demand, developed a second course, and ultimately expanded to two schools.

EXTERNAL FUNDING

Distance-Enabled Industry-Led Data Analytics Technician Pathway (ILDAP) (Award Number: 2202090). Mason Lefler (PI), Funding: National Science Foundation, ATE program, $577,503. 7/1/2022 -- 6/30/2025

Healthcare Workforce Initiative. Mason Lefler (Co-writer), Funding: Utah Talent Ready – Utah

System of Higher Education, $121,000. 6/1/2022 – Annual Ongoing

Bridgerland's Expanded Apprenticeship and Pre-apprenticeship Academy (BEAPA). Mason Lefler (PI), Funding: Utah Talent Ready – Talent Ready Connections, $455,000. 4/1/2022 – 6/30/2024

Teaching Technician Troubleshooting with Mini Industry 4.0 Factories (Award Number: 2100322). Mason Lefler (PI), Funding: National Science Foundation, ATE program, $547,981. 10/1/2021 -- 9/30/2024

Utah Data Analytics Pathway. Mason Lefler, Funding: Utah Strategic Workforce Investment, $325,000 Annually, 7/1/2021 – Annual Ongoing

Innovations in Advanced Machining Technician Education (Award Number: 2000786). Mason Lefler (PI), Funding: National Science Foundation, ATE program, $499,695. 5/1/2020 -- 4/30/2023

Core IT Statewide Stackable Credential Pathway, Kristy Bloxham & Mason Lefler, Funding: Utah Strategic Workforce Investment, $346,000 Annually, 7/1/2019 – Annual Ongoing

Controls Engineering Technician Training Through Work-based Learning. Mason Lefler, Funding: Talent Ready Utah, $225,000, 7/1/2018 – 6/30/2019

Scaling Up Utah's Automated Manufacturing Technician Pipeline (Award Number: 1801154). Mason Lefler (PI), Funding: National Science Foundation, ATE program, $225,000, 5/1/2018 -- 4/30/2021

RESEARCH EXPERIENCE

NSF Reese Grant
Graduate Researcher **2013 - 2016**
Literature Review – Meta-analytic Coding – Data Analysis – Undergraduate Researcher Mentoring

Canvalytics Research Group
Graduate Researcher **2014 - 2015**
IRB Proposal – Literature Review – Article Writing – Grant Writing

Utah STEM Initiative
Program Evaluator/Data Analyst **Summer 2014**
Evaluated STEM intelligent tutoring systems - Literature review - Proposal Writing – Evaluated technology integration at macro and micro levels.

Master's Thesis
Action Research **2011 - 2012**
Designed and piloted a 7th & 8th-grade cross-curricular academic vocabulary intervention.

FELLOWSHIPS

ECMC Foundation
2021 Career & Technical Education (CTE) Research Fellow **2021 - 2022**
Literature Review – Meta-analytic Coding – Data Analysis –
Undergraduate Researcher Mentoring

PUBLICATIONS

Kim, N. J., Belland, B. R., **Lefler, M.** et al. Computer-Based Scaffolding Targeting Individual Versus Groups in Problem-Centered Instruction for STEM Education: Meta-analysis. Educ Psychol Rev 32, 415–461 (2020). https://doi.org/10.1007/s10648-019-09502-3

Leary, H., Walker, A., **Lefler, M.**, & Kuo, Y. (2019). Self-Directed Learning in Problem-Based Learning: A Literature Review. The Wiley Handbook of Problem-Based Learning, 181-198.

Belland, B. R., Walker, A. E., Kim, N. J., & **Lefler, M.** (2017). Synthesizing results from empirical research on computer-based scaffolding in STEM education: A meta-analysis. Review of Educational Research, 87(2), 309-344.

Lee, J. E., Recker, M. M., Choi, H., Hong, W. J., Kim, N., Lee, K., **Lefler, M.**, Louviere, J., & Walker, A. (2016). Applying Data Mining Methods to Understand User Interactions within Learning Management Systems: Approaches and Lessons Learned. Journal of Educational Technology Development & Exchange, 8(2).

BOOK CHAPTERS

Leary, H., Walker, A., **Lefler, M.**, & Kuo, Y., (2019). Designing for Collaboration and Group Process in PBL Using a Learning-Centered Teaching Approach." In Hung, W., Dabbagh, N., & Moallem, M., (Eds.), Wiley Handbook of Problem-Based Learning.

Walker, A., Leary, H., & **Lefler, M**. (2015). A Meta-Analysis of Problem-Based Learning: Examination of Education Levels, Disciplines, Assessment Levels, Problem Types, Implementation Types, and Reasoning Strategies. In A. Walker, H. Leary, C. Hmelo-Silver, P. A. Ertmer (Eds.), Essential Readings in Problem-Based Learning: Exploring and Extending the Legacy of Howard S. Barrows (pp. 303-330). Lafayette, IN: Purdue University Press.

PRESENTATIONS

Lefler, M., *& Walker, A., (2022) – Forms of Computer-Based Scaffolding in Engineering Education: A Meta-Analysis*
Paper Presentation – AECT International Conference. Las Vegas,
NV **Fall 2022**

McBride, R., ***Lefler, M.,*** *Jeffers, M., & McNamee, T., (2021) – Rural Career and Technical Education: An Integrative Literature Review*
Roundtable Paper Presentation – ACTER Conference. New
Orleans, Louisiana **Fall 2021**

Lefler, M., *Diederich, M., & Hveem, J., (2021) – Determining Effectiveness between Various Rural Dual Enrollment CTE Courses Based Upon Time & Location*
Paper Presentation – AERA International Conference. Toronto,
Canada **Spring 2021**

Kim, N., Belland, B., Walker, A., & ***Lefler, M.,*** *(2016) – An Informed Synthesis of Experimental and Quasi-Experimental Computer-based Scaffolding Research*
Paper Presentation – AERA International Conference. Toronto,
Canada **Spring 2019**

Belland, B., Walker, A., Kim, N., & ***Lefler, M.,*** *(2016) – Network Meta-Analysis of Computer-based Scaffolding*
Paper Presentation – AERA International Conference.
Washington D.C. **Spring 2016**

Kim, N., & ***Lefler, M****, Belland, B., & Walker, A., (2016) – Scaffolding STEM Learning with Technology*
Roundtable – AERA International Conference. Washington D.C. **Spring 2016**

Choi et al., (2016) – Big Data Mining Methods in Learning Management Systems
Roundtable – AERA International Conference. Washington D.C. **Spring 2016**

Lefler, M., *Brasiel, S., & Felker, A. (2015) – Data Dashboards & K-12 Technology Integration*
Paper Presentation – AECT International Conference.
Indianapolis, IN **Fall 2015**

Belland, B., Walker, A., Kim, N., & ***Lefler, M.,*** *(2015) – Meta-Analysis of Computer-based Scaffolding*
Paper Presentation – AERA International Conference.
Washington D.C. **Spring 2015**

Felker, A., ***Lefler, M.,*** *& Brasiel, S., (2015) – K-12 Technology Integration*
Roundtable – SITE International Convention. Las Vegas, NV **Spring 2015**

Lefler, M.*, Belland, B., Walker, A., & Kim, N., (2014) – Scaffolding*
Paper Presentation – AECT International Conference.
Jacksonville, FL **Fall 2014**

Lefler, M. *(2014) Computer-based Scaffolding*
Oral Presentation – Graduate Research Symposium. Logan, UT **Spring 2014**
Belland, B., Walker, A., & Kim, N., & ***Lefler, M.,*** *(2014) – Scaffolding*
Poster – Cognitive Science International Conference. Canada **Spring 2014**

SERVICE/LEADERSHIP

Utah System of Higher Education (USHE), UT
UTTC Advisory Board Member – USHE Teaching Technologies Council **2018 - Present**

Utah System of Higher Education (USHE), UT
UTLG Advisory Board Member – USHE Teaching & Learning Group **2018 - Present**

Cache Makers, Logan, UT
Interim Board Member – Cache Makers **2018 - 2019**

Utah State University, Logan, UT
Doctoral Vice President - Instructional Technology Student Association **2014 - 2015**
Developed a supportive course in Canvas to aid M.S. and Ph.D. degree attainment ♦ Started a Ph.D. agraphia group ♦ Instigated the creation of two new ongoing instructional design internships with the Center for Innovative Design and Instruction ♦ Coordinated weekly professional development talks by experienced instructional designers, academic research leaders, hiring companies, educational entrepreneurs, and academic support services.

Creighton School District Leadership Academy, Phoenix, AZ
Invited Participant **2012 - 2013**
Received leadership instruction based upon district improvement plan, practiced high impact leadership practices to reduce teacher complaining, and then executed them at Gateway Elementary.

Creighton School District, Phoenix, AZ
Coach - Girls Softball/Boys Football/Boys Basketball **2010 - 2013**
Led all but one team to the district finals or semi-finals.

Pinal County Youth Leadership Camp, Oracle, AZ
Team Leader/Mentor **Winter 2008**
Inspired 20+ troubled adolescent youth to transform their lives through habits of mind, goal setting, and teamwork.

Slate Canyon Youth Detention Center, Provo, UT
Tutor - English **Fall 2007**
Spent 100 hours designing an English immersion program for three tutors of an incarcerated illegal alien.

LANGUAGES

English – native language
Spanish – speak/read fluently and write with high proficiency

MENTORSHIPS

2021 Cache County Chamber of Commerce Leadership Institute
2021 BILT Academy Cohort II
2019 College of the Canyons Grant Writing
2018 Mentor Connect Grant Writing

MEMBERSHIPS

American Educational Research Association (AERA)
Association for Educational Communications and Technology (AECT)
Society for Information Technology and Teacher Education (SITE)

AWARDS

Outstanding Legacy of Utah State Award for the Dept. of Instructional Technology and Learning Sciences	**2015**