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Explaining variation in student efforts towards using math and science knowledge in engineering contexts

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ABSTRACT

Previous research suggests that in classes that take an integrated approach to science, technology, engineering, and math (STEM) education, students tend to engage in fulfilling goals of their engineering design challenges, but only inconsistently engage with the related math and science content. The present research examines these inconsistences by focusing on student engagement, or effort, towards math and science concepts while working on an engineering challenge, through the lens of expectancy-value theory. Specifically, we examine how students' perceptions of the *value* of math and science and *expectancy* for success with the math and science relate to the *efforts* they put towards using math and science while working on engineering challenges. Our results suggest that subjective task value significantly predicts efforts towards both math and science, whereas neither expectancy, nor the interaction between expectancy and value predicted effort. We argue that integrated learning environments need to help students understand how the domains of math, science, and engineering support their work in fulfilling the engineering project design goals. In other words, we argue that we, as educators, must help students to recognise the value of each of the domains addressed within STEM integrated learning environments. This paper discusses strategies for accomplishing this goal.

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Engineering is an increasingly critical component of K-12 education. This rise in stature is apparent in the relatively new research journal titled *Journal of Pre-Collegiate Engineering Education*, and the development of state (see review in Carr, Bennett, & Strobel, 2012) and national standards (NGSS Lead States, 2013) for K-12 engineering. The introduction of engineering into visions of K-12 education highlights problems with the traditional 'siloed' approach to math and science education. In short, the 'siloed' approach 'does not reflect the natural connections among the four subjects, which are reflected in the real world of research and technology development' (National Academy of Engineering & National Research Council, 2009, p. 12). It is therefore inauthentic, and near-impossible, to imagine participating in engineering work without integrating across the disciplines of science, technology, engineering, and math (STEM). Thus, proponents of incorporating

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engineering education into K-12 classrooms argue that it will necessarily increase integration across the STEM domains.

In addition to being a more authentic and accurate experience of engineering, integrating across the STEM fields is seen as potentially supporting deep student learning of traditional science and math content. As argued in the *Framework for K-12 Science Education* (National Research Council, 2012), engineering is a central component of science education because it is a vital learning goal in and of itself, and because 'engineering and technology provide a context in which students can test their own developing scientific knowledge and apply it to practical problems; doing so enhances their understanding of science' (p. 12). And, in fact, a wide range of positive outcomes are associated with integrating engineering, science, and math education, including increased STEM literacy, interest and engagement, and content knowledge (National Academy of Engineering & National Research Council, 2014). Thus, instead of teaching each subject in isolation, researchers and policy-makers alike increasingly focus on teaching STEM subjects in an integrated fashion such that engineering challenges become contexts in which students can learn and apply science, math, technology, and engineering content.

Educators and researchers seeking to provide an authentic context in which to teach engineering in this integrated way have found that engineering design challenges are a vital tool for doing so (Dym, Agogino, Eris, Frey, & Leifer, 2005; Mentzer, Becker, & Sutton, 2015). Within this context, the cross-domain connections make sense because successful designs will apply traditional math and science content. In fact, the majority of k-12 engineering curricula generally highlight four characteristics of the engineering design process – (1) problem identification and definition, (2) generation and selection of multiple possible solutions, (3) modelling and analytic tools, and (4) iteration (cf. Guerra, Allen, Berland, Crawford, & Farmer, 2012) – each of which include opportunities for students to use math and science (Berland, Steingut, & Ko, 2014). For example, math is used, and mathematical strategies are developed, when engineers (and engineering students) turn qualitative characteristics or product goals into quantifiable criteria that can be measured. Science emerges as relevant when defining the problem which requires understanding the underlying scientific laws that will guide and constrain any future design, as well as when making sense of test results in order to determine next steps.

Engineering design challenges have appeared in math and science classes as a problem or project context and in engineering classes designed to apply traditional math and science content (Moore et al., 2014). For example, in the 'Engineering for Children: Structures' curriculum (Roth, 1996), the emphasis is on engineering with the expectation that the early elementary students will be introduced to key science ideas, develop positive attitudes towards science, and learn productive approaches to tackling ill-structured problems. Learning By Design™ (Kolodner et al., 2003) provides an integrated model in which the investigations of science content with engineering design work are interwoven such that students are constantly moving between the two domains with the ultimate goal of fulfilling the design challenge. 'Science Through LEGO Engineering' (Wendell & Rogers, 2013) similarly shifts between science content learning goals and engineering design goals throughout the unit.

Regardless of the specifics, these curricula, and the idea of learning science and math through engineering design challenges more generally, are based on a project-based approach to learning that argues for student learning by using the relevant knowledge and skills (Krajcik et al., 1998). These rich contexts enable students to build connected knowledge that is retrievable in a range of situations (Edelson, 2001; Hmelo-Silver, 2004; Kolodner et al., 2003). In addition, the design work in engineering contexts enables students to learn by doing or making; as stated by Roth (1996), 'design artifacts are important aspects of learning because they allow thinking through manipulating; they are objects students use to integrate acting and thinking' (p. 147).

Moreover, empirical research has demonstrated that an integrated approach to STEM education can support student learning of the traditional science content (Chiu & Linn, 2011; Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005; Kolodner et al., 2003; Penner, Giles, Lehrer, & Schauble, 1997; Silk, Schunn, & Strand Cary, 2009), engineering content (Hotaling, Fasse, Bost, Hermann, & Forest, 2012; Yadav, Subedi, Lundeberg, & Bunting, 2011), and the engineering design process (Dally & Zhang, 1993; Mentzer et al., 2015). For example, Mehalik, Doppelt, and Schunn (2008) compared the science learning gains of middle-school students who participated in a 'scripted inquiry approach' to that of those who participated in an engineering design context. Results reveal that the students learned more science content in the engineering condition and that the design task was particularly helpful for students who typically underperformed in science class.

However, other research highlights the complexity of this conclusion, revealing that students learn 'science concepts through design in some *but not all* situations' (National Academy of Engineering & National Research Council, 2014, p. 57, emphasis added). This research reveals numerous challenges associated with using engineering design challenges as a context for learning traditional math and science learning goals (e.g. Guzey, Moore, Harwell, & Moreno, 2016; Kanter, 2010; Puntambekar & Kolodner, 2005). For example, Tran and Nathan (2010) compared the math standardised test scores of students who enrolled in the Project Lead the Way (2013) engineering course to that of those who took more traditional math and science courses. These authors found that the engineering students performed worse on math assessments than the students who participated in the more traditional track. In addition, Cantrell, Pekcan, Itani, and Velasquez-Bryant (2006) found that when middle-school students participated in the engineering units, the achievement gap widened for some populations of students, while it diminished for others.

Even curricula that integrate the science or math learning goals into engineering contexts reveal challenges. For example, in a unit in which students created models of the human respiratory system, Hmelo, Holton, and Kolodner (2000) designed scaffolds to continually bring the science concepts to the forefront. Even so, there remained a

> poor connection between the research [the students] did early and the modeling they did later … Students' research had been focused on big issues but not on the details they needed to understand to be able to design and build something that could work. (p. 276)

Puntambekar and Kolodner (2005) similarly had to design extensive curricular scaffolds in order to support students in using the expected science ideas in their design work.

Taken together, this literature suggests that while integrated learning environments have immense potential for student learning, there exist numerous challenges with the goal of learning math, science, and engineering content in a single setting.

Analyses of student and teacher participation in integrated learning environments offer an explanation for the challenges associated with supporting student learning in integrated approaches to science, math, and engineering content: it is possible that students and teachers do not expend effort – diligent and persistent work (Dietrich, Dicke, Kracke, & Noack, 2015) – towards the math and science content in the engineering context. For example, using a combination of interview and written work, we found that students in a high school engineering course reported putting little effort into those parts of the process that utilise the math and science concepts (Berland et al., 2014). Crismond (2001) similarly found that novice engineers do not consistently take opportunities to use the science ideas underlying their engineering work. This finding is consistent with work such as Barnett's (2005) and Penner et al.'s (1997) analyses demonstrating that the aesthetic details of the students' designs often distracted student attention from the target content and designing functional products; students were not putting effort towards using and learning the expected math and science concepts because they were focused on other aspects of their design work.

The combination of this work suggests that the mixed success of integrated learning environments stems from the focus on the engineering context: students of integrated learning environments do not always put effort into learning and using the target math and science content. In fact, as argued by Nathan et al. (2013), 'A central challenge for high school engineering students is maintaining an awareness of key mathematics and science concepts as they thread through the steps of the typical project design cycle' (p. 77). This conclusion is sensible: inconsistent efforts towards target learning goals would explain inconsistent learning.

Given the observed potential of STEM integration, and the policy call for this integration (National Academy of Engineering & National Research Council, 2014; National Research Council, 2012), these studies raise key questions about why students might not be putting effort into using and learning the math and science content that educators and engineers see as directly related to the engineering design work. This paper addresses this question.

Our prior work demonstrates that students inconsistently recognise the ways in which math and science content can support their engineering work (Berland et al., 2013; Berland & Busch, 2012; Berland et al., 2012; Berland et al., 2014). This conclusion is similar to the knowledge integration conclusion that 'If students can complete homework assignments and earn passing grades, they may see no benefit to ensuring that their ideas about scientific phenomena are coherent' (Chiu & Linn, 2011, p. 3). That is, students may not seek to clarify or expand their understandings if they do not recognise the utility of that effort. This insight motivated us to use the expectancy–value theory (EVT) (Eccles & Wigfield, 2002; Eccles (Parsons), 1983; Wigfield & Eccles, 2000) to explore student effort because of its emphasis on the relationship between students' perceptions of task value and a variety of outcomes, including effort.

The EVT highlights two motivational processes: expectancy and subjective task value. Expectancy is defined as the individual's belief in the likelihood of success when doing the task: 'In general, when people [expect to be successful] they perform better … ' (Eccles & Wigfield, 2002, p. 111). Eccles and Wigfield define subjective task value in terms of four related sub-categories: the extent to which students think the task is enjoyable (intrinsic value), useful for future goals (utility value), and important to some aspect of his or her identity (attainment value), balanced against their perception of the drawbacks (i.e. cost) of doing the task.

According to the EVT, expectancy and value are both expected to predict achievement-related choices, such as persistence and performance. The EVT has been a useful framework for understanding outcomes in a variety of domains, such as mathematics, physics, English, and sports (Durik, Vida, & Eccles, 2006; Eccles (Parsons), 1983; Meece, Wigfield, & Eccles, 1990; Simpkins, Davis-Kean, & Eccles, 2006). And yet, to our knowledge, only one study has been conducted in engineering: Jones, Paretti, Hein, and Knott (2010). In line with prior research, Jones et al. found that high expectancy for success in engineering predicted undergraduates' achievement in engineering courses, while their value-related beliefs predicted career plans. This pattern – the relationship of expectancy to performance and of value to choices – is so consistent across studies that Eccles and Wigfield (2002) have suggested a modification to the model to reflect the different outcomes each construct predicts. These findings, however, do not suggest which construct might be more predictive of students' efforts towards learning, including using the target math and science, as effort is neither a measure of performance nor an explicit choice.

Trautwein, Lüdtke, Kastens, and Köller (2006) extended the EVT to explore this issue – to explore the relationship between expectancy, value, and students' self-reported effort. Their study suggests that while both subjective task value and expectancy predicted effort on homework, effort was more strongly related to subjective task value than to expectancy. In this paper, we examine these same relationships in the context of understanding the challenges of integrating math, science, and engineering design.

Research question

This study explores one possible explanation for the mixed success of integrating math, science, and engineering learning goals within the context of engineering design projects. Given that effort is a predictor of learning outcomes (Hughes, Luo, Kwok, & Loyd, 2008; Noftle & Robins, 2007; Richardson, Abraham, & Bond, 2012), students' varied learning outcomes are likely due to differences in students' efforts towards learning and using the target math and science content. For this reason, the present analysis uses effort as the outcome variable. In particular, the present study addresses the following research question: how do subjective task value and expectancy predict students' efforts towards learning and using math and science when working on engineering design challenges?

Methods

In order to address the relationships between subjective task value, expectancy for success, and efforts towards using and learning math and science content within the context of an engineering challenge, we administered a survey to high school students who were enrolled in classes enacting *Engineer Your World*, a year-long engineering course developed through collaboration between engineers, learning scientists, curriculum specialists, and teachers, including the lead author.

Study context

Engineer Your World is a year-long course in which students follow an engineering design process to complete multiple design challenges ranging from reverse engineering a handcranked flashlight, to designing and building a pinhole camera, and from analysing data to redesign a model wind turbine, to designing robotic vehicles.

Each of the units were developed following design principles that were rooted in best practices found in the STEM education and learning sciences literature (Berland, 2013). Key to the current study, this course was designed to create multiple opportunities for students to learn and apply traditional math and science concepts to their engineering design work. In fact, one of the design principles emphasised in the course is that 'all [target] science and math concepts … [will be] necessary for students' successful completion of the STEM-design projects' (Berland, 2013, p. 15). This principle underscores the expectation that the targeted science and math concepts would be explicitly connected to the engineering work. For example, in the second design challenge in the course, students apply mathematical concepts related to similar triangles in order to design a pinhole camera. This particular unit originally included a learning goal, and related lesson materials, associated with the physics of how light travels. However, classroom observations revealed that students could successfully design and construct a pinhole camera without this knowledge (Berland & Busch, 2012). This result suggested that the expected science content was unnecessary for the completion of the challenge. Thus, the emphasis on how light travels was removed from the course. However, given that successfully framing one's picture requires an understanding of similar triangles, this mathematics content and the connections to the design challenge were emphasised in revisions of the unit. Similar decisions were made throughout the course to ensure that all of the math or science content that we expected students to learn or apply was clearly connected to and useful for their engineering design work.

Participants and procedure

We collected survey data from 138 students from schools in the south-central U.S.A who were in classes enacting *Engineer Your World*, during the 2012–2013 school year. We limited analyses to the 113 students for whom we had appropriate consent. Students were missing consent forms as a result of either their explicit desire to not participate in studies related to the curriculum or because they joined the class after the consent process occurred. While a few students were high school sophomores and juniors, the majority were seniors who had completed, or were concurrently enrolled in, Physics.

The students came from one of 8 different schools. Teachers and/or principals in each of the schools volunteered to participate in this field trial of the curriculum. Demographic

Table 1. Demographics of schools participating in study.

School	District	District student population	District setting	Student population	% Economically disadvantaged	% Racial minority	# of participants
1	A	~85,000	Urban	~3000	14%	47%	15
2	A			~1000	88%	98%	3
3	A			~500	91%	98%	11
4	A			~2000	40%	58%	10
5	A			~2000	55%	35%	5
6	B	~20,000	Suburb	~2000	64%	89%	8
7	C	~45,000	Suburb	~2500	43%	70%	14
8	D	~5000	Exurban	~1500	10%	22%	13
9	E	Private	Suburb	~500	Not reported	Not reported	34 (2 classes)

information about each of the participating schools can be found in Table 1. In one school, two classes participated.

The survey was administered during class time by researchers who visited each class for this purpose. Surveys were given at the conclusion of the fourth unit in the course. Prior enactments of the curriculum suggested that all of the classes would complete the first four units, while the remaining 2 units would only be completed by a subset of the classes. Thus, this timing ensured that all participating students would be at a similar point in the curriculum at the time of the survey collection.

Materials

The survey was designed to explore the relationships between expectancy, value, and efforts towards using math and science content in engineering design challenges. The survey consisted of two blocks of items: one asked students about their expectancy, value, and efforts with respect to using math when working on engineering challenges and the second block asked the same questions with respect to science (see Figure 1).

Each block began with two introductory questions: first, a dichotomous question ('Do you use science (math) in engineering class?' and, second, an open-ended question (How do you use science (math) in engineering class?). Student responses to these two questions were not analysed. Instead, the questions functioned as a reminder to help students think about the ways in which they might have integrated the two disciplines in question. In fact, after asking the open-ended question, we answered it for them, by providing a list of ways they may have used science (e.g. power equations and energy transformation) and math (e.g. converting between different units of measurement) throughout their engineering course. These lists were based on the curriculum they had covered at the time of the survey and were created by comparing the traditional math and science standards to

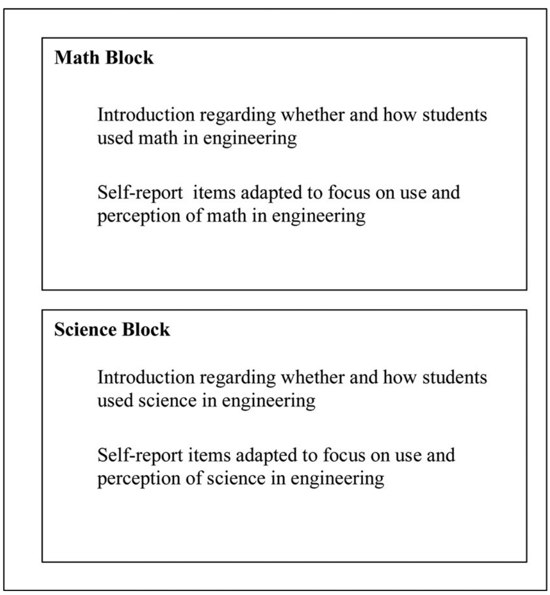

Figure 1. Survey organisation.

the learning goals of the unit; they were intended to provide examples for students to consider when answering questions.

As seen in Figure 1, after the introductory question in each block, students answered survey questions regarding their expected success using math or science in an engineering context (6 items), perceived value of math or science content (7 items), and their efforts towards learning and using the math or science content (5 items). The two blocks were presented in a fixed order: the math block was presented before the science block. However, within each block, the order of the 25 self-report questions was randomised.

Measures

Each construct of interest was measured with a sub-scale of the Intrinsic Motivation Inventory (IMI) (Ryan, 1982). Expectancy was measured using the perceived competence sub-scale of the IMI. Eccles and Wigfield (2002) do not make a conceptual distinction between competence and expectancy. Effort was measured using the effort/importance sub-scale of the IMI. Subjective task value was measured using the value sub-scale of the IMI.

McAuley, Duncan, and Tammen (1987) confirmed that the IMI is a valid scale; they found the reliabilities of the competence ($\alpha = .80$) and effort ($\alpha = .84$) sub-scales to be acceptable. The value sub-scale was not included in the scale at the time of the validation study and, therefore, its reliability was not reported in that study. In addition, McAuley et al. (1987) noted 'the items are all generally worded allowing the researcher to substitute the activity/task of interest' (p. 55). Thus, we adapted each item to focus on using math and science throughout engineering work (see Table 2).

Analysis

Our research question was related to student-level predictors (expectancy and value) and student-level outcomes (effort). However, in order to test the relationships among the variables, it was necessary to account for nesting of students within schools. Therefore, a mixed model was specified using Hierarchical linear modeling (HLM) software

Table 2. Sample adaptations of IMI items (emphases added to highlight adaptation).

Sub-scale	Original item	Math adaptation	Science adaptation
Effort	I put a lot of effort into this	I put a lot of effort into *using math in engineering class*	I put a lot of effort into *using science in engineering class*
	I tried very hard on this activity	I tried very hard *when using math in engineering class*	I tried very hard *when using science in engineering class*
Value	I believe this activity could be of some value to me	I believe *using math in engineering tasks* could be of some value to me	I believe *using science in engineering tasks* could be of some value to me
	I would be willing to do this again because it has some value to me	I would be willing to *use math in engineering class* again because it has some value to me	I would be willing to *use science in engineering class* again because it has some value to me
Expectancy	I think I am pretty good at this activity	I think I am pretty good at *math*	I think I am pretty good at *science*
	I am satisfied with my performance at this task	I am satisfied with my performance *when doing math tasks in my engineering class*	I am satisfied with my performance *when doing science tasks in my engineering class*

(Raudenbush, Bryk, & Congdon, 2004). Three student-level predictors were entered into a model predicting effort for using math in engineering class: perceived value for using mathematics in engineering, expectancy for using mathematics in engineering class, and the interaction between these two variables. Both value and expectancy were group-mean centred. The interaction term was created by calculating the product of the two group-mean-centred variables and then was entered into the model uncentred as suggested by Enders and Tofighi (2007). The same model was specified to predict effort for using science in engineering class.

Given the use of mixed models to account for school differences, no predictors were entered at the school level. According to Maas and Hox (2005), 'a small sample at level two (meaning a sample of 50 or less) leads to biased estimates of the second-level standard errors' (p. 86); had our model included school-level variables, such as the school's average socio-economic status, it would have resulted in a small power for the estimates and standard error of level 2 (school-level) coefficients. Thus, the present analysis includes a model with only student-level and not school-level predictors. As a result, our coefficients are all at level 1, ensuring that the small number of clusters would not impact the model estimates. Rather, the present model is akin to an ordinary least squares model with an adjustment for cluster (i.e. school) means.

Results

Preliminary analysis was completed by examining means and standard deviations (Table 3) of all variables as well as correlations between variables separately by domain (Table 4).

Primary analysis

Because students were nested in classrooms, which were nested within schools, we first sought to determine whether a two- or three-level model would be more appropriate. Given that only one school contained more than one class, we examined the two classes in order to determine if they were significantly different with respect to the variables in question. A multivariate analysis of variance suggested that the two classes did not differ on the predictor variables for mathematics (Wilk's λ $(2,3) = 1.72$, $p = .20$) or science (Wilk's λ $(2,3) = 2.77$, $p = .08$). Therefore, we ignored the classroom level and specified a two-level mixed model with students nested within schools designed to predict effort.

As shown in Table 5, results suggest that subjective task value was a significant predictor of effort for using math ($t(99) = 8.17$, $p < .001$). Specifically, as the subjective task value increases by 1 point, effort is predicted to increase by 0.88 points. Neither expectancy

Table 3. Means and standard deviations.

	Math variables			Science variables		
	Effort	Value	Expectancy	Effort	Value	Expectancy
Mean	5.03	5.74	5.27	5.03	5.51	5.29
Standard deviation	1.21	0.98	1.23	1.20	1.20	1.17
n	112	112	111	107	109	109

Table 4. Correlations.

	Effort	Value	Expectancy
Effort	1	0.71***	0.56***
		105	105
Value	0.70***	1	0.79***
	110		107
Expectancy	0.32***	0.52***	1
	109	109	

Notes: Correlations with respect to using science in engineering are presented above the diagonal. Correlations with respect to using mathematics in engineering are presented below the diagonal.
***Indicates $p < .001$.

Table 5. Two-level mixed-model results predicting math effort.

Fixed effect	*B*	*t*	df
Intercept	4.99		
Value	0.88	8.17***	99
Expectancy	−0.01	−0.11	99
Value*expectancy	0.11	0.11	99
Random effect	Variance	Df	
u_{0j}	0.17***	8	
r	0.76		

Note: *** refers to $p < .001$.

Table 6. Two-level mixed-model results predicting science effort.

Fixed effect	*B*	*t*	df
Intercept	5.03		
Value	0.62	5.88***	95
Expectancy	0.09	−0.85	95
Value*expectancy	0.01	0.19	95
Random effect	Variance	df	
u_{0j}	0.47***	8	
r	0.86		

Note: *** refers to $p < .001$.

($t(99) = -0.11$, $p = 0.91$) nor the interaction between expectancy and value ($t(99) = .11$, $p = .12$) predicted effort.

The science model (see Table 6) revealed similar relationships. In particular, subjective task value was again a significant predictor of effort ($t(95) = 5.89$, $p < .001$). In this case, as the subjective task value increases by 1 point, effort is predicted to increase by 0.62 points. In addition, perceived expectancy ($t(95) = -0.85$, $p = .4$) did not predict effort, nor did the interaction between expectancy and value ($t(95) = 0.19$, $p = .85$).

Discussion

This study was designed to understand the motivational processes underlying inconsistent outcomes of STEM integrated classrooms. Specifically, previous research suggested that, when classes integrate math and science learning goals into an engineering context, students tend to attend to the goals of the engineering challenge more than the math and science learning goals. In this situation, students are inconsistently using or attending to related math and science content (Barnett, 2005; Berland et al., 2014; Cantrell et al., 2006; Crismond, 2001; Hmelo et al., 2000; Penner et al., 1997). Drawing from psychological theories of motivation (cf. Eccles & Wigfield, 2002), the present study examined whether and how students' perceptions of the *value* of math and science and *expectancy* for successfully doing math and science related to the *effort* they put towards using math and science while working on engineering challenges. Our results suggest that subjective task value significantly predicts efforts towards both math and science, whereas neither expectancy, nor the interaction between expectancy and value did so. Our findings should not be interpreted to suggest that expectancy of successes is not an important motivational process when it comes to attending to math and science through engineering challenges; rather, the findings suggest that given the predictive power of subjective task value, it should be considered as a potentially useful lever for supporting successful STEM integration.

The unique importance of subjective task value is consistent with the literature throughout educational research: as summarised by the National Research Council: 'Learners of all ages are more motivated when they can see the usefulness of what they are learning' (1999, p. 61). The present work contributes to this literature in two ways. First, the existing curriculum design literature focused on STEM integration (e.g. Berland, 2013; Hmelo et al., 2000; Kolodner et al., 2003) is designed around the understanding that students' perception of the value or utility of their work impacts their participation in the activities. However, no study empirically has investigated this connection with respect to student effort towards using and learning math and science within the context of an engineering challenge, as we do here. In addition, our work utilises the EVT in an area where it has infrequently been applied: engineering education. In the present work, we use the EVT model to explain variance in students' use of math and science content, thereby addressing a key challenge facing STEM education: how can we support students in putting effort towards learning and using math and science content throughout their engineering design work? In the following sections, we explore the educational implications, focusing on strategies for supporting students in perceiving the value of using and learning math and science ideas that can support, constrain, and guide their engineering design work.

Educational implications

Given the integrated nature of engineering, K-12 engineering courses include the application of math and science topics throughout. In addition, research on STEM integration encourages educators to explicitly identify and discuss the math and science content that is being applied (Prevost, Nathan, Stein, Tran, & Phelps, 2009; Puntambekar & Kolodner, 2005; Schnittka & Bell, 2011). These studies argue that we must draw student attention to math and science content that is relevant to their engineering task. Our study suggests that we cannot stop there; we must also help students understand *why* it is relevant. In other words, we must emphasise the ways in which the math and science content is useful, or valuable.

Unfortunately, the value of math and science content – particularly the value of learning new content – is not immediately obvious to individuals focused on fulfilling a design task. As stated by Roth (1996): 'Although most professional design concentrates on the product as the essential outcome, learning to and through design makes process the central issue of education' (p. 130). That is, the emphasis in engineering is on the creation of the product, whereas learning through engineering requires stepping away from the product goal and attending to how the product is created and the math and science ideas that are guiding that work. As synthesised by the National Research Council (2012):

> In engineering the goal … [is to] produce the most effective design for meeting the specifications and constraints … [However], the aim of science is to find a single coherent and comprehensive theory for a range of related phenomena. (p. 3–5)

Thus, we see that the goals of traditional math and science education differ from the goals of an engineering design project – and that this difference may result in students not recognising the value of math and science content for engineering design work. And, in fact, in a detailed analysis of novice engineering students' discussions during their design work, Berland and Busch (2012) found that the students encapsulated math and science ideas into 'sound-bytes' that enabled them to complete their design efforts without investigating those math and science ideas. In that study, the students attended to the goal of building a functional product at the expense of attending to the underlying math and science. This suggests that they did not recognize the value of math and science content in their design work.

Thus, the question becomes: how can educators and learning environments support students in valuing math and science in the context of engineering design challenges? We draw from research in educational psychology, STEM education, and the learning sciences to describe three strategies for promoting this sense of value: making the value explicit, making math and science necessary, and explicitly investigating math and science.

Make the value explicit

Learning sciences research suggests that we should make the target math and science content explicit in the context of engineering design challenges (Prevost et al., 2009; Puntambekar & Kolodner, 2005; Schnittka & Bell, 2011). Psychological theory suggests taking this explicit expression one step further by providing a rationale, or an explicit description of a task's value (Reeve, Jang, Hardre, & Omura, 2002). Although this call to provide a rationale is closely related to the EVT in its emphasis on the subjective task value, the EVT does not put forth strategies of supporting perceptions of value. Rather, self-determination theory deals with this strategy more directly and predicts that rationale provision will lead to positive effects (Deci, Eghrari, Patrick, & Leone, 1994; Ryan & Deci, 2000).

The predictions of the self-determination theory are largely borne out by the evidence. A recent meta-analysis (Steingut et al., in press) suggests that rationale has a significant positive effect on subjective task value and several other adaptive motivation and performance outcomes. Most important to the present discussion, Steingut et al. found that, across the set of studies, rationale leads to a positive significant effect on engagement, broadly defined to include effort. However, the effects of providing an explicit rationale are not all positive. For instance, their preliminary findings suggest a negative effect of rationale on students' expectancy for success. Furthermore, several variables significantly moderated the effects of rationale, suggesting that rationales may vary in their effects depending on the content of the rationale, the sample, and how interesting the task in question is.

In order to explicitly offer a rationale for science and math concepts within engineering challenges, teachers may either express the value of the math and science content in its own right, or express the value of the math and science to completing the engineering design challenge. For instance, a teacher might state that 'today is a great opportunity to practice your algebra, which is useful in business careers'. Alternatively, another teacher might say 'the relationship between force, mass and acceleration that you learned in physics will help you design an excellent prototype'. Furthermore, the effects of a teacher's provision of rationale are likely related to how well that teacher knows his or her students. That is, a rationale that is targeted to the specific interests, goals, priorities, or identities of students is likely to resonate more with them and to lead to stronger effects on motivation and performance.

Given that students' subjective task value is personal, teachers who explicitly communicate one reason for valuing a task may resonate with some students but not others. Hulleman, Godes, Hendricks, and Harackiewicz (2010) drew on this insight in their development of an intervention that enables each student to reflect on his or her own reasons for valuing the activity. This intervention resulted in positive effects on interest, utility value, and performance. Applying the work of Hulleman et al. to the present context, a teacher might ask engineering students to write a paragraph about why they think that it is important to use math and/or science in engineering class in general, or in a particular engineering design challenge.

Make the math and science necessary

Growing out of constructivist theories of learning, Schank (1982) argued that when learners' efforts are stymied by the limits of their current understandings, they experience why the target content is useful and therefore have reason to put effort towards learning it. Edelson (2001) builds on this work in his Learning-for-Use framework for designing learning environments, in which he identifies creating a situation in which students 'experience the need for new knowledge' (p. 358) as the first step for curriculum design. This perspective is also found in Stern and Roseman's (2004) framework for evaluating science curricula, in which one of the criteria is whether the utility of the vocabulary and ideas was communicated to the students. Thus, we see that one strategy for supporting students' sense of the value of what they are learning is to create situations in which that content is necessary.

When working to make science content necessary within a project-based science unit, Kanter (2010) found that it was particularly difficult to create situations in which students 'experience the need for new knowledge' when that knowledge is unfamiliar to them – if students are unfamiliar with the content, they do not know it is needed. Kanter developed three design approaches to address this particular challenge. These include: (1) 'unpack the task' such that students identify areas of questions they must answer before they can complete the project; (2) 'highlight an incongruity' within the students' understanding to reveal areas that need additional exploration; and (3) 'try to apply', in which students might recognise the need for new knowledge as a result of the failure of their existing understandings.

Many of these strategies are easily applicable to engineering design contexts. For example, one might unpack the task during the initial stages of a design; when investigating customer needs and existing solutions or describing the required functionality, one is in a position to ask questions about what needs to be done and how. In fact, Kolodner's Learning by Design™

(2003) follows an explicit learning cycle in which problems of design create a 'need to know' and that drives further investigations into the target science concepts. In this case,

> each investigative module has its own mini design challenge—one that provides physical infrastructure for the full challenge or that helps with generating ideas about how to achieve it. The sequence of investigative modules helps the students focus on the essentials of the science curriculum by guiding them in directions that help them learn the science in the context of achieving the challenge. (p. 527)

In addition, trying an approach and recognising where it succeeds and fails are a hallmark of engineering –so much so that some research suggests that 'trial and error' can take the place of careful design processes in K-12 classrooms (Berland et al., 2014; Crismond, 2001; Crismond & Adams, 2012). As argued by Leonard (2005), this occurs because the students will have met the explicit goals of their coursework when they have a working product, not when they understand *why* it works. That is, the goals of the design challenge do not necessarily encourage students to explore the underlying science. Thus, we suggest that educators must create space and time for students to investigate why their designs succeeded and failed and give students a reason to reflect on their successive attempts (e.g. maybe students are expected to justify their decisions before building because of limited materials), when applying this strategy to engineering design challenges. In other words, the 'try to apply' approach must be paired with 'eliciting curiosity' about why various approaches did and did not work. As Hmelo et al. (2000) state: 'The best design challenges for promoting learning are those that afford construction, testing, timely and authentic feedback, and revision' (p. 297).

Taken together these curricular approaches suggest that one can help students experience the target math and science content as valuable or necessary by designing curricula that make that content indispensible. Specific strategies for making the content necessary or useful include allowing students to fail when they do not have the requisite knowledge; discussions in which the engineering challenge is unpacked to identify what students do and do not know about solving it; and using an iterative trial-and-error process in which students reflect on why various designs do and do not work in order to drive future revisions.

Explicitly investigate the math or science

Our final strategy for supporting students in experiencing the target math and science content as useful to their engineering design work comes from curricula in which students design and build models they can then use to explore the target math and science content. For example, Penner et al. (1997) and Penner, Schauble, and Lehrer (1998) describe elementary students designing and building a model elbow, and in Hmelo et al.'s (2000) work, middle-school students model the respiratory system. More recently, we see elementary students designing and building LEGO-based products to support science investigations in the curriculum 'Science Through LEGO Engineering' (Wendell & Rogers, 2013). For example, in one unit of this curriculum, the students construct LEGO instruments and then investigate those instruments to deepen their understandings of how sound is made. The unit concludes with the students applying their new understandings to design a novel instrument that fulfils design requirements.

Across each of these curricula, the design context is directly related to the target science ideas and, as such, becomes a context through which students can investigate that content. These curricula are, therefore, an interesting twist to engineering design – students are working within constraints to fulfil functional requirements (i.e. creating a joint that constrains the direction of the bend, or how to get the lungs to fill with air), but the 'product' they are designing is a functional model of the content under study. In this way, their artefact is a representation of their understanding (Roth, 1996). Moreover, the direct relationship between the designed object and the target science content provides a clear connection between the science content and design work – one cannot model the elbow or explore the principles of sound without figuring out how the elbow works or constructing tools with which to investigate sound. Thus, we see that a final strategy for supporting students in experiencing the target math and science content as valuable and useful is to tie the engineering design project and target content together so tightly that it is impossible to attend to one without the other. To be clear, this coupling is not meant to remove all design freedom. For example, in order to design an instrument that can play multiple notes, students will be developing understandings about the relationship between vibration, pitch, and volume, among others. However, this does not limit the multitude of instruments they might create to explore and create different vibrations.

Limitations

As with all studies, the findings of this study should be interpreted with caution because of limitations that result from methodological decisions and possible researcher biases. With respect to the data sample, it is worth noting that this study is based on a relatively small number of participants who come from only nine schools that all enacted the same curriculum. As curriculum and teaching practices directly influence student perceptions, one might question whether we would see similar results in a different course. However, this study explores the relationship between students' different perceptions, not the values themselves; our claim is that under a different curriculum with different teachers, students would be likely to have different perceptions of these constructs, but the relationship between them would be constant. This expectation is supported by the wealth of psychology studies demonstrating the strength of the EVT in general (see review in Eccles & Wigfield, 2002), and of the connection between perceived value and effort across domains and contexts more specifically (Trautwein, Lüdtke, Kastens, & Köller, 2006). In addition to the limited number of participating schools, the number of individuals per school varied, and so the estimates for some schools may be more accurate than for others. Although those estimates are not reported here, they are used within the mixed model.

A further reason for caution is the instruments used: the same measures were used for science and for math. Although the items were randomised within each block of question, the math questions always appeared before the science questions. For this reason, the effects of science outcomes are susceptible to order effects. Because we used the same scales for each domain and because we administered several scales, it is likely that participants did not fully attend to every item. In addition, each variable was measured using one self-report measure, which may not be particularly valid measures of behaviour. That said, self-report remains an important tool for measuring students' subjective assessments of their engagement (Fredricks & McColskey, 2012). Similarly, while research has demonstrated a positive correlation between effort and learning (Hughes, Luo, Kwok, & Loyd, 2008; Noftle & Robins, 2007; Richardson, Abraham, & Bond, 2012), the self-report data did not afford the opportunity to directly explore this connection. It is, therefore, possible that the students' self-reported effort might not explain variation in the math and science the participating students used and learned.

This study adds to the extant psychological research demonstrating a strong relationship between individuals' motivation to do a task, their perception of the value of that task, and their expectancy of success (see review in Eccles & Wigfield, 2002). In this case, we extend the existing body of work to examine a complex task. In particular, while typical uses of the EVT explore individual perceptions and work with a single activity (i.e. one might ask about doing math problems or completing an engineering design task), we are investigating a nested activity: what are students' perceptions of and efforts towards the activities of learning and using math (or science) when doing a larger activity of engineering design? While the IMI (Ryan, 1982) has been reliably adapted to work within numerous domains (McAuley et al., 1987), when we began this study, it was not clear whether adapting it to fit this nested task would result in valid and reliable results. However, even with this complex task, our study reveals that hypotheses of the EVT hold true: individuals' perception of the value of the task predicted their reported effort. This finding suggests a robustness of the EVT. In addition, given the demonstrated strength of this theory, the fact that the expected relationship emerged mitigates some of the above limitations by suggesting the theoretical validity of our findings.

Conclusions

Building on past work from the traditions of both learning sciences and psychology, this paper reveals that students' perception of the value of math and science content for engineering predicts their effort towards integrating math and science content into their engineering coursework. Thus, we argue that K-12 engineering courses should support students in recognising the value of math and science in this context. Specifically, curricula can be designed such that the math and science content is more explicit or more directly necessary for the fulfilment of engineering project design goals. In addition to curricular supports, teachers can also support students' sense of value by providing explicit rationales or by encouraging students to reflect on their personal perceptions of the value.

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References

Barnett, M. (2005). Engaging inner city students in learning through designing remote operated vehicles. *Journal of Science Education and Technology*, *14*(1), 87–100.

Berland, L. K. (2013). Designing for STEM integration. *Journal of Pre-Collegiate Engineering Education*, *3*(1), 22–31.

Berland, L. K., & Busch, K. C. (2012, June). *Negotiating STEM epistemic commitments for engineering design challenges.* Paper presented at the annual meeting of the American Society for Engineering Education, San Antonio, TX.

Berland, L. K., Martin, T., Ko, P., Peacock, S., Rudolph, J., & Golubski, C. (2013). Student learning in challenge-based engineering curricula. *Journal of Pre-Collegiate Engineering Education*, *3*(1), 52–64.

Berland, L. K., McKenna, W., & Peacock, S. (2012). Understanding students' perceptions on the utility of engineering notebooks. *Advances in Engineering Education*, *3*(2), Retrieved from https://www.researchgate.net/publication/287576495_Understanding_students'_perceptions_on_the_utility_of_engineering_notebooks).

Berland, L. K., Steingut, R., & Ko, P. (2014). High school student perceptions of the utility of engineering design process: Creating opportunities to engage in the engineering practices and apply math and science content. *Journal of Science Education and Technology*, *23*(6), 705–720.

Cantrell, P., Pekcan, G., Itani, A., & Velasquez-Bryant, N. (2006). The effects of engineering modules on student learning in middle school science classrooms. *Journal of Engineering Education*, *95*(4), 301–309. Retrieved from http://doi.org/10.1002/j.2168-9830.2006.tb00905.x

Carr, R. L., Bennett, L. D., & Strobel, J. (2012). Engineering in the K-12 STEM standards of the 50 U.S. States: An analysis of presence and extent. *Journal of Engineering Education*, *101*(3), 539–564. Retrieved from http://doi.org/10.1002/j.2168-9830.2012.tb00061.x

Chiu, J. L., & Linn, M. C. (2011). Knowledge integration and WISE engineering. *Journal of Pre-College Engineering Education Research (J-PEER)*, *1*(1), Article 2, 1–14. Retrieved from http://docs.lib.purdue.edu

Crismond, D. P. (2001). Learning and using science ideas when doing investigate-and-redesign tasks: A study of naive, novice, and expert designers doing constrained and scaffolded design work. *Journal of Research in Science Teaching*, *38*(7), 791–820. Retrieved from http://doi.org/10.1002/tea.1032

Crismond, D. P., & Adams, R. S. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education*, *101*(4), 738–797. Retrieved from http://doi.org/10.1002/j.2168-9830.2012.tb01127.x

Dally, J. W., & Zhang, G. M. (1993). A freshman engineering design course. *Journal of Engineering Education*, *82*(2), 83–91. Retrieved from http://doi.org/10.1002/j.2168-9830.1993.tb00081.x

Deci, E. L., Eghrari, H., Patrick, B. C., & Leone, D. R. (1994). Facilitating internalization: The self-determination theory perspective. *Journal of Personality*, *62*(1), 119–142.

Dietrich, J., Dicke, A.-L., Kracke, B., & Noack, P. (2015). Teacher support and its influence on students' intrinsic value and effort: Dimensional comparison effects across subjects. *Learning and Instruction*, *39*, 45–54. Retrieved from http://doi.org/10.1016/j.learninstruc.2015.05.007

Durik, A. M., Vida, M., & Eccles, J. S. (2006). Task values and ability beliefs as predictors of high school literacy choices: A developmental analysis. *Journal of Educational Psychology*, *98*(2), 382–393. Retrieved from http://doi.org/10.1037/0022-0663.98.2.382

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education*, *94*(1), 103–120. Retrieved from http://doi.org/10.1002/j.2168-9830.2005.tb00832.x

Eccles, J. S., & Wigfield, A. (2002). Motivational beliefs, values, and goals. *Annual Review of Psychology*, *53*(1), 109–132.

Eccles (Parsons), J. (1983). Expectancies, values, and academic behaviors. In J. T. Spence (Eds.), *Achievement and achievement motives: Psychological and sociological approaches* (pp. 75–146). San Francisco, CA: Freeman.

Edelson, D. C. (2001). Learning-for-use: A framework for integrating content and process learning in the design of inquiry activities. *Journal of Research in Science Teaching*, *38*, 355–385.

Enders, C. K., & Tofighi, D. (2007). Centering predictor variables in cross-sectional multilevel models: A new look at an old issue. *Psychological Methods*, *12*(2), 121–138. Retrieved from http://doi.org/10.1037/1082-989X.12.2.121

Fortus, D., Krajcik, J., Dershimer, R. C., Marx, R. W., & Mamlok-Naaman, R. (2005). Design-based science and real-world problem-solving. *International Journal of Science Education*, *27*, 855–879.

Fredricks, J. A., & McColskey, W. (2012). The measurement of student engagement: A comparative analysis of various methods and student self-report instruments. In S. L. Christenson, A. L. Reschly, & C. Wylie (Eds.), *Handbook of research on student engagement* (pp. 763–782). Boston, MA: Springer US. Retrieved from http://link.springer.com/10.1007/978-1-4614-2018-7_37

Guerra, L., Allen, D., Berland, L., Crawford, R., & Farmer, C. (2012). *A unique approach to characterizing the engineering design process*. Presented at the American Society for Engineering Education, San Antonio, TX.

Guzey, S. S., Moore, T. J., Harwell, M., & Moreno, M. (2016). STEM integration in middle school life science: Student learning and attitudes. *Journal of Science Education and Technology*, *25*(4), 550–560. Retrieved from http://doi.org/10.1007/s10956-016-9612-x

Hmelo, C. E., Holton, D. L., & Kolodner, J. L. (2000). Designing to learn about complex systems. *The Journal of the Learning Sciences*, *9*, 247–298.

Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn? *Educational Psychology Review*, *16*, 235–266.

Hotaling, N., Fasse, B. B., Bost, L. F., Hermann, C. D., & Forest, C. R. (2012). A quantitative analysis of the effects of a multidisciplinary engineering capstone design course. *Journal of Engineering Education*, *101*(4), 630–656. Retrieved from http://doi.org/10.1002/j.2168-9830.2012.tb01122.x

Hughes, J. N., Luo, W., Kwok, O.-M., & Loyd, L. K. (2008). Teacher-student support, effortful engagement, and achievement: A 3-year longitudinal study. *Journal of Educational Psychology*, *100* (1), 1–14. Retrieved from https://doi.org/10.1037/0022-0663.100.1.1

Hulleman, C. S., Godes, O., Hendricks, B. L., & Harackiewicz, J. M. (2010). Enhancing interest and performance with a utility value intervention. *Journal of Educational Psychology*, *102*(4), 880–895. Retrieved from http://doi.org/10.1037/a0019506

Jones, B. D., Paretti, M. C., Hein, S. F., & Knott, T. W. (2010). An analysis of motivation constructs with first-year engineering students: Relationships among expectancies, values, achievement, and career plans. *Journal of Engineering Education*, *99*(4), 319–336. Retrieved from http://doi.org/10.1002/j.2168-9830.2010.tb01066.x

Kanter, D. E. (2010). Doing the project and learning the content: Designing project-based science curricula for meaningful understanding. *Science Education*, *94*, 525–551.

Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., … Ryan, M. (2003). Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting learning by design into practice. *The Journal of the Learning Sciences*, *12*, 495–547.

Krajcik, J., Blumenfeld, P. C., Marx, R. W., Bass, K. M., Fredricks, J., & Soloway, E. (1998). Inquiry in project-based science classrooms: Initial attempts by middle school students. *Journal of the Learning Sciences*, *7*, 313–350.

Leonard, M. (2005). Examining tensions in a “design for science” activity system: science versus engineering goals and knowledge. *Tidskrift För Lärarutbildning Och Forskning [Journal of Research in Teacher Education]*, *3*, 132–146.

Maas, C. J., & Hox, J. J. (2005). Sufficient sample sizes for multilevel modeling. *Methodology*, *1*(3), 86–92.

McAuley, E., Duncan, T., & Tammen, V. V. (1987). Psychometric properties of the intrinsic motivation inventory in a competitive sport setting: A confirmatory factor analysis. *Research Quarterly for Exercise and Sport*, *60*, 48–58.

Meece, J. L., Wigfield, A., & Eccles, J. S. (1990). Predictors of math anxiety and its influence on young adolescents' course enrollment intentions and performance in mathematics. *Journal of Educational Psychology*, *82*(1), 60–70.

Mehalik, M., Doppelt, Y., & Schunn, C. (2008). Middle-school science through design-based learning versus scripted inquiry: Better overall science concept learning and equity gap reduction. *Journal of Engineering Education*, *97*(1), 71–85.

Mentzer, N., Becker, K., & Sutton, M. (2015). Engineering design thinking: High school students' performance and knowledge. *Journal of Engineering Education*, *104*(4), 417–432. Retrieved from http://doi.org/10.1002/jee.20105

Moore, T. J., Glancy, A. W., Tank, K. M., Kersten, J. A., Smith, K. A., & Stohlmann, M. S. (2014). A framework for quality K-12 engineering education: Research and development. *Journal of Pre-College Engineering Education Research (J-PEER)*, *4*(1), Article 2. Retrived from http://docs.lib.purdue.edu

Nathan, M. J., Srisurichan, R., Walkington, C., Wolfgram, M., Williams, C., & Alibali, M. W. (2013). Building cohesion across representations: A mechanism for STEM integration. *Journal of Engineering Education*, *102*(1), 77–116. Retrieved from http://doi.org/10.1002/jee.20000

National Academy of Engineering, & National Research Council. (2009). *Engineering in K-12 education: Understanding the status and improving the prospects*. Washington, DC: National Academies Press. Retrieved from http://www.nap.edu/catalog.php?record_id=12635

National Academy of Engineering, & National Research Council. (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research*. Washington, DC: The National Academies Press. Retrieved from http://www.nap.edu/openbook.php?record_id=18612&page=52

National Research Council, J. (1999). *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academies Press.

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: National Academies Press.

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. Washington, DC: The National.

Noftle, E. E., & Robins, R. W. (2007). Personality predictors of academic outcomes: Big five correlates of GPA and SAT scores. *Journal of Personality and Social Psychology*, *93*(1), 116–130. Retrieved from https://doi.org/10.1037/0022-3514.93.1.116

Penner, D. E., Giles, N. D., Lehrer, R., & Schauble, L. (1997). Building functional models: Designing an elbow. *Journal of Research in Science Teaching*, *34*(2), 125–143.

Penner, D. E., Schauble, L., & Lehrer, R. (1998). From physical models to biomechanics: A design-based modeling approach. *Journal of the Learning Sciences*, *7*, 429–449.

Prevost, A., Nathan, M. J., Stein, B., Tran, N., & Phelps, L. A. (2009). Integration of mathematics in pre-college engineering: The search for explicit connections. *Proceedings of the American Society of Engineering Education (ASEE)*, *2009*, 1763–1790.

Project Lead the Way. (2013, October 1). *Project lead the way [Text]*. Retrieved September 30, 2014, from https://www.pltw.org/our-programs

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. Retrieved from http://doi.org/10.1002/tea.20048

Raudenbush, S. W., Bryk, A. S., & Congdon, R. (2004). *HLM 6 for windows*. Skokie, IL: Scientific Software International.

Reeve, J., Jang, H., Hardre, P., & Omura, M. (2002). Providing a rationale in an autonomy-supportive way as a strategy to motivate others during an uninteresting activity. *Motivation and Emotion*, *26*(3), 183–207. Retrieved from http://doi.org/10.1023/A:1021711629417

Richardson, M., Abraham, C., & Bond, R. (2012). Psychological correlates of university students academic performance: A systematic review and meta-analysis. *Psychological Bulletin*, *138*(2), 353–387. Retrieved from https://doi.org/10.1037/a0026838

Roth, W.-M. (1996). Art and artifact of children's designing: A situated cognition perspective. *The Journal of the Learning Sciences*, *5*(2), 129–166.

Ryan, R. M. (1982). Control and information in the intrapersonal sphere: An extension of cognitive evaluation theory. *Journal of Personality and Social Pscyhology*, *43*, 450–461.

Ryan, R. M., & Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *The American Psychologist*, *55*(1), 68–78.

Schank, R. C. (1982). *Dynamic memory: A theory of reminding and learning in computers and people*. New York, NY: Cambridge University Press.

Schnittka, C., & Bell, R. (2011). Engineering design and conceptual change in science: Addressing thermal energy and heat transfer in eighth grade. *International Journal of Science Education*, *33*(13), 1861–1887. Retrieved from http://doi.org/10.1080/09500693.2010.529177

Silk, E. M., Schunn, C. D., & Strand Cary, M. (2009). The impact of an engineering design curriculum on science reasoning in an Urban setting. *Journal of Science Education and Technology*, *18*(3), 209–223. Retrieved from http://doi.org/10.1007/s10956-009-9144-8

Simpkins, S. D., Davis-Kean, P. E., & Eccles, J. S. (2006). Math and science motivation: A longitudinal examination of the links between choices and beliefs. *Developmental Psychology*, *42*(1), 70–83. Retrieved from http://doi.org/10.1037/0012-1649.42.1.70

Steingut, R. R., Patall, E. A., & Trimble, S. S. (in press). The effect of rationale on motivation and performance outcomes: A meta-analysis. *Motivation Science*.

Stern, L., & Roseman, J. E. (2004). Can middle-school science textbooks help students learn important ideas? Findings from project 2061's curriculum evaluation study: Life science. *Journal of Research in Science Teaching*, *41*(6), 538–568. Retrieved from http://doi.org/10.1002/tea.20019

Tran, N. A., & Nathan, M. J. (2010). Pre-college engineering studies: An investigation of the relationship between pre-college engineering studies and student achievement in science and mathematics. *Journal of Engineering Education*, *99*(2), 143–157. Retrieved from http://doi.org/10.1002/j.2168-9830.2010.tb01051.x

Trautwein, U., Lüdtke, O., Kastens, C., & Köller, O. (2006). Effort on homework in grades 5–9: Development, motivational antecedents, and the association with effort on classwork. *Child Development*, *77*(4), 1094–1111. Retrieved from http://doi.org/10.1111/j.1467-8624.2006.00921.x

Wendell, K., & Rogers, C. (2013). Engineering design-based science, science content performance, and science attitudes in elementary school: Engineering design-based science in elementary school. *Journal of Engineering Education*, *102*(4), 513–540. Retrieved from http://doi.org/10.1002/jee.20026

Wigfield, A., & Eccles, J. S. (2000). Expectancy–value theory of achievement motivation. *Contemporary Educational Psychology*, *25*(1), 68–81. Retrieved from http://doi.org/10.1006/ceps.1999.1015

Yadav, A., Subedi, D., Lundeberg, M. A., & Bunting, C. F. (2011). Problem-based learning: Influence on students' learning in an electrical engineering course. *Journal of Engineering Education*, *100*(2), 253–280. Retrieved from http://doi.org/10.1002/j.2168-9830.2011.tb00013.x