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Measuring Metacognitive Awareness: Applying Multiple, Triangulated, and Mixed-Methods Approaches for an Encompassing Measure of Metacognitive Awareness

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Abstract

The article provides an overview of the quantitative analysis of teachers' metacognitive awareness. The purpose of the overview is to express the need for encompassing measures of metacognition for improving metacognitive awareness in the field of technology and engineering education. The data presented come from using the Metacognitive Awareness Inventory to measure technology and engineering teachers' metacognitive awareness at the end of 2 specific professional development (PD) programs. The study had a sample size of 21. Participants were combined into 3 groups based on their participation in the PD programs. Group 1 consisted of teachers that actively participated in the Transforming Teaching through Implementing Inquiry (T2I2) PD program. Group 2 consisted of teachers that were selected for but did not actively participate in T2I2 PD program. Group 3 consisted of teachers that completed the National Board for Professional Teaching Standards PD program.

Keywords: Metacognition, metacognitive awareness, technology and engineering

Metacognitive awareness, the deliberate ability to explain one's knowledge and regulation of cognition, is woven into the philosophy of human experience. Surpassing lived (sensory) experience, we delve into cognizing related to lived experience, the apprehension of experience. "Any lived experience tends to evoke immediately a knowing of its characters . . . and experiencer" (Spearman, 1923, p. 48).[1] As with metacognition, not only can experiences be thought about but so can cognition itself.

> I can know, not only *that* I know, but also *what* I know . . .. Indeed, such a cognizing of cognition itself was already announced by Plato . . .. Aristotle likewise posited a separate power whereby, over and above actually seeing and hearing, the psyche becomes aware of doing so. (Spearman, 1923, p. 52)

[1] According to Spearman (1923), the term *characters* "includes all attributes that do *not* mediate between two or more fundaments. Its main divisions are quality and quantity" (p. 66).

Aristotle's ideology on the mind's powers further established a foundation for metacognition as well as the mind's awareness of metacognition. Later philosophers, followers of Plato and Aristotle's doctrines including Strato, Galen, Alexander of Aphrodisias, and Plotinus, ranging from about 300 B.C. into late antiquity, continued to develop notions preceding the apperception of metacognition (Spearman, 1923; Georghiades, 2004).

Much later, educational psychologists including but not limited to Baldwin (1909), Binet (1909), Buhler (1907), Dewey (1910), Huey (1908), Locke (1924), and Thorndike (1914) continued to infer from observed phenomenon and advocate for cognitive knowledge and regulatory processes now considered component and subcomponents that constitute the psychological construct metacognition (as cited in Brown, 1987; see also, Georghiades, 2004). Jean Piaget's work on cognitive development psychology revealed that the stages of cognitive development were distinguishable, observable, and, with the proper method, measurable. Furthermore, "Piaget (1978) discussed the importance to human intelligence of the concept of reflected abstraction, with the result that cognitions be made stable and available to consciousness" (Campione, 1987, p. 120), "at which point they can be worked on and further extended (Campione 1987)" (Georghiades, 2004, p. 367).

Expanding on the work of Piaget, John Flavell (1976) was the first scholar to conceptualize the term *metacognition*. Flavell (1976) used the term *metamemory* to describe a person's knowledge of their own memory. Flavell (1976) also defined metacognition as "one's knowledge concerning one's own cognitive processes and products or anything related to them, e.g., the learning-relevant properties of information or data. For example, I am engaging in metacognition . . . if I notice that I am having more trouble learning *A* than *B*; if it strikes me that I should double-check *C* before accepting it as fact" (p. 232).

Succeeding Flavell's definition, the term *metacognition* has become ambiguous and is used synonymously to express several separate non-inclusive processes that are at best part of a metacognitive framework. The processes that underlie metacognition include but are not limited to: cognitive control, evaluating, goal setting, information management, judgments of learning, metalearning, metamentation, modeling, reflection, self-appraisal, self-management, self-monitoring, self-reflection, self-regulation, and self-questioning. As an example, the term reflection that is well represented in Locke (1924) and later Piaget's work is currently used in educational settings to circumscribe the process of being metacognitive. The variety of terms and definitions used in isolation yet equivalently associated with metacognition may be part of the reason that metacognition is considered ambiguous. "Flavell's definition was followed by numerous others, often portraying different emphases on (or different understanding of) mechanisms and processes associated with metacognition" (Georghiades, 2004, p. 365) and further contributing to the ambiguous nature of metacognition. The abstract, often unclear structure of metacognition makes measuring metacognition difficult and variable.

Measuring Metacognitive Awareness

Measuring metacognitive awareness entails utilizing metacognitive and research literature to develop a thorough understanding of metacognition, metacognitive processes and subprocesses, and research approaches. The research approach needs to allow for comprehensive data collection, analysis, and interpretation. Schraw (2000, 2009) and many others point out that no single research method or procedure of inquiry will allow for a complete understanding of a complex phenomenon like metacognitive awareness. For this reason, research using multiple, triangulated, and mixed-methods approaches is recommended (Pintrich, Wolters, & Baxter, 2000; Schraw, 2000, 2009). In conjunction with research methods and procedures for inquiry, the research design also needs to include the researcher's analysis of philosophical assumptions and worldviews. The assumptions and worldviews should be explicitly stated because they can impact the researcher's approach, perception, and interpretation. The time required to conduct thorough metacognitive research often results in a research design with one method and one inquiry that measures metacognition superficially.

Researchers continue to use either quantitative or qualitative measures of metacognition awareness in isolation despite the trade-offs associated with individual metacognitive awareness measures. Schraw (2000) detailed six themes that emerged from the Buros Symposium. Theme four was "most available instruments that measure metacognition have unknown psychometric properties" (Schraw, 2000, p. 301). This fact creates two issues in the quantitative measurement of metacognition: (a) the instruments specific design and narrow usability and (b) the lack of background information development (Baker & Cerro, 2000; Pintrich et al., 2000; as citied by Schraw, 2000). The Learning and Study Strategies Inventory (LASSI), Motivated Strategies for Learning Questionnaire (MSLQ), and Metacognitive Awareness Inventory (MAI) are three examples of quantitative self-reported measures that have psychometric reliability (Schraw, 2000). However, the LASSI and MSLQ only have metacognitive subscales and are more focused on learning strategies. A positive attribute of questionnaires is the ability to provide quick and objective measurement of metacognition, even with large sample sizes (Schellings & Van Hout-Wolters, 2011). The negative aspect of questionnaires like the MAI relates to their validity (Harrison & Vallin, 2018). It is worth noting that researchers like Harrison and Vallin (2018) are doing the quantitative metacognitive measurement analysis research suggest by Schraw (2000) and others.

Using qualitative measures provides a more complete, in-depth perception of metacognition when paired with other methods of inquiry. The use of interviews to provide depth to an investigation is a positive reason for including interviews in the research approach (Creswell, 2007; Denzin & Lincoln, 1994). During an interview, the researcher can ask the participant to provide more detail about information that arises. This ability allows interviews to provide a more complete perspective of participant's metacognition in conjunction with quantitative measures. The required time for the participant and researcher to complete adequate length interviews is a major consideration when determining if interviews are appropriate. In addition to the time required for the interview, the time required to transcribe and code the interviews must also be considered (Creswell, 2007; Denzin & Lincoln, 1994). Interviews are also a self-reported measurement, implying that the participant's honesty, reluctance to share, and ability to understand the questions may be an issue. Consequently, it is important for the researcher to create an environment that is comfortable for both the researcher and the participant (Denzin & Lincoln, 1994).

Other qualitative objective behavior measures of metacognition include observations, think-aloud protocols, and performance evaluations. Think-aloud protocols are used so that the researcher can hear and see what the participant is doing during a task. There are two main problems with using a think-aloud protocol to measure metacognition (Scott, 2008). The first problem is that the participant may be more focused on thinking aloud rather than completing the cognitive task. The second problem relates to the functional use of think-aloud protocols. There is an appropriate time and place for think-aloud protocols (Scott, 2008). Group settings often make the use of think-aloud protocols inappropriate (Scott, 2008). In addition to think-aloud protocols, observations and performance evaluations also have trade-offs. Observations and performance evaluations can be used to determine participants' metacognitive actions. There may be a disconnect between apparent internal and external processes when using observations and performance evaluations. Additionally, like interviews, observations and performance evaluations are difficult and require time to implement and analyze even with a small number of participants.

Background

This study was purposefully conducted in conjunction with the research study presented in Hughes (2017). The combination of the data analyses in this study and in Hughes (2017) could aptly be considered a complementarity design. The overall purpose of the data collection, analysis, and interpretation presented in Hughes (2017) was to elaborate on the quantitative data collected and presented here. Other than complementarity, this design should also be considered convergent. As a convergent design, the analysis of the quantitative and qualitative data was performed separately. After the quantitative and qualitative data were analyzed separately, the data were then merged for comparative analysis to determine the convergence and divergence of metacognitive awareness components measured by the interview and MAI

(Creswell, 2014). The design of the interview being based on the MAI provided a deeper, more complete understanding of the participants' metacognitive awareness.

In the study of a complex phenomenon, it is recommended that the researcher selects from multiple, triangulated, and mixed-methods approaches to offer thorough data collection for an encompassing measure. As stated above, the researcher's assumptions and subjectivity become essential for the reader's interpretation of results from the study. A reader should understand that the researcher is innate in the presentation of findings. As the researcher in this study, being objective may allow my subjectivity to comprehend metacognition as it exists. However, my subjectivity and assumptions may bias my perception of reality, making their analysis and presentation important. Subjectively, metacognition is extremely important for teachers and students' success, especially because of the complexity involved in teaching and learning science, technology, engineering, and mathematics disciplines. Furthermore, the assumption that metacognition is an important attribute for teachers or anyone dealing with high levels of complexity is based on being metacognitive during personal experiences involving complex thinking in relationship to engineering and teaching. This assumption leads to the belief that for technology and engineering teachers to adequately prepare students metacognitively for complex disciplines like engineering, they will need to develop more awareness of their own metacognition (Brophy, Klein, Portsmore, & Rogers, 2008; Hughes, 2017).

This study involved two different professional development (PD) programs, Transforming Teaching through Implementing Inquiry (T2I2) and the National Board for Professional Teaching Standards (NBPTS). Although completion of either the T2I2 or the NBPTS programs involves metacognitive experiences, metacognitive development is not a primary focus of either PD program. Because of T2I2's connection with the NBPTS and its use of certain characteristics of PD, the T2I2 program had a notable connection to metacognitive practices. T2I2 sought to promote technology and engineering teacher' attainment of national board certification by aligning with NBPTS. Based on the alignment between T2I2 and NBPTS, the guiding question of this study was: How do T2I2 participants' compare to nationally board certified technology and engineering teachers in terms of metacognitive awareness? This study was conducted over a 16-week period during fall 2014. After participants made an informed decision to participate, each was assigned a unique identifying number. The participant's MAI was encrypted with that number. The participants were sent the MAI in an email. Once all the MAIs were returned, the analysis of the data began by entering the participants' self-reported values on the MAI into the Statistical Package for the Social Sciences (SPSS).

Rationale

Metacognitive research often focuses on students' thinking and regulation because of the belief that metacognitive awareness helps students to become better, more self-regulated learners (Harskamp & Henry, 2009; Schwartz & Perfect, 2002; Robson, 2006). Recently, metacognitive research has included a focus on teachers' metacognition corresponding with the belief that teachers lacking metacognitive awareness are unable to help students develop their metacognitive awareness (Harskamp & Henry, 2009; Kramarski & Michalsky, 2009; Prytula, 2012). Teacher PD has received attention as an available method to strengthen teachers' metacognitive awareness (Prytula, 2012; Wilson & Conyers, 2016).

The literature indicates that measuring metacognitive awareness is difficult (Akturk & Sahin, 2011; Harrison & Vallin, 2018; Schraw, 2009). In designing this study, previous studies provided information on common methods for measuring metacognition. The literature comprising the foundation of these studies was used to evaluate the strengths and weaknesses of different methods in measuring metacognition. As metacognitive and research literature suggested for studying complex phenomenon, this study in conjunction with Hughes (2017) used two methods and procedures of inquiry. The use of the MAI in this study was also supported by the metacognitive and research literature. The Kruskal-Wallis one-way analysis of variance by ranks was used to compare grouped participant's metacognitive awareness. The Kruskal-Wallis test was selected based primarily on three reasons: (a) the ability to compare two or more independent groups, (b) the small sample size of this study resulting in nonnormally distributed data, and (c) the ranking of data to decrease impact of outliers (Sheskin, 2004). The Kruskal-Wallis is considered an extension of the Mann-Whitney U test but is designed to be used with two or more independent samples (Sheskin, 2004). The Kruskal-Wallis test operates under the assumptions of randomized selection of participants, group independence, continuous variable, and homogeneity of variance. When using a nonparametric statistic like the Kruskal-Wallis test, many researchers believe that there is an increased importance placed on validating the assumptions (Sheskin, 2004). Metacognitive awareness is not a continuous variable when using the MAI. The continuous variable assumption is frequently not adhered to during the Kruskal-Wallis test with approval (Sheskin, 2004). Additionally, researchers commonly fail to check homogeneity of variance. There are several statistical tests that measure homogeneity of variance. Most commonly used with a Kruskal-Wallis test is a nonparametric Levene's test (Sheskin, 2004). The null hypothesis of the Kruskal-Wallis one-way analysis of variance by ranks is that the mean rank scores of Group 1 equal the mean rank scores of Group 2, which is continued for all *k* groups (Sheskin, 2004).

To test homogeneity of variance in the context of the Kruskal-Wallis test, the nonparametric Levene's test was used. The two most common tests for homogeneity of variance are the Levene's test and the Brown-Forsythe test (Sheskin, 2004). The Levene and the Brown-Forsythe test would have similar results. The Brown-Forsythe test is sometimes selected because it is less impacted by the violation of the normality assumption (Sheskin, 2004). The nonparametric Levene's test compares the absolute difference of the ranked scores of each participant's metacognitive awareness and the mean of the rank scores. The nonparametric Levene's test is considered the most powerful and robust test for homogeneity of variance with non-normal distributed data (Nordstokke & Zumbo, 2010).

Method

Instrumentation

In this study, the purpose of the MAI was to collect quantitative data on participants' current level of metacognitive awareness, knowledge of cognition, and regulation of cognition. The data were used to compare the three groups on their level of metacognitive awareness. Additionally, the groups were compared based on the knowledge and regulation of cognition components of metacognitive awareness. Schraw and Dennison (1994) indicated that the MAI provided a "reliable initial test of metacognitive awareness" when used with adults (p. 472). The MAI has been identified as the only currently available, reliable psychometric measure ($\alpha = .90$; Schraw and Dennison, 1994) that focuses on metacognitive awareness (Baker & Cerro, 2000; Pucheu, 2008).

The MAI consists of two main components and eight subcomponents of metacognition, which are rated at five levels of awareness. Each one of the 52 questions align with one of the eight subcomponents. One main component from the MAI, Knowledge of Cognition, includes the following subcomponents and corresponding items from the MAI: Declarative Knowledge (Items 5, 10, 12, 16, 17, 20, 32, and 46), Procedural Knowledge (Items 3, 14, 27, and 33), and Conditional Knowledge (Items 15, 18, 26, 29, and 35). The other main component, Regulation of Cognition, includes the following components and items from the MAI: Planning (Items 4, 6, 8, 22, 23, 42, and 45), Organizing (Items 9, 13, 30, 31, 37, 39, 41, 43, 47, and 48), Monitoring (Items 1, 2, 11, 21, 28, 34, and 49), Debugging (Items 25, 40, 44, 51, and 52), and Evaluating (Items 7, 19, 24, 36, 38, and 50). The five levels of awareness are *Always True* (5), *Sometimes True* (4), *Neutral* (3), *Sometimes False* (2), and *Always False* (1).

Participants

Participants in this study were divided into the same three groups as presented in Hughes (2017): (Group 1) teachers who actively participated in and completed the T2I2 PD program; (Group 2) teachers who had been selected for but did not participate in the T2I2 program, completing less than 11% of the PD program; and (Group 3) teachers who had received National Board

Certification (NBC) in CTE from the NBPTS. The participants were technology and engineering teachers from three states: Illinois, North Carolina, and Virginia. A combined total of 73 state-certified technology and engineering teachers were initially identified for possible participation in this study based on their involvement in one of the two PD programs. In an attempt to have equal group sizes and knowing the group with the least possible participants, 10 teachers from each group where randomly selected to participate. The 30 teachers received an email explaining the study and requesting their participation. A total of 21 teachers initially responded and completed the MAI, and a total of 18 teachers completed both the MAI and interview presented in Hughes (2017). Three participants only completed the MAI portion of the study with almost no demographic data collected, two females from Group 1 and one female from Group 3 (Table 1).

Table 1
Participant Group Demographics

	Gender *n* (%)		Years of Experience			Grade level taught *n* (%)	
Group	M	F	*n*	Mean	*SD*	Middle school	High school
Group 1	5 (62.5%)	3 (37.5%)	6	20	11	3 (50.0%)	3 (50.0%)
Group 2	4 (66.7%)	2 (33.3%)	6	17.3	8.5	1 (16.7%)	5 (83.3%)
Group 3	3 (42.9%)	4 (57.1%)	6	21.5	8.2	3 (50.0%)	3 (50.0%)
Combined	12 (57.1%)	9 (42.9%)	18	19.6	8.9	7 (38.9%)	11 (61.1%)

Comparing Participants

The Kruskal-Wallis one-way analysis of variance by ranks was used to test if gender, teaching experience, path to certification, or grade level taught was resulting in a difference between participants metacognitive awareness based on their completion of the MAI. The first analysis compared the males' metacognitive awareness to the females' metacognitive awareness. The Kruskal-Wallis test using gender as the independent variable resulted in a chi-square value of 2.79, 1 degree of freedom, and a *p*-value of .095 (Table 2). Based on these findings, the null hypothesis that males' metacognitive awareness equaled females' metacognitive awareness was supported. Next, the Kruskal-Wallis test was used to determine whether the participants' teaching experience impacted their metacognitive awareness. For this test, participants were compared in three reformed groups based on experience: (a) participants with 5 to 14, (b) 16 to 23, and (c) 27 to 34 years of teaching experience. The Kruskal-Wallis test using experience as the independent variable resulted in a chi-square value of .947, 2 degrees of freedom, and a p-value of .623 (Table 2). Based on these findings, the null hypothesis that groups based on years of experience are equal in terms of their metacognitive awareness was supported.

Then, the Kruskal-Wallis test was used to compare lateral-entry teachers' metacognitive awareness to traditionally certified teachers' metacognitive awareness. The Kruskal-Wallis test using certification path as the independent variable resulted in a chi-square value of .316, 1 degree of freedom, and a p-value of .574 (Table 2). Based on these findings, the null hypothesis that lateral entry teachers' metacognitive awareness equaled traditionally certified teachers' metacognitive awareness was supported. Then, the Kruskal-Wallis test was used to compare middle school teachers' metacognitive awareness to high school teachers' metacognitive awareness. The Kruskal-Wallis test using grade level taught as the independent variable resulted in a chi-square value of .461, 1 degree of freedom, and a p-value of .497 (Table 2). Based on these findings, the null hypothesis that middle school teachers' metacognitive awareness equals high school teachers' metacognitive awareness was supported.

T2I2 Amount Completed

The primary focus of this study was based on the premise that Groups 1 and 2 completed different amounts of PD in the T2I2 program. Group 1 completed from 20% to 100% of T2I2. It is also worth noting that the majority (75%) of Group 1 participants completed 100% of T2I2. Group 2 had a range of T2I2 completed from 0% to 11%. The majority (75%) of Group 2 participants completed 5% or less of T2I2. The Kruskal-Wallis test was used to determine whether the difference in the amount of T2I2 completed between Groups 1 and 2 was significant. The Kruskal-Wallis test using amount of T2I2 completed as the independent variable resulted in a chi-square value of 10.4, 1 degree of freedom, and a p-value of .001 (Table 2). Based on these findings, the null hypothesis that the amount of T2I2 completed by Group 1 equals the amount of T2I2 completed by Group 2 was rejected. Group 3 was not involved with T2I2 and therefore was not involved in this analysis. Additionally, for Group 3 participants to have NBC, they were required to complete 100% of the NBPTS PD.

Table 2
Kruskal-Wallis Test Comparing Participants

Variables	*n*	Mean rank	Chi square	*df*	*p*
Gender					
Male	12	13.81	2.793	1	.095
Female	9	4.00			
Experience (in years)					
5 to 14	6	8.00			
16 to 23	6	9.50	.947	2	.623
27 to 34	6	11.00			
Certification					
Traditional	6	10.50	.316	1	.574
Lateral	12	9.00			
Grade taught					
Middle	7	10.57	.461	1	.497
High	11	8.82			
Amount of T2I2 completed					
Group 1 (20–100%)	8	10.50	10.40	1	.001
Group 2 (0–11%)	6	3.50			

Procedure

The nonparametric Levene's test was used to validate the homogeneity of variance assumption (Sheskin, 2004). The null hypothesis of the nonparametric Levene's test is that the variances are equal. The nonparametric Levene's test resulted in an F-statistic of 2.249 and a p-value of .134. This indicated that the homogeneity assumption was valid for the metacognitive awareness data collected with the MAI.

Each group's level of metacognitive awareness was determined by the mean of responses to the 52 items by participants in that group. To determine each participant's awareness of their knowledge of cognition, the mean value was calculated based on the person's answers to the 17 items that corresponded with the knowledge component. The participant's awareness in the regulation of cognition component was the mean value of the other 35 items on the inventory that corresponded with the regulation component. The groups were compared on metacognitive awareness and its components using the Kruskal-Wallis test.

The Kruskal-Wallis test was used to compare the groups on three items from the MAI, including: (a) metacognitive awareness, (b) knowledge of cognition, and (c) regulation of cognition. The Kruskal-Wallis test was used four times for the different group combinations: Groups 1, 2, and 3 (Table 3); Groups 1 and 2 (Table 4); Groups 2 and 3 (Table 5); and Groups 1 and 3 (Table 6). Using SPSS to calculate Kruskal-Wallis produced a chi-square value that could be used to calculate an effect-size estimate known as eta squared. The effect-size estimate determined the percent of variability in the rank scores from the Kruskal-Wallis test, and it accounted for differences in the teachers' metacognitive awareness based on their participation in PD. In this study, the effect size was used to represent the strength of the relationship between the independent and dependent variables.

Results

Table 3 shows the results of the omnibus Kruskal-Wallis analysis, which included all three groups. In this case, the Kruskal-Wallis test looked for any difference in the three components among the three groups. Table 3 displays the mean rank scores for each group in each component. Group 2 had the lowest mean rank score in each component. In Table 3, the significance column illustrates that all three of the components were statistically significant at an alpha level of .05. In this test, the analysis did not indicate which group was different from another group. Later tests directly compared one group to another group. Also shown in Table 3 is the eta-squared value for each component. Eta squared quantifies the amount that the groups differed for each component. In Table 3, the eta-squared value for metacognitive awareness was .535, signifying that 53.5% of the variability in the rank scores for metacognitive awareness was accounted for based on the groups' participation in PD.

Table 3
Kruskal-Wallis Test for Metacognitive Awareness All Three Groups

Component	Group	*n*	Mean rank	Chi square	Eta squared	*p*
Metacognitive awareness	1	8	13.81	10.705	.535	.005
	2	6	4.00			
	3	7	13.79			
Regulation of cognition	1	8	13.63	11.239	.562	.004
	2	6	3.83			
	3	7	14.14			
Knowledge of cognition	1	8	13.50	6.299	.315	.043
	2	6	5.67			
	3	7	12.71			

Table 4 shows a direct comparison between Groups 1 and 2 using the Kruskal-Wallis test. In this case, the Kruskal-Wallis looked for a difference in the three components between Groups 1 and 2. Group 2 again had the lower mean rank score in all three components. The results of the Kruskal-Wallis test comparing Groups 1 and 2 indicated that Group 1 had a higher level of metacognitive awareness.

Table 4
Kruskal-Wallis Test for Metacognitive Awareness Groups 1 and 2

Component	Group	*n*	Mean rank	Chi square	Eta squared	*p*
Metacognitive awareness	1	8	10.38	8.817	.678	.003
	2	6	3.67			
Regulation of cognition	1	8	10.38	8.836	.680	.003
	2	6	3.67			
Knowledge of cognition	1	8	9.69	5.127	.394	.024
	2	6	4.58			

Table 5 shows a comparison between Groups 2 and 3 using the Kruskal-Wallis test. The results of this test were not unlike the comparison of Groups 1 and 2 because Groups 1 and 3 had similar mean rank scores and Group 2 had the lowest mean rank scores. The Kruskal-Wallis was again testing to determine whether the differences in mean rank scores was significant between Groups 2 and 3. The results of the Kruskal-Wallis test comparing Groups 2 and 3 indicated that Group 3 had a higher level of metacognitive awareness with a chi-square value of 7.388, 1 degree of freedom, and a *p*-value of .007 (Table 5).

Table 5
Kruskal-Wallis Test for Metacognitive Awareness Groups 2 and 3

Component	Group	*n*	Mean rank	Chi square	Eta squared	*p*
Metacognitive awareness	2 3	6 7	3.83 9.71	7.388	.616	.007
Regulation of cognition	2 3	6 7	3.67 9.86	8.186	.682	.004
Knowledge of cognition	2 3	6 7	4.58 9.07	4.315	.360	.038

The previous Kruskal-Wallis tests showed that Groups 1 and 3 had a higher level of metacognitive awareness than Group 2 based on the data from the MAI. Table 6 shows a comparison between Groups 1 and 3 using the Kruskal-Wallis test. In Table 6, the significance column shows that all three components were above the alpha of .05. This use of the Kruskal-Wallis tested the null hypothesis that Group 1's metacognitive awareness was equal to Group 3's metacognitive awareness. Based on the *p*-values in Table 6, Group 1's metacognitive awareness was similar to Group 3's metacognitive awareness. In fact, metacognitive awareness had a chi-square value of .003, 1 degree of freedom, and a *p*-value of .954, indicating a significant similarity.

Table 6
Kruskal-Wallis Test for Metacognitive Awareness Groups 1 and 3

Component	Group	*n*	Mean rank	Chi square	Eta squared	*p*
Metacognitive awareness	1 3	8 7	7.94 8.07	.003	.000	.954
Regulation of cognition	1 3	8 7	7.75 8.29	.054	.004	.817
Knowledge of cognition	1 3	8 7	8.31 7.64	.085	.006	.771

Implications

The findings of this research in relation with the findings presented in Hughes (2017) relate to metacognitive research design; PD effectiveness, design, and focus; and teachers in general. However, the technology and engineering education field might find the results presented here and in Hughes (2017) of particular interest. Knowing how to measure and ensure positive influence on metacognitive awareness will benefit both students and teachers in the technology and engineering education field. Technology and engineering teachers focus on hands-on learning and associated thinking; integrally applying science and mathematics to solve ill-structured open-ended problems; and numerous other complex concepts including design, modeling, systems, and creativity inflating the need for metacognitive awareness (Brophy et al., 2008). Brophy, Klein, Portsmore, and Rogers (2008) do not explicitly state metacognitive awareness as a need but do reference content and cognitive knowledge and regulation (control) components of metacognitive awareness as key to advancing the teaching and learning of engineering. Remembering that when the technology and engineering education field discusses higher order thinking, systems thinking, critical thinking, cognitive processes, aspects of cognitive control (e.g., reflection), and other intrinsically cognitive activities, the field is referencing processes that are and should be considered part of a metacognitive framework.

The first finding from this study indicated that Groups 1 and 3 had similar levels in metacognitive awareness, knowledge of cognition, and regulation of cognition components. The metacognitive awareness interview results presented in Hughes (2017) converged with this finding of the MAI data analysis. Overall, based on the MAI and interview results, Groups 1 and 3 had similar levels of metacognitive awareness, knowledge of cognition, and regulation of cognition. The second finding indicated that Groups 1 and 3 had higher levels of metacognitive awareness, knowledge of cognition, and regulation of cognition when compared with Group 2. Hughes (2017) implies that each group's metacognitive awareness could indicate their likelihood to successfully complete PD, especially self-regulated PD programs like T2I2 and NBPTS. The interview results converged with MAI results that Groups 1 and 3 had higher levels than Group 2 in metacognitive awareness and regulation of cognition but diverged on the knowledge of cognition component (Hughes, 2017). The MAI results indicated that Groups 1 and 3 had higher levels in the knowledge of cognition component. Based on the interview results, all three groups had similar, medium to low, levels of knowledge of cognition (Hughes, 2017). The MAI and interview data also diverged in another area. The MAI and interview results suggested a difference between the groups on the regulation of cognition component. However, the MAI data only indicated a difference, whereas the interview data expressed unique differences.

The similarities and differences in the MAI and interview data support that no single research method or procedure of inquiry will allow for a complete understanding of a complex phenomenon like metacognitive awareness. Additionally, the uniqueness of each group's metacognitive awareness, especially in the regulation of cognition component, seen during the interview data analysis further supports that no single method will provide a thorough understanding of metacognitive awareness. The uniqueness of each group's metacognitive awareness seen in the interview results further supports the ambiguity of metacognition (Hughes, 2017). There is no single word or process that would adequately describe each group's metacognition. Metacognition encompasses several components, subcomponents, and processes that function together in varying combinations. The uniqueness of each group's metacognition further supports the importance for the researcher to have an informed understanding of metacognition. Metacognition is complex because it characterizes a multitude of cognitive as well as noncognitive processes. Metacognition has surpassed its philosophical acknowledgement by becoming a mainstay in educational psychology, teacher preparation, teacher PD, and modern classrooms. As technology and engineering education continues to include increasingly complex connections between thinking and doing, teachers' and students' metacognitive awareness will remain important for teaching and learning.

Conclusions

The intent of this article was to acknowledge the complexity of metacognition, demonstrating that metacognition should be measured using more than one method and procedure of inquiry for encompassing results. The intent of the data collection presented here was to provide an initial measure of metacognition awareness for each group of participants to compare their level of metacognitive awareness. Prior to collecting data, it was believed that successful PD completers would have higher levels of metacognitive awareness, knowledge of cognition, and regulation of cognition. Based on the MAI data presented in this article, that would appear to be the case. However, when the MAI data are compared with the interview data from Hughes (2017), there is convergence and divergence between both data analyses. The significant differences seen in the knowledge of cognition component of the quantitative data were not paralleled by the results of the qualitative data. The qualitative data suggested similarity between groups in the knowledge of cognition component (Hughes, 2017). The significant differences from the quantitative data in regulation of cognition were represented as more of uniqueness differences in the regulation of cognition subcomponents between groups in the qualitative data (Hughes, 2017).

Technology and engineering teachers engage students in ill-structured, open-ended problem-solving and design activities integrating science, technology, engineering, and mathematics content requiring thoughtful teacher practices. The complex thinking involved with the interdisciplinary approach of content and pedagogical knowledge required for technology and engineering education requires teachers to cognitively prepare, monitor, adapt, and reflect (Barak, 2010; Kramarski & Michalsky, 2009; Lin, Schwartz, & Hatano, 2005). Metacognitive awareness expressed by content and cognitive knowledge and regulation components from the technology and engineering education field implies the importance of metacognitive awareness development (Barak, 2010; Hughes, 2017; Petrina, Feng, & Kim, 2008). This article is applicable to future work in measuring complex phenomenon like metacognitive awareness and the approach to studying metacognition.

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Task Affect and Task Understanding in Engineering Problem Solving

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Abstract

Within the self-regulated learning literature, motivation is considered to be an essential feature of students' self-regulatory processes. Additionally, task affect (i.e., personal objectives and task value) is thought to influence students' self-regulatory processes; insufficient task affect may lead to failures to self-regulate effectively. In a school setting, task affect is a form of motivation for completing the course tasks in order to attain course-level goals that are inherently valued. In this study, motivation is operationalized as students' personal objectives and task values, and self-regulation refers to students' understanding of tasks (also called task interpretation skill) involved in a course. This study investigates changes in students' task interpretation skill, personal objectives for learning, and task values, if any, while engaged in engineering problem-solving activities in a 2nd-year introductory thermodynamics course. This study also seeks to explore whether patterns exist between students' task understanding, personal objectives for learning, and task value while engaged in problem-solving activities throughout the course. The findings suggest that, as the semester progressed, both students' task value for the course and their focus on mastering the course material were continuously developed. Similarly, students' explicit and implicit task interpretation skills also improved as they engaged in problem-solving activities. However, it was found that implicit task interpretation skill was not developed as fully as explicit task interpretation when solving a complex problem; students seemed to understand 64–77% of the explicit and 39–49% of the implicit information presented to them.

Keywords: Engineering education; Personal objectives; Problem solving; Self-regulated learning; Task values; Task understanding

The idea for this study was generated by researchers' claims that students' motivation influences their self-regulatory processes (Butler & Cartier, 2004b; Miller & Brickman, 2004; Schunk, 1994). When confronted with a problem or task, students usually begin by generating thoughts, feeling, and actions focused on attaining the best solution to that problem (Butler & Cartier, 2005; Pekrun, 2006). Ideally, those self-generated thoughts, feelings, and actions support effective forms of self-regulation.

Task interpretation (TI) is an important key component of self-regulation in action (Butler & Cartier, 2004a, 2004b; Cartier & Butler, 2004). Students' TI skill is an essential work habit in the pursuit of effective learning. Task interpretation skill includes students' ability to thoroughly interpret the demands of activities or tasks they are assigned. Research, however, suggests that students do not always approach activities as instructors intend (Butler, 1998; Cartier, 1997; Lawanto, et al., 2018; Wong, 1999). For example, significant gaps have been found between instructors' and students' TI skills in solving engineering problems (Lawanto et al., 2018).

Although Calkins, Willoughby, and Arnold (1982) reported that students' personal attributes may contribute to their academic achievement, it is not yet clear how students' personal attributes contribute to the quality of their task interpretation TI during engineering problem solving. Task affect (TA), such as students' personal objectives and task values in a course, interact with their TI and shapes the quality of their problem-solving activities. Thus, TA is part of students' metacognitive knowledge about tasks (Flavell, 1979). This study focused on the key roles of TA and TI as part of iterative problem-solving processes.

Literature Review

Task Understanding as the Heart of Self-Regulated Learning

Self-regulated learning (SRL) posits that students' metacognitive, behavioral, and motivational engagement in their cognitive processes play an essential role in successful and enduring learning (Andrade & Valtcheva, 2009; Boekaerts, 1997; Coutinho, 2007; Lawanto, Butler, Cartier, Santoso, & Goodridge, 2013; Otero, Campanario, & Hopkins, 1992; Wolters, 1998; Zimmerman, 1989). According to Zimmerman (1989), self-regulated learners are "metacognitively, . . . motivationally, and behaviorally active participants in their own learning process" (Zimmerman, 1989, p. 329); therefore, self-regulated learners are skilled in goal setting, self-monitoring, self-instruction, and self-reinforcement (Schraw, Crippen, & Hartley, 2006). In this study, SRL is defined as students' repository of knowledge and skills for planning, implementing, monitoring, evaluating, and continually improving the learning process (Butler & Cartier, 2005; Butler & Winne, 1995). Students with strong SRL skills are considered more knowledgeable and responsible for their cognition (Pintrich, 2002) and expected to accomplish cognitive actions more successfully (Paris, 1986). Students with weak SRL skills may benefit from instructional practices that are purposely designed to improve students' metacognition, interest, and motivation for learning (Coutinho, 2008; Marchis, 2011; Samuelsson, 2008).

Although SRL is directly tied to metacognition as a cognitive control process, it also involves the actions that students take based on their metacognitive knowledge. For example, Dinsmore, Alexander, and Loughlin (2008) suggest that there is a "clear cognitive orientation for metacognition, while self-regulation is as much concerned with human action than the thinking that engendered it" (p. 405). Researchers maintain that to understand the interplay between self-regulation and metacognition is to understand "the correspondence between metacognition and action. How do thoughts and feelings of students guide their thinking, effort, and behavior?" (Paris & Winograd, 1990, p. 21).

The dynamic and iterative interplay between metacognitive and cognitive activities is described by Butler and Cartier (Brydges & Butler, 2012; Butler & Cartier, 2005; Butler & Winne, 1995). Their model involves layers of context, individual attributes, mediating variables, TI and personal objectives, self-regulating processes, and cognitive strategies. During engineering problem solving, multiple contexts may include learning expectations in engineering as a field of study, the nature of problem-solving tasks, and the expectations of the instructor.

Recognizing the ways in which multiple interwoven contexts shape and constrain the quality of student engagement in learning is essential for SRL understanding. The individual attributes that students bring to the learning context are, among others, strengths, challenges, interests, and preferences. Over time, students accumulate a learning history that shapes the development of knowledge, skills, self-perceptions, attitudes toward school, and concepts about academic work (Butler & Cartier, 2004a; Cartier & Butler, 2004; Schoenfeld, 1988). The mediating variables include students' knowledge, perceptions about competence and control over learning, and perceptions about activities and tasks. Variables also include emotions experienced before, during, and after completing a task. These mediating variables impact the way students interpret any tasks they encounter.

Task interpretation refers to students' construction of an internal representation of the externally assigned task (Butler & Cartier, 2004b; Hadwin, Oshige, Miller, & Wild, 2009) and is the heart of SRL, insofar as it shapes key dynamic and recursive self-regulating processes. It is anticipated that TI and TA influence how students activate self-regulating and cognitive actions during problem-solving activities. This research focuses on explicit and implicit information about tasks, two layers of information suggested in Hadwin, Oshige, Miller, and Wild's (2009) model of task understanding. Explicit features of a task include information that is overtly presented in problem descriptions found in the course textbook and class discussions. Implicit features of a task include any information beyond the problem description, such as relevant concepts and useful resources needed to solve problems.

Through effective TI and SRL, problem solving can be conceptualized as a series of steps that may include self-perception about the value of the class or assigned problems associated with the class, reading the problem statements, self-asking critical questions associated with explicit and implicit features of the task, and understanding of the problem to be solved. In previous studies, it has been found that students generally have an incomplete understanding of the assigned tasks and often struggle to establish a connection between what they have learned and tasks they are required to complete (Lawanto et al., 2018; Lawanto, Butler, Cartier, Santoso, Goodridge, Lawanto, & Clark, 2013).

Task Affect in Problem Solving

Task affect is broadly defined as students' emotion toward an engaged task, which may manifest as their personal objectives (PO) and task value (TV) during the TI process. Students' PO relate to the reasons why individuals engage in given tasks. In this study, PO refers to the beliefs that induce one to approach, engage in, and respond to tasks in different ways (Ames, 1992). Research on goal orientation (GO) has shown that there are two general GO: mastery and performance. Mastery refers to the one's focus on learning and mastering the material; performance refers to one's demonstration of abilities and achievement to others (Wolters, Yu, & Pintrich, 1996). Mattern (2005) found that there is a difference in terms of students' achievement between mastery-learning and performance-learning groups and that students who held mastery-learning GO obtained higher achievement outcomes compared with those who held performance-learning GO.

Task value refers to students' perceptions of the extent to which the task is important (attainment value), interesting (intrinsic value), and useful (utility value; Eccles, 1983; Pintrich, Smith, Garcia, & McKeachie, 1991). Task attainment value refers to students' perceived importance of a task with respect to their identity or competence in a particular domain (Wigfield, 1994). Using a cognitive perspective, Markus and Wurf (1987) related this aspect to individual self-schemata. Understanding students' prior knowledge will be helpful to posit the design task in their existing schemata. Interest refers to subjective interest in the activity. Usefulness is determined by the extent to which students relate the task to their short- and long-term goals. Previous studies have reported that TV is often positively related to self-efficacy, and both TV and self-efficacy have been documented as effective predictors of academic outcomes (Bong, 2004; Multon, Brown, & Lent, 1991).

Research Design and Method

Purpose and Research Questions

The purpose of this study is to investigate changes in students' task interpretation (TI) skill and task affect (TA), if any, while engaged in problem-solving tasks during an introductory engineering thermodynamics course. This study also seeks to understand whether improvements in students' task value (TV) and emergent use of mastery learning goal orientation (GO) are reflected in changes in students' task interpretation skill during the course. Findings from this research are expected not only to improve the effectiveness of teaching engineering problem solving but also to develop more positive attitudes toward problem solving among engineering students.

Two research questions were developed to guide this research:

1. How are changes in students' TV, if any, reflected in changes of students' PO throughout the course?
2. How do student's TI skills change while engaged in problem-solving tasks throughout the course?

Context of the Study

Engineering Thermodynamics, a foundational sophomore-level course that is required for mechanical engineering and related majors, was selected as the context of this study. The goal of this course is to examine the relationships between different energy forms (i.e., heat and work) and to develop students' ability to analyze energy transformation processes and cycles. Within the course, weekly problem sets were assigned in the manner proposed by Kearsley and Klein (2016). Problem solving assignments were posted electronically to the course learning management system (LMS) and students were given one week to solve and turn in their handwritten solutions by scanning and uploading them to the LMS. Once students submitted their prepared solutions, the instructor posted detailed solution procedures for the problem sets. Students were expected to review their work against the posted solutions, correct their work with a different color marker, and re-submit their corrected work to the LMS. Students were also asked to reflect on their work and add notes or comments to their papers highlighting ideas or concepts they learned during the correction process. Student assignments were graded using a rubric that considered the effort exhibited during the first submission and the manner the work was corrected and annotated for the second submission.

Initially, 112 students volunteered to participate in the study; however, only sixty-eight (68) students (10 female and 58 male) completed all the data collection tasks during in the study. Participation was voluntary and participants were reminded that they could withdraw at any time. The participants were informed of the purpose of the study during class by a researcher who was not the course instructor. The researchers encouraged students to participate by offering compensation for their participation in the form of a maximum of eight extra credit points. Students who chose not to participate were given the opportunity to earn equivalent extra credit points by working on other assignments requiring a similar level of effort. Students who participated were required to sign a consent form as part of the processes approved by the Institutional Review Board.

Instruments

The participants' PO, TV, and TI were collected using an open-ended survey, a modified version of the Motivated Strategies for Learning Questionnaire (MSLQ), and Task Analyzer Questionnaires (TAQ), respectively.

The open-ended survey asked students to provide an explanation of three personal objectives clarifying what they would like to gain from taking this class.

The MSLQ is a self-reporting instrument developed by Pintrich, Smith, Garcia, and McKeachie (1991) to assess college students' motivational orientations and their use of different learning strategies. The Cronbach's alpha coefficient of this TV scale was .90. For this study, MSLQ's modifications were made in order to restate the questions in the context of this study. For example, the statement "It is important for me to learn the course material in this class" in the MSLQ and was modified to read "It is important for me to learn the skills/content taught in MAE2300 Thermodynamics." The wording of the questionnaire became the focus of instrument modification because students typically distinguish between their capabilities for dealing with two or more characteristically different topics or problems within the same measurement parameter (Bong, 1999). Face validity was conducted prior the data collection by involving five students and two content experts, and found these modifications did not introduce any threat to the instrument validity. When filling-out the modified TV-MSLQ, students rated themselves on a 7-point Likert scale, from ''not at all true of me'' (a score of 1) to ''very true of me'' (a score of 7). The modified TV-MSQL is presented in the Appendix.

In order to collect students' TI of the problems they were required to solve during the semester, the researchers purposely selected three problems (Tasks 1, 2, and 3) from Çengel and Boles (2015) that represented core issues in weeks 7, 12, and 15 of the course. Each problem was related to one unique course topic including (Task 1) Closed System Energy Analysis (First Law), (Task 2) Open System Entropy Balance (Second Law), and (Task 3) Ideal Cycle Analysis. The level of difficulty of the problems assigned during this study reflected the same level of difficulty as the problems that were discussed in class, assigned for preparation out of class, and assessed during exams. Due to the cumulative nature of content within the course, the first problem could be considered as the least complex and the last problem as the most complex if compared against each other. The students' TI were collected through the TAQs, and unique TAQs were developed for each assigned problem. Each TAQ consisted of eight open-ended questions and included items related to both explicit and implicit aspects of TI. The TAQ for Task 1 is presented in the appendix as an example.

Data Collection and Analysis

Data were collected from participants who were enrolled in Engineering Thermodynamics course throughout the spring 2017 semester. Students' TV and PO were assessed twice, at the first and last weeks of the semester using the modified TV-MSLQ and open-ended survey, respectively. These recorded PO were coded and categorize into mastery or performance goal orientations (GO) by two coders and 96% of inter-rater reliability score between the two coders was achieved. Frequency count was then performed for each category to identify students' GO.

Two raters assessed students' TI of each problem: the course instructor and another engineering faculty content expert. The instructor provided initial TAQ responses, which were evaluated by the expert. After discussions between the instructor and content expert, revisions were made to the instructor's responses and were used to score students' responses. We believed the revised instructor's TAQ responses had minimal bias.

TAQ scores ranged between from 0 to 2; a TI score of 0 was assigned to a blank or incorrect answer and a score of 2 was given to a correct answer. The score applied to an incomplete answer was mutually agreed on by the raters. The agreement between raters also served to minimize bias and improve score reliability. When students were only able to describe less than half of the possible correct responses, they were given a 1 for their TI score. Together, the two raters achieved an inter-rater reliability score of 97% agreement. This TI score represented students' TI skill on a particular problem-solving task. At this point, all the qualitative data were converted into quantitative data. Examples of students' complete and incomplete answers are provided in the Appendix.

To investigate any potential changes of students' TV from the beginning to the end of the semester, their TV mean and standard deviation scores were calculated and compared. Furthermore, the frequency (in percent) of students' mastery and performance GO of the course at the beginning and end of the semester were compared. The sign test and paired-sample *t*-test were used to assess whether the changes of TV and GO were statistically significant. The sign test was used due to the nature of the paired-TV data which were in an ordinal scale and did not have a similar shape.

The answer to the second research question was achieved by comparing means of students' TAQ responses among the three problem-solving tasks and task affects (TA) (i.e., TV and PO). Next, two-tailed paired-sample *t*-tests were conducted. A cutoff value of .05 for Type 1 error was used to determine whether the results of the TAQ before and after are significant. Descriptive statistics were also performed to determine changes, if any, in students' TA and their TI skill through the semester.

Results

Addressing Research Question 1: How are changes in students' TV, if any, reflected in changes of students' PO throughout the course?

Descriptive statistics results show a trending pattern of continuous increase of students' development of TV scores (i.e., overall, utilities, importance, interesting) for the course (see Table 1) and all except the importance score were statistically significant (see Table 2). Similarly, there was a trend of a growing focus on mastery GO towards the end of the semester which suggests that as the semester progressed, both students' task value for the course and their focus on mastering the course material were continuously developed (see Table 3). The *t*-test confirmed these transitions were statistically significant for both mastery ($t = -4.146$, $p = <.001$) and performance ($t = 5.889$, $p = <.001$) GO. As the semester progressed, students perceived the material learned was more interesting (from a mean value of 5.220 to 5.676) and useful (from a mean value of 6.008 to 6.153). This finding suggests that if students value course content, they might consequently become more focused on mastering the course material (i.e., mastery GO) rather than simply getting good grades and/or passing the course (i.e., performance GO).

Table 1
Students' Task Value Mean (SD) Score at the Beginning and End of the Semester

At the beginning of the semester				At the end of the semester			
Overall TV	Utility TV	Importance TV	Interest TV	Overall TV	Utility TV	Importance TV	Interest TV
5.757 (0.815)	6.008 (0.999)	6.045 (1.005)	5.220 (1.193)	5.957 (0.972)	6.153 (1.045)	6.042 (1.140)	5.676 (1.275)

Table 2
Significant Changes of Students' Task Value

	At the beginning vs. end of the semester	
Task value	*z*	*p*
Overall	-2.785	< .01
Utility	-2.729	< .01
Importance	-0.912	> .05
Interest	-4.556	< .001

Table 3

Students' Learning versus Performance Frequency (Percentage) Count at the Beginning and End of the Semester

At the beginning of the semester		At the end of the semester	
Mastery GO	Performance GO	Mastery GO	Performance GO
71%	29%	90%	10%

Addressing Research Question 2: How do student's TI skills change while engaged in problem-solving tasks throughout the course?

It was interesting to find that, despite engaging in increasingly complex problem-solving activities, students demonstrated increased TI scores (overall, explicit, and implicit) during the course (see Table 4). The overall TI score increased from 1.028 (i.e., 51%) to 1.159 (58%). Similarly, students' explicit TI scores increased from 1.283 (i.e., 64%) to 1.546 (i.e., 77%); students' implicit TI scores increased from 0.774 (39%) to 0.985 (i.e., 49%). A decreased implicit TI in Problem #3 might be caused by the complexity of the particular problem (further discussion for this can be found in Lawanto, Minichiello, Uziak, and Febrian (2018).

To investigate whether there was TI skill change during the course, six sets of paired *t*-tests were conducted (see Table 5). The first test was conducted to evaluate the mean differences between TI scores on early semester (TAQ #1) and mid semester (TAQ #2), and between TI scores on mid semester (TAQ #2) and end semester (TAQ #3). The results suggest that there was a significant increase of students' overall TI score between solving problem at the beginning (TAQ #1) and mid semester (TAQ #2), $t(68) = -0.348$, $p < .001$. This significant increase of overall TI score may be caused by a significant increase of students Implicit Task Interpretation score, $t(68) = -4.901$, $p < .001$, whereas the increase of students' explicit task interpretation score was noted but was not significant, $t(68) = -0.888$, $p > .05$. There was a significant increase of students' explicit interpretation score between solving problem at the mid (i.e., TAQ #2) and end semester (i.e., TAQ #3), $t(68) = -4.455$, $p < .001$. There was a significant decrease of students' implicit score during solving problem at the end of the semester compared to mid semester, $t(68) = 4.639$, $p <,001$. This may be due to the increased complexity of the problem that students were required to engage at the end of the semester (i.e., Task 3), see a study reported by Lawanto et al. (2018). These significant increase and decrease of students explicit and implicit task interpretation scores appeared to make change in students' overall TI score of solving problem between mid and end semester, $t(68) = 0.000$, $p > .05$.

Table 4
Students' Task Interpretation Scores (Mean and Percentage) over the Three Assigned Problems

	Problem 1 early semester	Problem 2 mid semester	Problem 3 end semester
Overall TI score	1.028 (51%)	1.159 (58%)	1.159 (58%)
Explicit TI score	1.283 (58%)	1.333 (67%)	1.546 (77%)
Implicit TI score	0.774 (39%)	0.985 (49%)	0.772 (39%)

Table 5
Significant Changes of Students' Task Interpretation Scores over the Three Assigned Problems

	Problem 1 (early semester) vs. Problem 2 (mid semester)		Problem 2 (mid semester) vs. Problem 3 (end semester)	
	t	*P*	*t*	*p*
Overall TI score	-0.348	< .001	0.000	> .05
Explicit TI score	-0.888	> .05	-4.455	< .001
Implicit TI score	-4.901	< .001	4.639	< .001

Conclusions and Discussion

Most engineering instructors may expect that students become more appreciative to their teaching and interested in mastering the course content as the academic semester progresses. That expectation was fulfilled in the Engineering Thermodynamics class in this research study. Students' task value about the course at the end of the semester was higher than when they just began taking the class. The students seemed to be able to see the usefulness of the course content and perceived that the course had become more interesting as they continued participating in the class. The increase in students' perceptions of the usefulness and attractiveness of the course were also reflected by the shift of their personal objectives. As the semester progressed, students seemed to be more focused on mastering the course content than merely getting good grades or passing the course.

Moreover, it was also found that as the semester progressed, and the problems became more complex, students' task interpretation scores improved. Students' explicit and implicit task interpretation scores continued to increase except when students were engaged in solving a complex problem (i.e., Task 3). Further analyses of the *t*-tests revealed significant differences between the students' ability to identify the explicit and implicit information associated with the assigned task (see Tables 4 and 5). Student scores indicate a higher ability to identify the explicit understanding of problem than the implicit one. This suggests that the students seemed to experience more challenges to identify information beyond the problem description, such as identifying the purpose of the problem assigned and connections to learning concepts. Although implicit information often seems obvious to the instructors, students may face difficulty in making the connections between information that is presented in problem description and information that the students need to extrapolate beyond the problem description.

Despite higher explicit task interpretation scores, instructors may not expect students to be able to grasp all of the explicit information given by the problem description. The findings show that students seem to be able to grasp 64–77% of explicit and 39–49% of implicit information presented to them while engaged in problem-solving activities. This finding aligns with the novice-expert research findings that suggest experts spend more time on understanding the task and engaging in monitoring and evaluation, in the attempt to develop more complete representation of the problems before finding the appropriate strategies to solve them (Abelson, 1981; Glaser, 1992; Herbig & Glöckner, 2009; Hoffman, 1998; Lesgold et al., 1988).

Although it is inconclusive, the analyses revealed a trending pattern in that students' TI scores improved as their appreciation of course topics and focus on the mastery of the course content increased. The results indicate that the change of students' affect (represented by students' TV and PO) seemed to be reflected on the change of their TI skill. Although it is statistically inappropriate to correlate these outcomes since the interplay between students' perception of the course (i.e., students' TA) and their TI of specific course-related problems is still unclear. These results suggest that engineering students' TA may be related to their explicit TI skill. Further research is suggested in this area.

Although continuous improvement of students' explicit TI skills was apparent during problem-solving activities, improvement in students' implicit TI skill was noted only during the beginning and mid of the semester (i.e., Tasks 1 and 2). Students seemed to have trouble identifying implicit information in a more advanced problem that required them to gather the cumulative content knowledge learned within the course. Further investigation is needed to better understand how students' PO and TV for solving particular problems relate to their explicit and implicit TI skill.

Implications

The results of this study, which point to the malleability of student TA and TI in engineering problem solving, have important implications for teaching practice. First, results suggest that both the value that students place on engineering problem-solving tasks and their ability to interpret problem-solving tasks of increasing complexity can be substantially improved during a semester. Moreover, results may further suggest that the ways in which graded problem solving assignments are administered may positively affect students' TA and explicit TI. For example, purposeful attempts by instructors to engage students in reflection, correction, and self-evaluation of their problem-solving skills and performance on each assignment may be an effective approach for improving engineering students' TA and TI.

Second, the results showcase the varying degrees to which instruction might affect explicit and implicit TI of engineering students. Results of this study show that it is important for instructors to realize the multi-faceted nature of TI so that they can adequately scaffold and support both explicit and implicit TI. Results further suggest that instructors should devote more time to promoting development of implicit TI during engineering problem solving with increasingly complex problems.

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Appendix

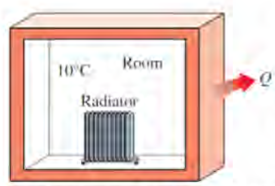
Modified Task Value Survey

These questions were taken and modified from the MSLQ:

1. I think I will be able to use what I learn in MAE2300 Thermodynamics in other courses and/or contexts in my life.
2. It is important for me to learn the skills/content taught in MAE2300 Thermodynamics.
3. I am very interested in the skills/content area of MAE2300 Thermodynamics.
4. I think the skills/content gained in MAE2300 Thermodynamics are useful for me to learn.
5. I like the subject matter of MAE2300 Thermodynamics.
6. Understanding the subject matter of MAE2300 Thermodynamics is very important to me.

Problem Example

An example of a TAQ problem used in this study[1]:



A 40-L electrical radiator containing heating oil is placed in a 50-m3 room. Both the room and the oil in the radiator are initially at 10°C. The radiator with a rating of 2.4 kW is now turned on. At the same time, heat is lost from the room at an average rate of 0.35 kJ/s. After some time, the average temperature is measured to be 20°C for the air in the room, and 50°C for the oil in the radiator. Taking the density and the specific heat of the oil to be 950 kg/m3 and 2.2 kJ/kg·°C, respectively, determine how long the heater is kept on. Assume the room is well-sealed so that there are no air leaks.

Task Analyzer Questionnaire (TAQ)

The TAQ are problem-specific questionnaire. These are the TAQ items for the first problem (see the above problem example):

1. (Explicit) What were your goals in solving this problem?
2. (Explicit) Describe the problem-solving procedure you used in solving this problem?
3. (Explicit) In this problem, what substance(s) made up the system you analyzed?
4. (Explicit) In this problem, what forms of energy transferred into or out of the system you analyzed?

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5. (Implicit) What resources or information, beyond what is presented in the problem statement, did you use in solving this problem?
6. (Implicit) What kind(s) of thinking (remembering, understanding, applying, evaluating, creating) did you use in solving this problem?
7. (Implicit) List the major concepts and/or principles discussed in class that you used in solving this problem.
8. (Implicit) What was the purpose of solving this particular problem?

An example of possible students' correct responses for the first TAQ item of the given problem was "determine how long the heater was left on in the sealed room based on the change in temperature." An example of a partially correct answer was "find how long the heater had been on." An example of an incorrect answer was "find the Voltage of the source and draw a P-V diagram."

A Comparison of the Types of Heuristics Used by Experts and Novices in Engineering Design Ideation

Raymond A. Dixon & Jason Bucknor

Abstract

This study explored the use of heuristics in the design space by novice and expert engineers in the initial ideation of a design solution. Verbal protocol analyses were conducted with four engineering students and four professional engineers as they generated ideas to solve a design problem. Overall, both experts and novices used various types of heuristics. Although novices' heuristics tend to focus on improving the function of the design, experts' heuristics tend to focus on improving both function and form. The implication is that the deliberate teaching of design heuristics, along with other strategies, will help in the development of generative skills of students, stimulating more creative and innovative designs. Validated design heuristics can be integrated within engineering design content at appropriate grade levels to aid in building the repertoire of heuristics used by engineering and technology education students.

***Keywords*:** Experts; design space; heuristics; novices; problem space; solution space; verbal protocol analysis

> We make decisions and judgments every day [on uncountable matters of our lives]—if we can trust someone, if we should do something (or not), which route to take, how to respond to someone's question [, which strategy to use to solve a problem]—the list is endless . . . . Thankfully, our mind makes things easier for us by using thinking strategies known as heuristics. (Dale, 2015, p. 93)

Heuristics guide human judgment and decision making. In short, heuristics are the shortcuts for problem solving that specify simple strategies for assessing and manipulating information and provide us with effortless quick responses in some decision-making tasks (Dale, 2015).

> The term heuristic is of Greek origin and means, "serving to find out or discover." Einstein included the term in the title of his Nobel prize-winning paper from 1905 on quantum physics, indicating that the view he presented was incomplete but highly useful (Holton, 1988, pp. 360–361). (Gigerenzer & Gaissmaier, 2011, p. 454)

Our brain has a limited capacity to process all the information that bombards our sensory system, and we would not function effectively if our brain tried to analyze all information in order to arrive at a decision (Cherry, 2019). Quite often, “when we are trying to solve a problem [such as a design problem] or make a decision, we often turn to mental shortcuts when we need a quick solution” (Cherry, 2019, “Why Do We Use Heuristics,” para. 2). “A heuristic is a mental shortcut that allows people to solve problems and make judgments quickly and efficiently” (Cherry, 2019, para. 1). “Heuristics play important roles in both problem-solving and decision-making” (Cherry, 2019, “Why Do We Use Heuristics,” para. 2). It allows us “to think through the possible outcomes of a decision quickly and arrive at a solution that will work for your unique problem” (Cherry, 2019, “Why Do We Use Heuristics,” para. 6).

Literature Review

Heuristics and Problem Solving

There are many definitions of heuristics. A heuristic is often described as a cognitive strategy that “assesses a target attribute by another property (attribute substitution) that comes more readily to mind” (Kahneman & Frederick, 2002, as cited in Gigerenzer & Gaissmaier, 2011, p. 454). “Research in psychology describes heuristics as simple, efficient rules to explain decision making, judgments, and problem solving, especially when faced with complex problems with vague information” (Nisbett & Ross, 1980, as cited in Yilmaz, Daly, Seifert, & Gonzalez, 2011, p. 4; see also Kahneman & Frederick, 2002; Gigerenzer, Todd, & ABC Research Group, 1999; Tversky & Kahneman, 1974). Others (e.g., Shah & Oppenheimer, 2008) refer to heuristic as a cognitive process aimed at effort reduction. Shah and Oppenheimer (2008) propose[d] that all heuristics rely on one or more of the following methods for effort-reduction:

1. Examining fewer cues.
2. Reducing the difficulty associated with retrieving and storing cue values.
3. Simplifying the weighting principles for cues.
4. Integrating less information.
5. Examining fewer alternatives. (p. 209)

Gigerenzer and Gaissmaier (2011) defined a heuristic as “a strategy that ignores part of the information, with the goal of making decisions more quickly, frugally, and/or accurately than more complex methods” (p. 454).

The classical explanation of heuristics is that they allow people to save effort but often at the cost of accuracy. Therefore, in problem solving, the use of heuristics does not guarantee an accurate solution or the best solution. Humans, therefore, rely on heuristics because information search and computation cost time and effort (Shah & Oppenheimer, 2008; Gigerenzer & Gaissmaier, 2011). According to Mangal (2007), some common heuristics used to solve problems are: “sub-goal analysis,” “means-ends analysis,” “working backward,” and “using an analogy” (p. 290). In *sub-goal analysis*, “a complex problem is reduced to a series (or hierarchy) of smaller, more easily solvable problems” (p. 390). In *means-ends analysis*, “while solving a problem, it is always better to have a proper analysis of the nature of the problem in perfect coordinated with the means, materials, and resources at hand” (p. 390). The goal, the strategy, and the outcome that is desired are all “issues [that] should be carefully analyzed with respect to the means available for coping with these issues” (p. 390). In *working backward*, the problem solver begins at the goal and moves back to the initial problem. *Using an analogy* allows the problem solver to limit his or her solutions to situations, artifacts, or experiences that have something in common with the present problem. Usually, the focus is not on surface similarities but on underlying meaning.

Researchers have identified some domain-specific heuristics in education. For example, Klahr (2000) highlighted several heuristics used to search the experimental space by both students and adult scientists but acknowledged that there were developmental differences in how these heuristics were used. According to Klahr (2000), “the four principle heuristics” were: (a) “use the plausibility of a hypothesis to choose experimental strategy” (p. 113), (b) “focus on one dimension of an experiment or hypothesis” (p. 114), (c) “maintain observability” (p. 115), and (d) “design experiments giving characteristic results” (p. 115).

Heuristics and Engineering Design

Engineering design has several definitions that are influenced by the various specialties within the field of engineering. However, using a somewhat eclectic or global definition, Koen (2003) defines “engineering design, or the engineering method, . . . [as] the use of *heuristics* to cause the best change in a poorly understood situation with the available resources” (p. 28). Koen’s definition implies that engineering design situations are usually poorly understood initially. This may not be the situation in all design cases; none-the-less, heuristics are important, and indeed essential, problem-solving strategies that are used by designers. Koen further indicated that

> A heuristic has four definite signatures that make it easy to recognize:
> 1. A heuristic does not guarantee a solution,
> 2. It may contradict other heuristics,
> 3. It reduces the search time for solving a problem, and
> 4. Its acceptance depends on the immediate context instead of on an absolute standard. (p. 29)

He grouped heuristics under five major categories:

1. Some simple rules of thumb and orders of magnitude
2. Some factors of safety
3. Some heuristics that determine the engineer's attitude toward his work
4. Some heuristics that engineers use to keep risk within acceptable bounds
5. Some miscellaneous heuristics that do not seem to fit anywhere. (pp. 65–66)

According to Koen (2003), "the terms *rule of thumb* and *order of magnitude* are closely related, often used interchangeably, and usually reserved for the simplest heuristics," for example, someone estimating "the size of a room by knowing the order of magnitude for standard column spacing" (p. 66). Another example would be: "The yield strength of a material is equal to a 0.2 percent offset on the stress-strain curve" (p. 66). Factor of safety heuristics are used because there are uncertainties in calculated values used by engineers. So, a factor of safety allows for a degree of error, for example, "use a factor of safety of 1.2 for leaf springs" calculations (p. 68). Attitude determining heuristics refer to the general attitude or behavior of the designer when confronted with a problem. Two examples of this type of heuristic are: "quantify or express all variables in numbers" (p. 70) and "work at the margin of solvable problems" (p. 72). "Because the engineer will try to give the best answer he can, . . . some risk of failure is unavoidable" (p. 73). Risk controlling heuristic are used to reduce these risks. An example of a risk-controlling heuristic is: "Use feedback to stabilize engineering design" (p. 77). Miscellaneous heuristics are those that "do not seem to fit under any of the previous categories" (p. 79). Examples include: "break complex problems into smaller, more manageable pieces" and "design for a specific time frame" (p. 79).

In a study designed to empirically validate design heuristics, Yilmaz, Daly, Seifert, and Gonzalez, (2011) "characterized three types of cognitive design heuristics that prompted different types of movements in the design space": local, transitional, and process.

- *Local* heuristics define characteristics and relationships of design elements within a single concept . . . .
- *Transitional* heuristics provide ways to transform an existing concept into a new concept . . . .
- *Process* heuristics prompt a designer's general approach to idea generation . . . . They serve as cognitive tools used to initially propose ideas by directing the designer's navigation of the solution space. (p. 5)

Table 1
Examples of Local, Transitional, and Process Heuristics (Yilmaz et al., 2011)

Heuristic	Description
Local	
Attach components with different functions	Adding a connection between two parts that function independently
Attach the product to another existing item	Utilizing an existing product as part of the function of the new product
Attach the product to the user	The user becomes part of the product's function
Compartmentalize	Separating the product into distinct parts or compartments with different functions
Transitional	
Change the geometrical form	Using different geometrical forms for the same function and criteria
Split	Taking a piece of the previous concept to generate a new concept
Substitute	Replacing the material, form, or a design component with another to achieve the same function
Process	
Contextualizing	Changing the context in which the product would be used, and using that context to inspire a concept that satisfied the nature of the context
Problem Restructuring	Shifting or redefining what the actual problem is and generating products that satisfy the identified real problem
Constraint Prioritizing	Putting more emphasis on certain criteria than others and using the emphasized criteria to focus and guide concept development

Redesigning	Re-designing existing products with similar functions
Simplifying	Generating and building on the simplest way to solve the problem

Note. This table is adapted from Tables 3 and 4 in Yilmaz et al. (2011) on pp. 11–13.

In their study with engineers and industrial designers, Yilmaz et al. (2011) proposed that the use of "specific design heuristics [local, transitional, and process] would help designers explore new types of potential designs, leading to the generation of innovative solutions" (p. 6). They found

> that heuristics are effective in generating diverse concepts. Design heuristics may, at times, be sufficient to stimulate divergent thinking. Furthermore, the study reveals some differences between these two types of designers in how they approached this open-ended, novel design problem. Specifically, we found that engineers produced a more diverse set of designs from among all of the concepts generated. Industrial designers, however, generated more design concepts in the same period [, but these designs were less diverse]. (p. 20)

In their study, and like the study before, they coded heuristics that served both as local and transitional heuristics. According to Yilmaz et al. (2011), "local and transitional heuristics are listed together because the same heuristic can be used for defining the relationship of the elements within one design concept, or as a transition in moving from one concept to a new one" (p. 10). Table 2 illustrates heuristics that were both local and transitional. Process heuristics were those applied by the designers to the idea generation process as a whole. They reflected a designer's general approach to ideation within the session, and the heuristics observed do not include all possible heuristics for the design task. However, they represent a set of possible heuristics appropriate for idea generation for this design problem.

Table 2
Heuristics That Are Both Local and Transitional (Yilmaz et al., 2011)

Heuristic	Description
Adjust functions by moving parts	By moving the product's parts, the user can achieve a secondary function
Change the configuration of elements	Performing different functions based on the orientation or the angle of the design elements in the product
Cover	Overspreading the surface of the product with another component to utilize the inner surface
Detach / Attach	Making the individual parts attachable /detachable for additional flexibility
Fold	Creating relative motion between parts by hinging, bending, or creasing to condense the size
Offer optional components	Providing additional components that can change the function or adjustability
Repeat	Dividing single continuous parts into two or more elements, or repeating the same design element multiple times, in order to generate modular units
Replace solid material with flexible	Changing a product's material into a flexible one for creating different structural and surface characteristics
Scale	Changing the size of a feature of the product

Note. This table is adapted from Table 3 in Yilmaz et al. (2011) on pp. 10–12.

The Framework

"The model for creative design, which illustrates the co-evolution of the problem and solution spaces during engineering design problem solving (see Dorst & Cross, 2001; Maher, Poon, & Boulanger, 1996)" (Dixon & Johnson, 2011, p. 49), was used for this study. According to Maher, Poon, and Boulanger (1996), "whenever engineers are solving design problems, their problem and solution spaces co-evolve with an interchange of information between the two mental spaces" (Dixon & Johnson, 2011, p. 49). Dorst and Cross (2001) confirmed the accuracy of the Maher et al. (1996) model in a protocol study of nine experienced industrial designers whose designs were evaluated on overall quality, creativity, and a variety of other aspects. For simplicity, we illustrate the coevolution of the problem and solution spaces in Figure 1. The overlapping space represents the space in which an exchange of information between the solution and problem spaces takes place; in this space, the designer is transitioning or moving back and forth, exchanging information between the two spaces.

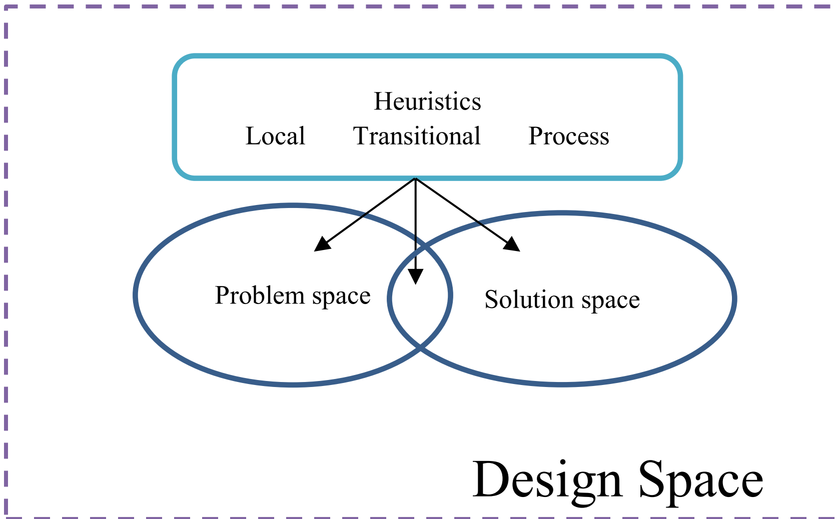

Figure 1. Conceptual model.

Idea generation, as a phase in the design process, is the stage where designers consider multiple alternatives. It is not restricted to a single phase; rather, it occurs throughout the design process as ideas are transformed and developed. For initial idea generation, the goal is to explore, in both depth and breadth, the *design solution space*, which is the theoretical space containing all possible solutions for a given design problem (Daly, Seifert, Yilmaz, & Gonzalez, 2016; Dorst & Cross, 2001; Newell & Simon, 1972). As the designer explores solutions, heuristics are used as one of the ideation techniques to generate concepts. Multiple heuristics can be employed within a single design, and each heuristic can be applied repeatedly to initiate ideas, transform existing ideas, and generate ideas for subcomponents of complex design (Yilmaz, Seifert, & Gonzalez, 2010; Kramer, Daly, Yilmaz, Seifert, & Gonzalez, 2015). Heuristics can focus on the form or function of the design idea. Function tells what the device or mechanism does, whereas form relates to any aspects of physical shape, geometry, construction, material, or size (Ullman, 2003).

Research Questions

This study explored types of heuristics (local, transitional, and process) used by experts and novices in the design space as they go through the initial ideation of a design problem. The following research questions guided this study:

1. What is the predominant type of heuristics used by novice designers in the problem, solution, and overlapping spaces during the initial ideation of a design problem?
2. What is the predominant type of heuristics used by expert designers in the problem, solution, and overlapping spaces during the initial ideation of a design problem?
3. How do experts and novices differ when using heuristics directed at function and form of design?

Method

A qualitative comparison of novice and expert engineers was conducted. A purposeful sampling procedure was used to select participants. According to Gall, Gall, and Borg (2007), "in purposive sampling the goal is to select cases that are likely to be 'information rich' with respect to the purposes of the study" (p. 218). The use of heuristics by a small group of mechanical engineering students was compared with a small group of professional mechanical engineers.

Participants

An email was sent inviting juniors and seniors enrolled in a 4-year mechanical engineering program at a Midwestern university to participate in the study. Four mechanical engineering students agreed to participate, two juniors and two seniors. The four professional engineers were recommended by a member of the American Society of Mechanical Engineers. Each professional engineer is recognized as an expert in mechanical engineering design. Each professional engineer had at least the minimum 10 years of experience that it generally takes to be considered an expert in a particular domain (Phye, 1986). The small sample size is typical of verbal protocol studies (Jiang & Yen, 2009; Trickett & Trafton, 2009).

The Design Task

Each participant was given the same design problem to generate ideas for a solution. The design task was vetted by two professionals in the field: an engineering technology professor with over 20 years of teaching experience and a mechanical engineering professor with over 10 years of experience as a manufacturing consultant and over 3 years of experience teaching manufacturing principles. This review helped ensure that the design task was sufficiently ill-structured and of an appropriate difficulty level to engage the students and professional engineers (see Figure 2).

Procedure

The design task was administered at a time and place convenient for each participant. Pencils, erasers, and sketchpads were provided, along with the instructions for the design task. Each participant was allowed approximately 1 hour to complete the design solution. Participants were required to produce only one conceptual design. Data were collected primarily using concurrent verbal protocol analysis.

Each participant had the choice of doing a verbalization practice session of about 5 minutes, thinking aloud as they solved a simple mathematical problem, to prepare them for the study. After they were comfortable with the think-aloud process, the task was administered. The participants were encouraged to speak aloud whatever they were thinking as they solved the problem. Their think-aloud verbalizations were audio recorded. If the participants stopped talking, they were prompted or reminded to continue to speak their thoughts aloud.

THE DESIGN TASK

The objective of this engineering design activity is to understand the cognitive process of engineering designers as they solve a design problem. Verbal Protocol Analysis will be used. This means that as you solve the problem, you will be required to **"think aloud"** (say aloud) what you are thinking. If you stop speaking, I will remind you to resume speaking aloud as you solve the problem. Please include all the notes and sketches of your solution on the sketch pads that are provided.

Duration: 1 hour

The Context
Fonthill is a hilly terrain in the District of Saint Mary with narrow tracks and virtually nonexistent roads. This area also experiences high amounts of rainfall yearly. There are several communities like Fonthill on this mountainous tropical island. Because of the very poor state of the roads, the most frequent mode of transportation are motorcycles. Motorcycles are used to take residents to and from work, market, and school. Although the residents see this system of transportation as essential, the government has serious concerns about the safety of the riders and their passengers. The government therefore secured a loan to purchase a fleet of motorcycles that are specially built to handle these rugged terrains. These motorcycles will be leased as taxis to specially trained riders.

The Design Problem
The Honda CRF230 shown on the next page is a cross between a dirt bike and a street bike. Modify the Honda CRF230 so that it is robust enough to handle repeated journeys through these mountainous terrains that are prone to a lot of rainfall annually. The average cost of a new car in this country is about US $25,000.00, and the government expects that the cost of this motorcycle will not exceed one third this cost. The motorcycle must also:

- Be equipped with more cargo carrying capacity and at the same time make the rear seating (pillion) more comfortable.
- Have an improved rack or a holding system for carrying packages, books, or a reasonable amount of groceries on the motorcycle. The rack must be non-metallic but of sufficient sturdiness to withstand a rugged terrain, occasional brushing against rocks, and a lot of rainfall.
- Be capable of enough horsepower to climb sections of mountains with slopes of 30 degrees, carrying the rider and the pillion passenger.
- Have a device to prevent the theft of helmets from the motorcycle.

Figure 2. The engineering design task. This task was previously presented in Figure 2 in Dixon and Johnson (2011) on p. 53.

Data Analysis

The audio recordings of the protocols were transcribed. The transcribed protocols were then segmented into think-aloud utterances, divided into sentences, and coded. The quality of the sketches was not evaluated because the objective of the study was to examine the heuristics used by the engineering students and the professional engineers. The sketches and notes, however, acted as a reference to clarify some sections in the protocols.

The purpose of segmenting is to break the transcribed verbal protocol text into units (or segments) representing discrete thoughts that can be coded with a predefined coding scheme. Each segment was coded manually using the following predefined constructs: local heuristic, transitional heuristic, process heuristic, local and transitional heuristic, problem space, solution space, and overlapping space (Daly, Yilmaz, Seifert, & Gonzalez, 2010; Dorst & Cross, 2001; Yilmaz et al., 2011). Each heuristic was further coded for function or form. Reliability coding was conducted using two coders to code seven pages of one transcript (Miles & Huberman, 1994). A reliability kappa coefficient of 0.76 was obtained. One coder then completed the coding of the remaining transcripts.

Results

Predominant Types of Heuristics Used by Novice and Expert Designers

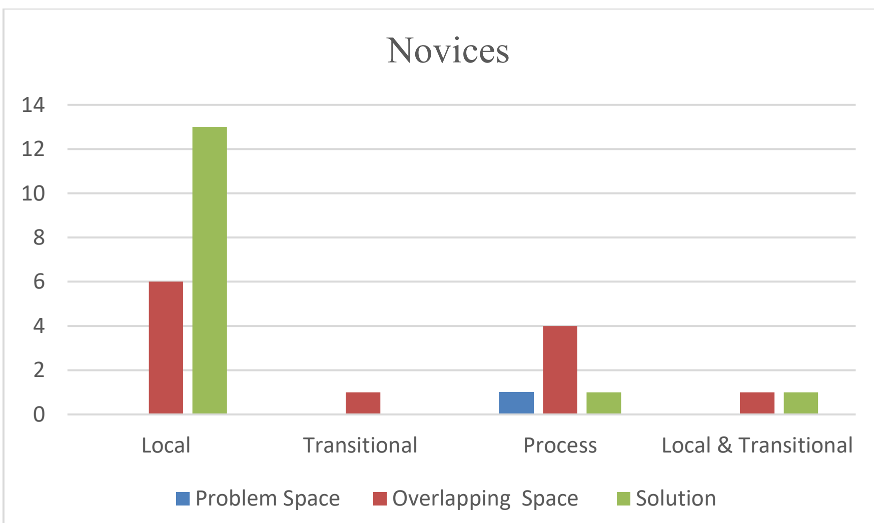

Figure 3. Heuristics used by novices.

The transcripts of the novices revealed that local heuristics were used more often (19 in total), and they were mainly concentrated in the solution space and the overlapping space. The overlapping space is the space in which an interchange of information between the two mental spaces are taking place. That is, as the designer focuses on a solution within the solution space, she or he may move back to the problem space to retrieve information about the problem. Process heuristics were used in all three spaces. Transitional heuristics were used only in the overlapping space, and local and transitional heuristics were used in the overlapping and solution spaces (see Figure 3).

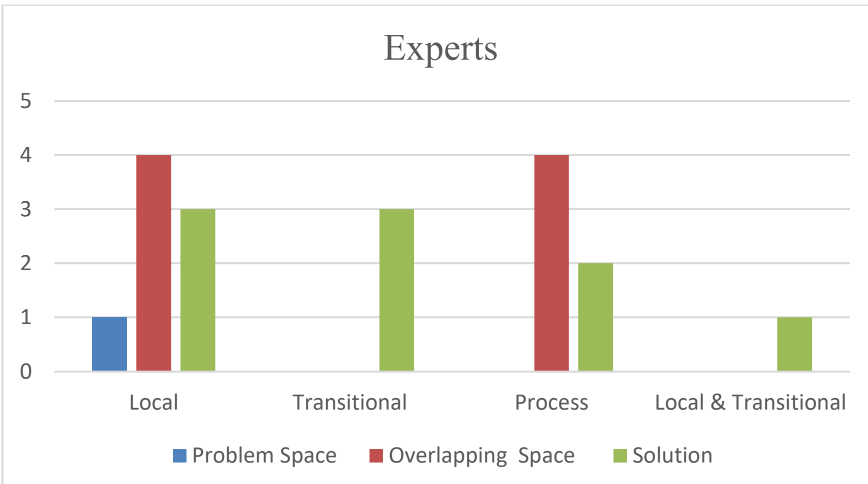

Figure 4. Heuristics used by experts.

In contrast, transcripts revealed that the experts used fewer heuristics than the novices (16 compared to 28 by novices). However, like the novices, the majority of heuristics used were local. Almost equal amount of heuristics were used in the overlapping and solution spaces. No transitional heuristics were used in the problem and overlapping space, and process heuristics were used only in the overlapping and solution spaces. Local and transitional heuristics were only used in the solution space (see Figure 4).

Differences in Use of Heuristics Directed at Function and Form

Transcripts were examined to determine whether the heuristic used related to the function or the form of the design.

Novices. The majority of local heuristics used by the novices related to design form. They used heuristics to elevate parts of their design component, scale the size of components of the design, or extend the component to ensure that the design concept center of mass was properly distributed, allowing proper balance of the vehicle. These heuristics were used mainly in the solution space of the designer.

> If you are going to have an engine in this thing that's not or that's elevated off the ground by I'd say a half foot or foot. You are going to have a fairly high center of gravity.
>
> The concern about or the possible concern about tipping would require B to be some not too small fraction. I'm am not entirely sure what requirement would be that would be based on the kind of weight distribution, which of course would be depending on the size of the trunk that would be attached.
>
> The only problem with that is it might throw off the balance of the bike but you probably just have to put more of a counter weight in front. Like shift the engine more forward to allow for more weight to be in the back of the bike.
>
> Because if you use an external rack you're either going to have to put it on the sides you probably want it on both sides so it didn't throw off the weight distribution so you probably could put, like container on both sides to do things, but then that would add to the width again and you'd be likely to hit things more that you would with this.

The local heuristic, scaling, was also used to improve structural soundness at the rear of the vehicle, traction, and horsepower. These however were mainly used in the overlapping space.

> Another problem with added weight as your traction you might have to upgrade your entire selection to a little more meaty tire.
>
> Along with this improved rack comes more weight, so therefore, you could have some problems with the horse power not being sufficient enough.

Transitional heuristics were used for both function and form of the design. Ideated form included making the vehicle longer and transitioning from a vehicle without cover to one with cover. Ideated function included increasing airflow in order to increase the horsepower of the engine.

I am thinking I'm going to make the motorcycle longer than they had in the past.

> Almost thinking of putting a covering on it let's see how that works though, . . . okay I'm going to keep the original design with the dirt guards for now.
>
> I do know that the cylinder can easily be bored out so that they have more displacement with more horse power, but that would be very expensive . . .

> you might be able to do something with the intake to increase the air flow or something like that.

Process heuristics were used primarily to improve function. The novices focused on the context in which the vehicle is to operate and drew on analogies of vehicles that operate in a similar context. They redesigned the existing concept from a two-wheel to a three-wheel vehicle in order to increase carrying capacity, improve safety, and decrease cost.

> Because I'm am thinking when going to the market or grocery store around here you would need a lot more than a motorcycle to carry because I've walked home with 50 pound of food and you're not going to carry that on a motorcycle. So my first thing would be to try to get away from that and use at least like a three wheel system that would give more carrying capacity in the back.

> If you're are going do that you might as well just go to an ATV and those would work well enough and not cost $25,000.00 Um which would probably be safer.

Local and transitional heuristics were used in the solutions space and overlapping space and focused on both function and form of the design. They included folding components on the design for safety and lowering the frame for better balance.

> You wouldn't want the rods to hurt the operator in any way, so you'd have to look at maybe some way whenever it is in use they could fold away, you know to where it's not sticking out.

> Although I would still of course recommend that the frame be lower in the back for this. This would have also lowered the center of mass.

Experts. Unlike the novices, local heuristics used by experts in this study referenced both form and function of the design in most cases in which they were used. For example, experts focused on a wider array of features than the novices. They included scaling the size of the engine to increase horsepower, scaling the width of the tire to increase traction and safety, changing number of rear wheels from one to two to increase heat dissipation, and relocation of a component to improve balance. Local heuristics were used in all three spaces.

> I think the rear tire need to be wider, concern that if the tires are not wider then it will help to prevent swerving or hydroplaning.

> Yea I would probably go. I'd would start a motor at 1.5 time the size right now. So I would look at 1.5 times current size as a starting point without doing the actual analysis.
>
> And my thinking there was maybe I would go to two tires in the rear to provide additional heat dissipation capability because of the smaller diameter.
>
> Because we probably don't want to because of the need of the luggage we don't want to add too much weight to the overall size of this, but frankly what weight we do want to add we want it on the front.

Transitional heuristics were used less frequently by the experts and primarily referenced the form of the design. In addition, they were used only in the solution space and focused on lowering and extending components as they shift to new concepts in their ideation.

> So the whole thing is much lower to the ground and look at the lowest part of the seat is only just slightly above the rear wheel. Whereas this one the lowest part of the seat is significantly above the rear wheel and I would want to lower it.
>
> I like the fixed tunnel that runs through the rear of the vehicle, where the load deck is, um up to the frame recognizing that if these they will provide torsional rigidity.

Process heuristics used related to both form and function of the design. Like the novices, the experts focused heavily on the context in which the vehicle is to operate; however, unlike the novices, they focused on simplifying the design as an overall strategy in solving the problem.

> I say that because I think we are better off coming here, cantilevering back, adding more steel, and keeping my tires this span apart to allow for um movability or to handle roads.
>
> The other thing is I'm wondering for the same roughly the same price and ah durability why you're are not looking at something like one of these all-terrain vehicles…Yeah the ATV kind of thing would be more stable for the rider I mean that not the present task.

Discussion

Both experts and novices used various types of heuristics in their ideation. What was different, however, is that novices used more local heuristics than experts. These were noticeable in the solution space as they explored the problem and solution spaces, referred to in this study as the overlapping space. The novices focused on making adjustments to the existing design problem based on specifications given in the design brief, using mainly local heuristics to improve the form of certain subcomponents of the vehicle. Comparatively, the experts used more transitional heuristics as they navigated the solution space, focusing on improving both the function and form of the design through the substitution of new concepts.

Studies in design cognition show "that successful ideation involves exploring the problem and solution spaces simultaneously [(Dorst & Cross, 2001; Maher, Poon, & Boulanger, 1996)]" (Gray, Seifert, Yilmaz, Daly, & Gonzalez, 2016, p. 1350), and "design thinking often involves analogy to past solutions, or precedents, that can be usefully applied in future work [(Cross, 2004; Hofstadter & Sander, 2013; Kolodner, 1993; Lawson & Dorst, 2009)]" (Gray et al., 2016, pp. 1350–1351; see also Cross, 2007; Dorst & Cross, 2001; Maher, Poon, & Boulanger 1996). Experienced designers possess a vast knowledge of particular precedents, and they also carry with them a conceptual repertoire that they are able to apply to design problems. According to Gray, Seifert, Yilmaz, Daly, and Gonzalez (2016), "this *conceptual repertoire* represents a collection of intermediate-level knowledge [or design heuristics] that is built on experiential precedents, containing successful patterns of design reasoning that, in their formation and use, assist the designer in creating new design concepts" (p. 1351). This repertoire of experiential precedent would explain why experts would focus on function and form concurrently in their ideation as they search for a solution.

Novices' usage of heuristics, even at a greater rate than the experts, as was the case in this study, indicates that they do possess knowledge of particular precedents and have a conceptual repertoire. This, however, is limited by the extent and quality of their experience in designing, and thus may constrain their ability to use heuristics to focus on both function and form simultaneously. It is interesting that, overall, the general ideas presented by both experts and novices were not vastly different. They both focused on (a) stabilizing the vehicle by adjusting the center of mass and certain components on the vehicle, (b) increasing the load carrying capacity of the vehicle, (c) using a three wheel configuration for stability, and (d) using an ATV analogy type design. The experts, however, spent less time generating solutions than the novices. The heuristics used by both groups led to similar solutions.

Gray et al. (2016) purported that ideation quality can improve when designers are exposed to design heuristics that may have a bearing on their conceptual design. For example, using heuristic cards has been shown to scaffold the metacognitive development of both early design students and experienced designers and to facilitate the generation of novel concepts (Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Yilmaz, Daly, Christian, Seifert, & Gonzalez, 2014). Therefore, using design cards as an instructional strategy in the teaching of engineering design, and more specifically for prompting and scaffolding during the idea generation phase, can help students generate creative and innovative solutions.

Gray et al. (2016) also argued that "some forms of design education are predicated on the knowledge of canon first, only allowing the implementation of variation later in the learning experience (e.g., copying successful designs before creating ones' [*sic*] own)" (p. 1353). "Educational approaches to teaching design thinking in other design disciplines (e.g., architecture, industrial design) have focused primarily on the learner's exposure to precedent examples—or ultimate particulars . . . [(Nelson & Stolterman, 2012)]—to build this repertoire . . . [(Lawson, 2004)]. The traditional studio educational experience pioneered in design education centuries ago follows this pattern, with an explicit focus on learning a relatively well-defined canon of examples . . . [(e.g., Pasman, 2003)]" (Gray et al., 2016, p. 1353). The searching for a solution stage of the design process used in high school curriculum also expose students, to some extent, to precedent examples. However, Gray et al. (2016) "propos[ed] that *Design Heuristics* offer a conceptual bridge between design theories and the individual design precedents often provided to learners, forming a body of intermediate-level knowledge that is valuable in engineering design education and practice" (p. 1354). Using design heuristics as an instructional technique may help "to enhance the elaboration of ideas, as well as facilitate more attention to particular components of concepts [(Christian, Daly, Yilmaz, Seifert, & Gonzalez, 2012)]," and "support the development of practical and functional ideas across diverse design problem contexts [(Kramer, Daly, Yilmaz, & Seifert, 2014; Kramer, Daly, Yilmaz, Seifert, & Gonzalez, 2015)]" (Daly et al., 2016, p. 3).

Conclusion

The teaching of design heuristics should be among the instructional strategies used in engineering and technology education. It is obvious that engineering college students will acquire a repertoire of heuristics through engineering design content, experience through the designing and the making of artifacts, and exposure to precedent examples. Students, like professional engineers, often become fixated on a single concept early in the design process, failing to consider a variety of design solutions (Cross, 2001; Jansson & Smith, 1991). The deliberate teaching of design heuristics, however, along with other strategies, will help in the development of the generative skills of students, stimulating more creative and innovative designs. Several design heuristics that have been empirically validated (see Daly, Christian, et al., 2012; Daly, Yilmaz, et al., 2012) can be used in the classroom to teach design problem solving. Gray et al. (2016) recommend that: (a) instructors develop students' knowledge of design heuristics as they work on organic idea generation, (b) instructors and students relate design heuristics to design artifacts being generated, and (c) students are allowed to transfer design heuristics to new concepts in different context.

The strategies recommended to teach design heuristics to college students can equally be applied to high school students who are doing engineering design. Selected design heuristics from the list of validated heuristics that are deemed to be grade-level appropriate can be introduced in the high school curriculum to provide the cognitive prompt and scaffold that students will need to generate creative and innovative ideas as they conceptualize design solutions.

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A Six-Course Meal for Technology of Design

Chamila T. Subasinghe

Abstract

Entry-level technology studies in architecture often baffle first-year university students, and academic staff in turn tend to resist teaching foundational studies in the technology of design (ToD). ToD has often been considered "high risk," as evidenced by a high proportion of dropouts and retakes, and has been deemed the least preferred subject among both students and academics. Based on activated awareness of design as a mode of pedagogy, the new learning design transformed technology education, enabling students to learn through technology interaction instead of theory recitals and memory testing. The improved undergraduate ToD unit took on the form of a project hub, and the technology that students studied was immersive and hands on. This new learning design utilized real-world occurrences. When students could apply concepts and gain a clear grasp of their principles, learning outcomes became spontaneous. Design activism, which was conceptualized in the six-course meal model, built excitement around learning and assignment tasks. Backed by established learning and teaching concepts such as the controlled guidance procedure- and scenario-based learning, the ToD unit achieved increased student performance by reducing effort, inhabiting learning, and facilitating memory retention. The increased performance and retention rates among students demonstrated that design activism can help students approach learning via cyclic deductive–inductive learning routes with multiple entry points.

Keywords: Deductive–inductive learning circle; design activism; learning design; technology of design

The technology concepts articulated in architectural education take an integrative approach to respond to ecological concerns that account for the environmental impacts of development (Guy & Farmer, 2001). The learning outcomes in technology of design (ToD) lay foundations for key technological concepts in architecture. However, students struggle with these advanced concepts, and teachers often avoid having to teach technology, particularly for entry-level architecture students. Therefore, educators worked to transform the learning design of foundational ToD units by employing learning and assignment tasks based on design activism to enhance student engagement via immersive, hands-on technology education. This new learning design featured scenario- or project-based learning and assignment tasks and prepared students to gain essential competencies needed to take on their assignments, including the final exam, which is often considered the barrier to passing the first year.

Acquisition of these competencies entailed a hybrid of deductive and inductive reasoning, as conceptualized in the model of the six-course meal.

In the broadest sense, technology knowledge and skills play pivotal roles in shaping future job profiles for architecture. Currently, the acquisition of technological concepts relies heavily on teacher-centered lectures and tutorials that tend to treat students as passive recipients rather than interactive partners in the learning process (Ward, 1990). Although an interactive learning design is not widely used in architecture education, the existing literature strongly supports its ability to promote comprehension and retention of advanced technological concepts (Nooriafshar, 2007; Wickens, 1992; Paivio, 1986).

Additionally, broader opportunities of interactive technology learning have the potential to innovate learning and teaching practices across disciplines beyond architecture. Being the vehicle for physical manifestation of design thinking and learning, technology studies play a pivotal role in accredited architecture programs in which graduates are considered candidates on track for professional licensing. This factor is emphasized in the professional practice of architecture in which a firm grasp of ToD components is perceived as a clear indication of a student's job readiness and, therefore, his or her ability to excel in meeting the ever-changing technological demands of the job.

With regard to design education, the literature offers limited insights into the ability of design activism to influence student learning via application of key technology concepts to real-world scenarios. According to Prensky (2001), direct feedback from students demonstrates overwhelmingly positive results regarding the use of application-based approaches to teaching technology in physical, social, and cultural contexts. Furthermore, integration of professional competencies becomes easy when design practices integrate interactive human platforms to comprehend and convey complex technical concepts to their clients (Aldrich, 2004).

Although scenario-based design activism has proven effective when design is the focus in addressing basic civic and societal problems, its capacity in terms of issues such as the comprehension and appropriation of complex subjects, including technology, must be examined carefully. The underlying theory behind design activism revolves around the notion of knowing in practice, most of which is tacit for experienced practitioners but still unknown by students and other budding designers (Schön, 1983). The scenario- and project-based tasks inherent to design activism offer uninhibited platforms for students to contest their knowledge via action and gain know-how for coping with uncertain and complex content situations (Song & Lou, 2016). Such tasks also prompt content learning, whereas design activism approaches inform and activate people to participate in design-based interventions and to improve their present conditions in local and global communities (Seliger, 2014). Design activism also has the capacity to harness appeal and aptitude for learning tasks that can facilitate technology learning via application. It further offers ample opportunities to spot and reinforce strategic learning points as they appear, making them more accessible, effective, lasting, and replicable (Manzini, 2015). Design activism not only enables problem solving and makes sense but also encourages all forms of collaboration, multidisciplinary integration, and proactive intervention, which are essential in innovative learning (Margolin & Margolin, 2002; Manzini, 2015). Although still embryonic and somewhat uncharted, design activism potentially can influence the way in which students apply technological concepts that appeal to human goodness and wellbeing through supporting positive socioenvironmental change (Fuad-Luke, 2009; Lou, 2015; Manzini, 2015). The capability of this approach in helping students decode, analyses, synthesize, organize, and evaluate problems is linked closely to applied research because "no single individual can master this comprehensive background stock of knowledge" (Friedman, 2003, p. 511).

Approach

At Curtin University, which is located in Perth, Western Australia, not only is ToD one of the units with the highest enrolment numbers in the School of Built Environment (SoBE), but it also serves as the critical threshold for the retention of first-year students. Thus, ToD plays a pivotal role in securing and curating talent for successive semesters. In addition, the unit is the only foundational technology course common to both architecture and interior architecture, and as such, it demands an innovative range of didactic tools to engage students in interactive learning.

From the perspectives of both students and teachers, learning design involves the challenge of dealing with students with limited numeracy skills while providing them with a foundation on which they can continue to build their content knowledge and application in an immersive, hands-on manner (Ginsburg, 1998). Within a single unit such as this, it is neither possible nor desirable to cover the full range of technological competencies from principles of structural systems to building performance analysis required for beginning designers. Instead, the learning approach stimulated learners' cognitive faculties by offering them tools and techniques conducive to exploiting ethnological concepts in day-to-day practice. The design of the learning experience further helped students ask informed questions because they had the opportunity to encounter complex, scenario-based issues while completing sequential tasks leading to specific learning outcomes. The participatory aspects of hands-on learning, such as distinction, investigation, and application, enabled students to grasp technological concepts in a nonthreatening manner because they served to awaken students to the possibility of design that empowers—that is, design activism.

Because design activism only offers a platform of expression, a research tool was needed to facilitate the emergence of this learning approach. Therefore, instead of completing an assignment or product, students employed an action-research approach, which offers an uninhibited platform for works in progress (Brydon-Miller, Greenwood, & Maguire, 2003). According to Whyte (1991), action research synthesizes multimode learning and teaching desirable for foundational studies in technology, as reflected in some forms of participatory approach, action learning, praxis, colearning and design, collaborative inquiry, action inquiry, and cooperative inquiry (Lewin, 1946; Peters & Robinson, 1984). Action research also enables collaboration among tutors, unit coordinators, and students as stakeholders. The intent of this strategy is to clarify complex technology concepts using speculative explorations and unresolved questions. Design activism based on action research made scenario-centered technology learning a hands-on process by synchronizing learning and assignment tasks. In generating enlightened views via exciting discoveries, a theory–practice dialectics core to action research made the intervention particularly appealing to learners. This theory–practice dialectic further facilitated immersive and empirical learning essential to technology education in advanced leaning environments such as universities.

Intervention

End of semester student evaluations speak of a somewhat contradictory truth to their one-on-one feedback in the class, even though it may not be critically useful to address urgent issues of learning and teaching. In addition to mid-semester evaluations, students used an unmarked ballot box to deposit their comments on their weekly learning activities and teaching delivery. The transformed learning design, which was an evaluations-based response to students' lukewarm attitude towards content-heavy learning and assignment tasks, adapted a conceptualized French six-course meal as the impetus for learning innovation. Although a broad reference to a concept similar to the six-course meal design is not quite familiar, formulation of discrete learning palettes based on a scaffolded learning outcome is not an uncommon practice in innovative learning design. Particularly, innovation in the entry, operation, and conclusion of each assessment and learning task formed a cycle in this learning design, which took the form of sequential scenarios for learning by engagement, as is true of design activism. This intervention capitalized on the inherent ability of design activism educational approaches to provide hands-on, immersive yet controlled learning applications that target familiar and effective ways to engage foundation-level design students (Tversky, 2001). Redesigned tutorials and assignment tasks formed this educational six-course meal by means of professional practice workshops that constituted real-world scenarios purposefully choreographed for the application of cognitive, skill-based, technological concepts that replaced conventional memory testing of theories. Likewise, the scenario-based assignment tasks, including exams, took the six-course meal format with each course leading and feeding into the next, starting with an "hors d'oeuvres" of technology in a global context, which was followed by a focus on technology in a regional context and ultimately technology in the immediate context.

Course 1: Hors d'Oeuvres (the Stimulator— Technology in "Breaking News")

Concept. *Hors d'oeuvres* translates as "out of works." The "works" in this case refers to the main course of a six-course meal. *L'entrée* (the appetizer) is intended to stimulate the appetite and start the meal, acting as the palate preparation forerunner for an orchestrated sequence of taste scenarios. Unique to classic French cuisine, the ingredients and thus the term *entrer* (to enter) usually depend on the season and occasion. The first course does not simply stimulate the taste buds; it also refreshes the other senses for forthcoming courses.

Activism scenario. The ToD equivalent of the hors d'oeuvre was a focus on technology in a broader context. One example is how calamities of nature affect the built environment, an occurrence that often pops up in the news. Such scenarios would typically start with a grand tour question: What is going on in the world today?

Task. If the focus is on a distinction of environmental loads from live and dead loads, this task might present, for example, a recent climate extremity that was breaking news, especially because of its impact on the structural stability of the impacted buildings.

Example. Periodically, torrential rains and severe windstorms damage properties and lives in Queensland. Understanding of how environmental loads and resultant forces act upon buildings are critical to disaster resilient design.

a. Considering fluctuating nature of the environmental forces, identify a suitable classification system for environmental loads.
b. In an event of a similar disaster situation to that described above, indicate different types of environmental loads that can act upon a single-story residential building on a suitable architectural representation.

Course 2: The Fish Course (the Palate Teaser— Technology of Housekeeping)

Concept. The fish course comes between the starter and the protein (meat) courses and sometimes is garnished with vegetables. Usually, the palate teaser is followed by a dish of lemon or lime sorbet, which prepares the diner for the upcoming major calorie intake: the main course. The fish course thus offers glimpses of future courses or teases the palate, serving as a culinary bridge to the main course.

Activism scenario. The second scenario builds on everyday technologies, leading students to understand the measures needed to cope with local weather conditions as they affect one's own household or locale. This scenario could take into account the question: What's happening in your neck of the woods?

Task. A learning task for this scenario typically would require an awareness of the built structures in and around one's area of commute or neighborhood. In a typical task, students would be prompted to make structured observations of the built fabric in their surroundings that may or may not respond effectively to local weather conditions.

Example. Natural levees such as earth embankments with ground vegetation not only accommodate a change in the ground level without creating a slope but also resist and control surge damages in the event of heavy rain-related natural disasters.

a. Explain resultant forces and possible deformations to structures due to environmental loads.
b. Identify the human-made structure in Figure 1 also used to control surge damages.
c. Propose a way to drain ground water away from these structures, and briefly explain why such measures are necessary.
d. Propose a way to drain ground water away from these structures, and briefly explain why such measures are necessary.

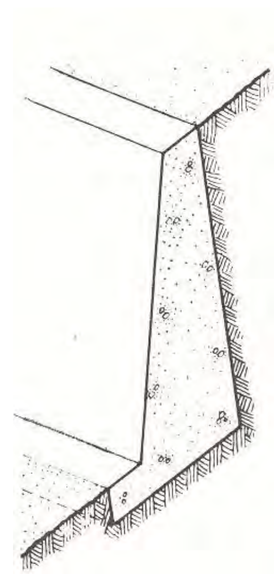

Figure 1. A typical retaining wall along earth embankments that prevent erosion yet allow surface drainage during heavy rains.

Course 3: The Main Course (the Palate Pleaser Technology of Makeup)

Concept. This course is the gastronomic culmination of the meal and includes an elaborate meat or poultry cuisine accompanied by a vegetable garnish. The garnish, mostly seasonal vegetables, may not appear on the plate but rather may be placed on the side. This side dish serves to make the main course more palatable by balancing protein with fibers and sometimes carbohydrates such as potatoes, couscous, or steamed rice. This course is designed to provide diners with a sense of dietary contentment, and it launches the gradual termination of the six courses.

Activism scenario. In the classroom, this course takes the form of a spontaneous launch into the epicenter of ToD: material appropriation for design. A typical scenario would ask a what's good here type of question.

Task. Application of content knowledge should test students' analytical skills in finding context-appropriate materials and assembly options. The below example demonstrates one of the tasks that could challenge learners to make the familiar unfamiliar by deconstructing known built structures in their locality into their (unfamiliar) constituents and then making these unfamiliar deconstructed parts familiar again by thinking of ways to put the building back together.

Example. Locally available materials and technology best understand potentials and constrains of context and equilibrium.

a. Identify the make or species of at least two locally available or manufactured construction materials widely seen in Perth residential constructions.
b. Draw an annotated section through a typical domestic masonry wall system with a concrete floor and a clay or concrete tile roof (using a specific scale is not required). Name each different element to clearly show clearly how:
    i. the roof structure is connected to the wall structure,
    ii. the wall structure is connected to the footing, and
    iii. rainwater and ground water are kept outside of the building.

Course 4: The Salad (Cleanser and Digestive Aid Physical and Technology of Character)

Concept. In a traditional French six-course meal, simple greens tossed with vinaigrette follow the main course to stimulate digestion. A complementary combination of ingredients and dressings works to cleanse and adjust the palate for the remaining courses, specifically the intensity of the cheese platter and the saccharinity of dessert.

Activism scenario. This scenario culminates in a deductive process, allowing students to explore the mechanical and physical properties of building material performance. A typical scenario would ask what the material feels like, causing learners to investigate the restrictions and potentials of materials that are locally manufactured, commonly used, and familiar from the previous scenario. This step enables learners to draw connections between materials and their performance in relation to their physical and mechanical properties.

Task. An ability to draw on technical properties is an integral part of decision-making and establishes a robust foundation for a rationalistic approach to design implementation. A typical task would involve a comparison and projection of structural possibilities for a range of commonly used construction materials based on their stress and strain probabilities.

Example. Based on physical and mechanical properties, the graph in Figure 2 offers an understanding of the way a particular material may respond to various structural and environmental loads.

a. Appropriately identify and label variables (X and Y) of the graph, and use the graph to build a relationship between the variables.

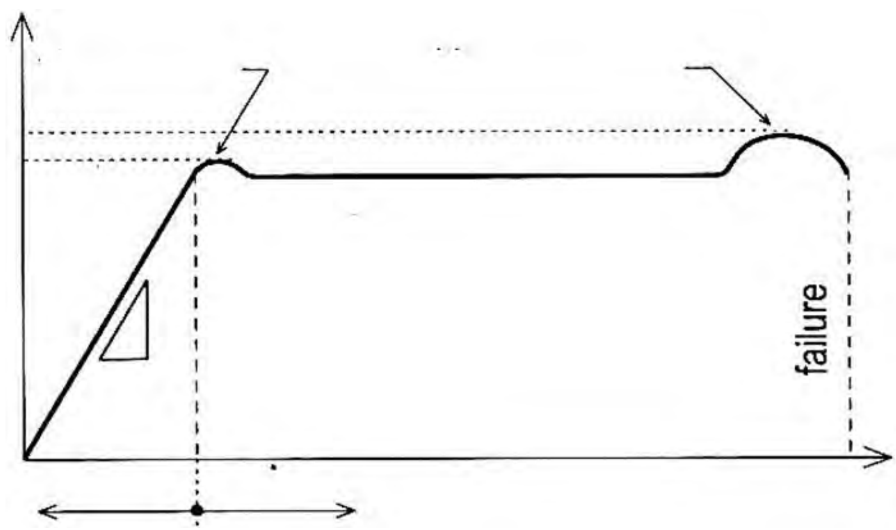

Figure 2. Metaphorically, clearing up a preconceived misconception behind performance of a material by introducing the relationship between its mechanical properties.

b. On the graph, indicate:
   i. plastic and elastic ranges and
   ii. yield and ultimate stresses.

c. If Figure 2 represent steel, indicate the relative positions of graphs for concrete and glass on Figure 2.

Course 5: The Cheese Plate (the Neutralizer Technology of Making)

Concept. This course comprises a myriad range of cheeses and plays the role of the neutralizer. This plate could appear before or after the salad or even replace the dessert. French chefs often prefer to let the cheese speak for itself; when complemented by specialty regional bread, the cheese platter neutralizes the acid left by previous courses and acts as the pre-dessert course. On some occasions, fruit and a few condiments may accompany the cheese platter. Although a formal meal proceeds to a desert course, the cheese plate typically signals the conclusion of the meal in regular, home-style dinning.

Activism scenario. This scenario exploits students' inquisitiveness stimulated by the process of making the familiar unfamiliar and vice versa during the previous course. This scenario allows learners to appropriate materials for a range of building assembly systems based on their ability to accommodate context and achieve equilibrium.

Task. The ability to draw on constructability is an indispensable component of the design decision-making process, and the purpose of this task is to establish a robust foundation in the rationalistic approach to design implementation. A typical task would involve a synthesis between the structural possibilities of commonly used construction materials and their practical implementation via rigorous 2D documentation using architectural details.

Example. A floor system is more than just a floor surface. It also includes all the construction on or in the ground or at an upper level of a building or structure that supports the floor surface. Elevated floor systems provide easy escape routes for ground water drainage, particularly in an event of floods.

a. Sketch and annotate typical detail of a steel-framed floor system complete with a hardwood floor finish for a small-scale residential project. The system should be supported on reinforced concrete stumps.
b. Identify at least two widely used floor framing systems in Western Australia.

Course 6: Dessert (the AftersTechnology of Tomorrow)

Concept. The French term *desservir*, meaning "to clean the table," marks the conclusion of the six-course meal. Indulgent, rich, well-presented desserts typically leave taste buds heightened in the process of digestion. Among a plethora of sweet desserts, often called "afters," sweet, savory, or sour delectable treats conclude the meal's fusion of different tastes. This portion of the meal usually is accented by a small demitasse of freshly brewed coffee or sweet wine. According to Krondl (2011), once the table is cleared of other dishes, desserts are presented as a *service à la russe* (presenting a meal in courses), which is a more recent adaptation of the *service à la française* (setting a variety of dishes on the table at the same time).

Activism scenario. This portion of the learning process brings the cyclical deductive and inductive processes of technology breakdown back to their grandeur: the technology of the future. A typical scenario would be the development of a broad discourse about what is going to be in the coming years using the familiar question: What's the future looking like?

Task. This task would foster students' ability to project and propose informed concepts for a future scenario through a set of data collected in the present. Supported by selected theories such as biomimicry and biophilia, students typically would systematically record active energy use in their own household to gain a tangible idea of carbon footprint creation and to extend such evidence-based ideas to future proofing of the built environment.

Example. Maintain a formal "use" diary related to your use of the place you live in. Choose from one of the following: the quantity of water you use inside and outside the place you live during 10 days or the quantity of energy you use in the place you live for water heating, refrigeration, lighting, cooking, and air-conditioning during 10 days.

When analyzing the diary results,

a. Establish where that water came from and what happens to the waste water in Perth. Further, establish how your usage compares with average usage for Perth and for at least one other city. How would you achieve net-zero water use?
b. If you have measured electricity use, establish where that electricity comes from and the greenhouse gases emitted from your use. Further, establish how your greenhouse gas emissions compare with the average emissions for Perth and average emissions for at least one other city. How would you achieve net-zero energy use?
c. Up to 35% of energy cost of a building is spent on artificial lighting. "Alight at night" is also a common phenomenon for most nonresidential buildings as they require cleaning, security, legibility (aesthetics), and safety as well as suffering from forgetfulness. If local and general lighting strategy can reduce energy cost and improve quality of space, then a building can influence nocturnal use as much as use during the day and maximize the benefits of the technology in the building.

Exercise. You will be assigned to examine future forward design strategies of a recently constructed on-campus building to evaluate its potentials for both diurnal and nocturnal use.

Conclusion

Backed by established teaching and learning concepts such as controlled guidance procedures, coaching, and leading the learner to exploit a familiar metaphor to learn a technological concept, scenario-based learning achieved increased student performance by reducing effort, inhibiting learning, and promoting long-term memory retention. Although inconclusive, exuberance in the classroom suggests that importance of further investigations into design activism's ability to enhance the way that students seize key technological concepts via scenario-based learning tasks and the six-course meal exam design (Figure 3).

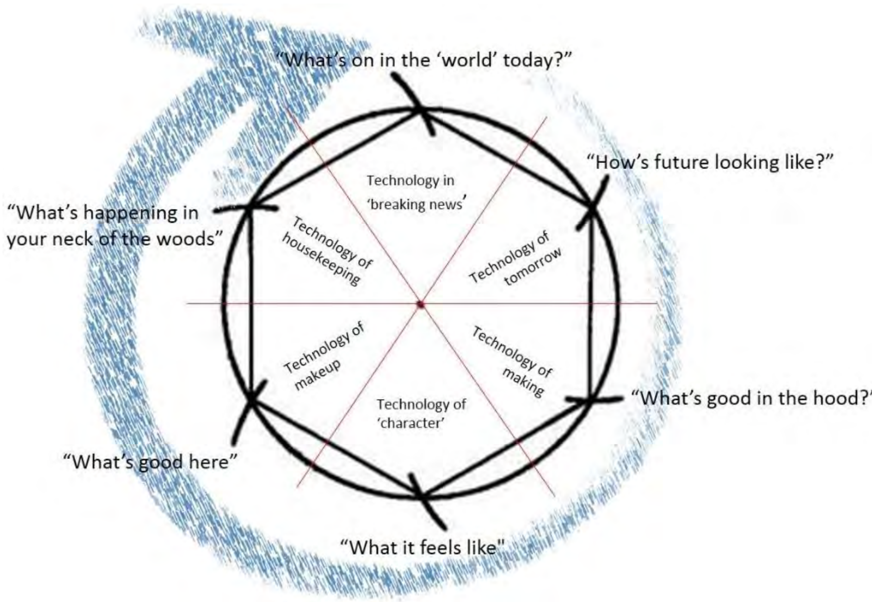

Figure 3. Scenarios and corresponding ToD concepts.

Design activism encouraged an understanding of unfamiliar technological concepts using familiar events of the present and investigation of the unfamiliar, allowing students to deconstruct the unfamiliar in such a way that it becomes familiar and can be applied to unfamiliar events of the future. Based on a six-course meal learning design, the processes of deduction (general to specific) and induction (specific to general) transformed linear technology education, making it a cyclical experience with multiple entry points. The transformation of the learning design tapped students with a range of competency levels and offered broadened options for multimode teaching and learning delivery. The inductive–deductive cycle further simplified the operational rationale of the ToD unit because one scenario fed reciprocally into the next, letting leaners travel back and forth between adjacent scenarios for both clarity and coherence.

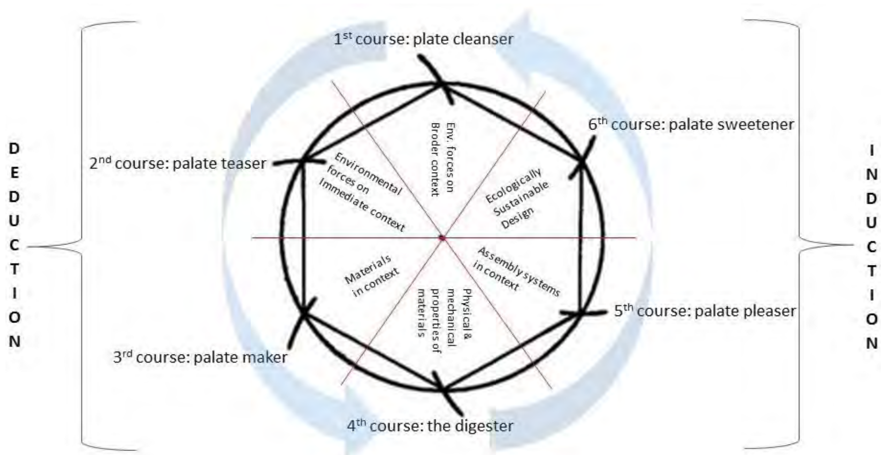

Figure 4. Deductive-inductive operational rationale of ToD.

The six-course meal learning design further transformed content-heavy technological concepts into activism-scenario-based learning and assessment tasks, particularly the final exam that introduced learners to complex structural, mechanical, and environmental concepts. The new learning design simulated real-world experiences in a deductive-to-inductive route via user-friendly interfaces and tools, such as familiar greetings during daily routines or mundane practices that led to the spontaneous elicitation of knowledge and skills. The finesse of formative learning outcomes such as artefacts, analytic drawings, and simulations also demonstrated the benefits of investing in learning design to increase the skill of learners in an effort to develop a professional path to job readiness. Although tutors and peers contribute greatly to the feedback experiences offered to the learners, a vertical integration must exist between facilitation and management to make the experience more valuable; an experienced faculty member would be needed at all phases of the operational circle. Strategic scenarios targeting distinction, investigation, and application not only established an internal logic for ToD but further facilitated multiple platforms for specialization by allowing students and teachers to learn together without taking on the entire task (Figure 5).

Figure 5. Internal logic of ToD phased through key concepts in foundational technology studies.

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Teacher Preparedness: A Comparison of Alternatively and Traditionally Certified Technology and Engineering Education Teachers

Bradley Bowen, Thomas Williams, Larry Napoleon, Jr., & Adam Marx

Abstract

There is a national conversation about a secondary teacher shortage and the lack of qualified teachers in the classroom. Over recent years, there has been a rise in the number of alternatively certified teachers to fill these positions. This is particularly true in the field of career and technical education. However, there is a debate on whether an alternatively certified teacher is as effective as a traditionally certified teacher. The level of preparedness has been identified as a critical factor in teacher effectiveness. This study looks at the differences in perceived preparedness of early career technology and engineering education teachers to determine if there is a difference between alternatively and traditionally certified teachers. The Schools and Staffing Survey Teacher Questionnaire was used as a generalizable national dataset. The results show that there is no statistically significant difference in the level of perceived preparedness of early career alternatively and traditionally certified technology and engineering education teachers. One construct within preparedness, behavior management, was statistically significant for traditionally certified teachers. By better understanding the nature of teachers in regard to preparedness and certification type, further research can be conducted to better prepare teachers in the field of technology and engineering education.

Keywords: Alternative certification, schools and staffing survey teacher questionnaire, technology education, teacher preparedness

Every child deserves the opportunity to have a quality education. Therefore, teachers need to have high levels of understanding in both content and pedagogical knowledge. Due to a teacher shortage in recent years, teachers have been placed into the classroom who may not be considered highly qualified as defined by the No Child Left Behind Act of 2001 (NCLB; Darling-Hammond, Holtzman, Gatlin, & Heilig, 2005; Koehler, Feldhaus, Fernandez, & Hundley, 2013; National Education Association [NEA], 2016). Now that NCLB has been revised to become the Every Student Succeeds Act, the qualifications for teacher preparedness now falls under state control but still holds teachers accountable for meeting state licensure requirements (NEA, 2016). The route that teachers take to earn their certification and obtain a teaching license has been a discussion of national importance. The two main pathways that secondary teachers can take to get a teaching license is the traditional route and an alternative certification route. Although originally used as a stopgap measure to fill open positions (Hoepfl, 2001), alternative certification has become more commonly used to fill regular teaching positions (Cohen-Vogel & Smith, 2007; Gimbert, Cristol, Wallace, & Sene, 2005; Jacob, 2007). This is particularly true for the field of career and technical education (CTE; Litowitz, 1998), which includes technology and engineering education.

Many technology and engineering education teachers have come into teaching positions bringing in years of authentic work experience. However, these teachers may lack the pedagogical knowledge that they would gain from a traditional teacher preparation program. This has caused some concern about the quality of these teachers. There is mixed data on the effectiveness of alternatively certified teachers compared to traditionally certified teachers (Bowen, 2013; Boyd, Grossman, Lankford, Loeb, & Wyckoff, 2009; Bradshaw & Hawk, 1996; Hawley, 1992; Koehler et al., 2013). Research demonstrates that, overall, it is difficult to determine statistically significant differences between the two groups of teachers (Bowen, 2013; Bradshaw & Hawk, 1996; Darling-Hammond et al., 2005; Feiman-Nemser, 1989; Hoepfl, 2001; Litowitz, 1998; Reese, 2010; Sindelar, Daunic, & Rennells, 2004; Stoddart & Floden, 1995). In the field of technology and engineering education, there has been little research in regard to the teaching effectiveness of alternatively certified and traditionally certified teachers (Foster, 1996; Haynie, 1998; Hoepfl, 1997, 2001; Merrill, 2004; Pavlova, 2005). More research is needed to understand the level of preparedness that these teachers feel when beginning their teaching experience and if there are any differences in perceived preparedness between alternatively and traditionally certified teachers in technology and engineering education.

Traditional Versus Alternative Certification

Traditional Certification

Most secondary education teachers earn their teaching license through a traditional teacher education program. The most common route is to attain a teaching license by attending a 4-year university. By obtaining a Bachelor's degree in a specific teaching content area, teachers gain content knowledge as well as educational pedagogical knowledge. Certification requirements can differ among universities and states in regard to the amount of coursework, quantity of field experiences, and length of time spent student teaching (Townsend & Bates, 2007).

Alternative Certification

A shorter and sometimes less costly option for those that want to go into teaching after spending time in industry is an alternative certification program. Alternative certification programs prepare individuals to take the knowledge used in their previous jobs and apply it in a way that relates to students in the classroom. "The term *alternative teacher certification* (AC) has historically been used to refer to every licensure avenue outside of traditional college-based programs" (Cohen-Vogel & Smith, 2007, p. 733). The structure and content of these programs can vary based on the content area and the state in which it is located. However, individuals are expected to be adequately prepared to teach after participating in an alternative certification program. Depending on the program, a bachelor's degree may not even be required to be a classroom teacher when participating in an alternative certification program. The number of years of experience in the field can be equated to schooling experience, meaning that, in some cases, the education level of these teachers may not exceed an associate's degree.

Teaching Effectiveness

There is a debate in the educational community as to the effectiveness of alternatively certified teachers compared to traditionally certified teachers. Some educators believe that an alternatively certified teacher lacks understanding of pedagogical theories and practices that they would gain by completing a traditional education program (Boyd et al., 2009; Darling-Hammond et al., 2005; Gray & Taie, 2015; Hawk & Schmidt, 1989; Koehler et al., 2013; Stoddart & Floden, 1995). Darling-Hammond (1992) reports,

> Studies of teachers admitted through quick-entry alternate routes frequently note that the candidates have difficulty with curriculum development, pedagogical content knowledge, attending to students' differing learning styles and levels, classroom management, and student motivation (Feiman-Nemser & Parker, 1990; Grossman, 1989; Lenk, 1989; Mitchell, 1987). (p. 131)

Because of this lack of pedagogical knowledge, this teacher would not be able to develop and deliver lesson plans that effectively accommodate students' educational needs. This, in turn, may result in lower student achievement. Several studies have found that students taught by alternatively certified teachers had lower achievement than students taught by traditionally certified teachers (Baines, 2006; Darling-Hammond, 2000). Allen (2003) reported that "overall, the research provides limited support for the conclusion that there are indeed alternative programs that produce cohorts of teachers who are ultimately as effective as traditionally trained teachers" (p. 3).

On the other side of this debate, some studies have shown that through practical work experience, alternatively certified teachers have gained content knowledge that is more in-depth than content knowledge gained through a traditional teacher education program (Darling-Hammond et al., 2005; Sindelar et al., 2004). Through corporate work experience, a teacher learns more authentic applications of the content and can provide students more relevant and authentic real-world applications than a traditionally certified teacher (Bowen & Shume, 2018). Several studies show that students taught by alternatively certified teachers achieved just as much, and in some cases more, as the students taught by traditionally certified teachers (Bowen, 2013; Gimbert et al., 2005; Jacob, 2007; Tournaki, Lyublinskaya, & Carolan, 2009). These teachers are also shown to be as competent as traditionally certified teachers, as evidenced by having no difference in scores on the National Teachers Exam (Hawk & Schmidt, 1989).

Research Questions

In recent years, the number of practicing teachers with alternative certifications has increased. Feistritzer (2011) reported that between 2005 and 2010, as many as four out of every 10 public school teachers were hired through an alternative certification program. This emphasizes a strong need for understanding the differences in how teachers from both traditional and alternative certification routes perceive different aspects of their preparation. To fully understand the preparation needs of both alternatively and traditionally certified teachers, we need to better understand how these teachers perceive their initial preparedness. Therefore, the goal of this study is to inform the educational community about the perceived preparedness of alternatively and traditionally certified teacher in technology and engineering education as a means to inform future research. This study analyzes the differences between alternatively certified and traditionally certified technology and engineering education teachers in regard to their perceived preparedness during their early years of teaching.

This study was guided by two research questions specific to beginning technology and engineering education teachers' perceptions of school preparedness. The two questions posed by the researchers were:

1. To what extent are there differences in the overall perception of preparedness for beginning technology and engineering education teachers who entered the field through an alternative versus traditional certification program?
2. To what extent are there differences in perceptions of preparedness for elements of preparedness for beginning technology and engineering education teachers who entered the field through an alternative versus traditional certification program?

By understanding how these teachers perceive their preparedness, both alternative and traditional preparation programs can better align their methods to more effectively prepare technology and engineering education teachers. Also, by using a national dataset, better conclusions can be drawn than from previous research that primarily uses localized populations and relatively small sample sizes.

Methodology

Participants

In this study, beginning teachers who had less than 3 years teaching experience in technology and engineering education were identified and separated by discipline. Participants had provided subject-matter codes relating to technology and engineering education for the Schools and Staffing Survey Teacher Questionnaire (SASS TQ) question: "This school year, what is your MAIN teaching assignment field at THIS school?" Table 1 shows the codes for placing teachers into the category of technology and engineering education. Next, data for the respondents were categorized by whether they entered teaching through an alternative certification program. This determination was made by teachers' answer to the SASS TQ question: "Did you enter teaching through and alternative certification program? (An alternative program is a program that was designed to expedite the transition of non-teachers to a teaching career, for example, a state, district, or university alternative certification program)."

Table 1
Technology and Engineering Educator SASS TQ Codes and Summary Descriptors Representing Main Teaching Assignment

Code	Summary description
246	Construction technology (construction design and engineering, CADD and drafting)
249	Manufacturing technology (electronics, metalwork, precision production, etc.)
250	Communication technology (communication systems, electronic media, and related technologies)
255	General technology education (technological systems, industrial systems, and pre-engineering)

Data from the SASS TQ for teachers with alternative certification and traditional certification were analyzed using descriptive statistics. All data presented were weighted data as detailed in the procedures section. This resulted in 3,720 teachers within the weighted results for alternative certification and 5,660 teachers for traditional certification. Each state was represented with at least one teacher with an alternative certification. Basic demographic information for these teachers are reported in Table 2.

Table 2
Descriptive Information for Alternatively and Traditionally Certified Technology and Engineering Education Teachers

	Certification	
Variable	Alternative	Traditional
Weighted sample	3,720	5,660
Mean age in years	40.22 (10.05)	34.28 (10.92)
Male	77.4%	74.4%
Female	22.6%	25.6%

Note. Standard deviation is in parentheses.

Instrumentation

The Schools and Staffing Survey (SASS) consists of five questionnaires: a School District Questionnaire, Principal Questionnaire, School Questionnaire, Teacher Questionnaire (SASS TQ), and a School Library Media Center Questionnaire. According to Tourkin et al. (2010), the SASS

> is conducted by the National Center for Education Statistics (NCES) on behalf of the U.S. Department of Education in order to collect extensive data on American public and private elementary and secondary schools. SASS provides data on the characteristics and qualifications of teachers and principals, teacher hiring practices, professional development, class size, and other conditions in schools across the nation. (p. 1)

The goal of the SASS is to collect data "for a comprehensive picture of elementary and secondary education in the United States" (p. 2). "The SASS was designed to produce national, regional, and state estimates for public elementary and secondary schools and related components" (p. 9) and is an excellent resource "for analysis and reporting on elementary and secondary educational issues" (p. 1).

Variables Analyzed

Gender and age. The gender of technology and engineering education teachers was determined by SASS TQ Question 78: "Are you male or female?" The teachers' ages were determined by their date of birth.

Perceived preparedness. Perceived preparedness was a composite variable that was created by summing eight questions on the SASS TQ that asked the participants to rate how prepared they were during their first year of teaching. For the purposes of this study, we labeled the composite variable as perceived preparedness because it was a self-rating by the teachers. It was their perception of preparedness, not their actual ability or performance. The SASS TQ question for preparedness was Question 33: "In your FIRST year of teaching, how well prepared were you to –" (a) "handle a range of classroom management or discipline situations," (b) "use a variety of instructional methods," (c) "teach your subject matter," (d) "use computers in classroom instruction," (e) "assess students," (f) "differentiate instruction in the classroom," (g) "use data from student assessments to inform instruction," and (h) "meet state content standards?" The participants responded to each question on a four-point Likert scale: *not at all prepared*, *somewhat prepared*, *well prepared*, or *very well prepared*.

Procedures

This ex-post-facto study analyzed data from the SASS TQ restricted-use dataset. The methodology included appropriate protocol, as required by the NCES and Institute of Education Sciences (IES). NCES specific reporting protocols required that the results intended for submission be sent to the NCES and IES for approval and authorization for release. The results were authorized for release. The NCES and IES require that all weighted *n*'s be rounded to the nearest 10 to assure participant anonymity and that all degrees of freedom in statistical tests be rounded to the nearest 10. Therefore, data in the tables and associated narrative may not add to the total *N* reported because of rounding requirements.

The perceived extent of influence of certification route over perceived preparedness and the eight components of preparedness were analyzed using AM Statistical Software. Independent samples *t*-tests were used to identify statistically significant differences between the self-ratings of those who entered teaching though an alternative certification program and those who entered through a traditional certification program. Probability levels of .05 or less were deemed to be statistically significant. Data were weighted using the Teacher Final Sampling Weight (TFNLWGT) variable, and the SASS TQ supplied 88 replicate weight variables, as required by IES, to approximate the population of teachers under investigation in this study. A balanced repeated replication procedure was utilized, as required by the IES, to adjust standard errors. Tourkin et al. (2010) provides a detailed explanation of SASS sampling, weighting, and replication procedures.

Results

Descriptive statistics and independent samples *t*-tests were used to investigate teacher perceptions of preparedness. A descriptive account of composite scores and item scores for perceived preparedness is presented in Table 3.

Table 3
Composite and Item Descriptive Statistics

Variable	Mean	*SE*	*SD*	Min	Max
Traditional certification					
Perceived preparedness	22.711	0.746	4.828	8	32
Behavior management	2.788	0.115	0.786	1	4
Instructional methods	2.850	0.169	0.917	1	4
Subject matter	3.179	0.105	0.793	1	4
Computers	3.138	0.188	0.89	1	4
Assessment	2.757	0.106	0.764	1	4
Differentiate instruction	2.640	0.121	0.805	1	4
Student assessment for instruction	2.427	0.100	0.712	1	4
Content standards	2.932	0.125	0.777	1	4
Alternative certification					
Perceived preparedness	22.294	1.366	5.129	10	32
Behavior management	2.326	0.162	0.822	1	4
Instructional methods	2.615	0.226	0.883	1	4
Subject matter	3.422	0.136	0.7	1	4
Computers	3.231	0.166	0.923	1	4
Assessment	2.751	0.224	0.857	1	4
Differentiate instruction	2.480	0.233	0.812	1	4
Student assessment for instruction	2.490	0.23	0.860	1	4
Content standards	2.980	0.189	0.761	1	4

Note. SE is standard error; *SD* is standard deviation; Min is minimum score; Max is maximum score.

T-Tests

The first research question was analyzed using independent samples *t*-tests, and the results are reported in Table 4. The results showed that there were no statistically significant differences between traditionally and alternatively certified technology and engineering education teachers on their overall perceived preparedness.

Table 4
Results From t-Tests for Perceived Preparedness and Preparation Variables for Technology and Engineering Education Teachers

Variable	Alt. mean score	Trad. mean score	Mean score diff.	*df*	*t*	*p*
Perceived preparedness	22.294	22.711	-0.417	90	-0.269	0.789
Behavior management	2.326	2.788	-0.462	90	-2.354	0.021
Instructional methods	2.615	2.850	-0.235	90	-0.848	0.399
Differentiate instruction	2.480	2.640	-0.160	90	-0.613	0.541
Student assessment for instruction	2.490	2.427	0.063	90	0.240	0.811
Assessment	2.751	2.757	-0.007	90	0.027	0.979
Computers	3.231	3.138	0.093	90	0.399	0.691
Subject matter	3.422	3.179	0.243	90	1.433	0.155
Content standards	2.980	2.932	0.048	90	0.211	0.834

Note. df is degrees of freedom; *t* is *t*-test value; *p* is probability level.

The second research question was analyzed using independent samples *t*-tests, and the results are reported in Table 3. The question concerning how prepared the teacher was to "handle a range of classroom management or discipline situations" was the only statistically significant finding. Traditionally certified teachers ($M = 2.788$, $SD = 0.786$) perceived themselves to be better prepared to handle classroom management and discipline issues when compared to those who received an alternative certification ($M = 2.326$, $SD = 0.822$; $t(90) = -2.354$, $p = 0.021$). However, the effect size for this difference was small (Cohen's $d = .08$).

Discussion

This study deals specifically with technology and engineering education teachers. Of the weighted total of 9,380 teachers, approximately 40% (3,720) were certified through an alternative program. The results show that, based on this national sample of technology and engineering education teachers, there are no overall statistically significant differences in the perceived preparedness of beginning teachers when comparing alternatively and traditionally certified teachers. Within the constructs of preparedness, the only individual component that was statistically significant is behavior management. This is a very interesting finding when comparing it to the existing research on the two types of routes to teaching. Previous research claims that alternatively certified teachers have difficulty with curriculum development, pedagogical practices, and differentiated instruction (Darling-Hammond, 1992). However, according to the results of the current study, alternatively certified teachers did not feel differently than traditionally certified teachers in their ability to complete these types of activities. When reviewing the results of the eight individual constructs, the alternatively certified group had a higher mean in four of the constructs, and the traditionally certified group had a higher mean in the other four constructs. This supports the literature that there does not seem to be any statistically significant or distinguishable differences in the two groups of teachers. Research does support that, generally speaking, behavior management is one of the issues that many teachers struggle with (Evertson & Weinstein, 2006; Flower, McKenna, & Haring, 2017; Melnick & Meister, 2008; Piwowar, Thiel, & Ophardt, 2013). These findings indicate that alternatively certified teachers felt less prepared to handle classroom management and behavioral issues than did traditionally certified teachers, although the effect was small.

Conclusions and Recommendations

As previously mentioned, current research shows that there are mixed data when comparing the effectiveness and performance of alternatively and traditionally certified teachers. This study was designed to target technology and engineering education teachers within a national sample in order to contribute to the literature in a way that has not been previously reported. According to Kee (2012), traditionally certified teachers felt slightly more prepared in regard to early career preparation when accounting for teachers of all subject areas. However, the study only considered preparedness as a whole and did not analyze each individual construct. Studies by Darling-Hammond, Chung, and Frelow (2002) reported that teacher ratings of traditionally certified teachers were significantly higher than those of alternatively certified teachers. Both of these studies had different sample sizes and different disciplines than the current study, which uses a national dataset specific to technology and engineering education. By analyzing the perceived preparedness of early career technology and engineering education teachers, we are able to see that alternatively and traditionally certified teachers do not perceive their overall preparedness to be different. The only item with a statistically significant difference was behavior management.

The results of the current study would suggest that the population of teachers of technology and engineering education may not follow the national trend in regard to their perceived preparedness during their early career years. This study, however, did not measure any specific differences in teacher behavior, content or pedagogical knowledge, or student test scores. This study only analyzed the perceived preparedness of the teacher. Further research is needed to further investigate how technology and engineering education teachers compare to the general teaching population and investigate any specific differences that could be measured at the classroom level.

Supporters of each certification type can make a case that teachers from both teacher certification routes produce educators with different expertise and skill sets (Bowen, 2013; Feiman-Nemser, 1989; Stoddart & Flodon, 1995). Technology and engineering education is a field that has content ranging from trade-based activities to engineering design. The content required by the teacher to accommodate this range of knowledge lends itself to incorporating skills obtained by teachers of both certification types (Bradshaw & Hawk, 1996; Darling-Hammond et al., 2005; Reese, 2010). Therefore, more empirical research is needed to distinguish these differences. We believe that teachers from both types of certification provide value to the classroom. If the characteristics of teachers from both types of certification are better understood, then alternatively certified teachers can be better supported, traditional preparation programs could be improved, and targeted professional development could help early career educators. By better understanding the differences and similarities in the teacher behaviors produced by these two types of certification programs, more effective teacher preparation can be designed to create more high quality student learning environments.

Limitations and Future Research

Although this study has limitations, this data collected by the IES was weighted to approximate the total population of teachers and provides insight into beginning teachers' perceptions of their abilities. A major limitation is that it is possible that the SASS TQ items might not be able to adequately discriminate between the two groups because the questions measure perceived preparedness. It is plausible that beginning teachers, both traditionally and alternatively certified, do not have a realistic idea of what knowledge and skills are necessary to be an effective teacher. In essence, they might not realize how much they do not know or need to know, and they might underestimate or overestimate their ability. We have no way to actually verify their performance or abilities. This presents some interesting areas for future research such as comparing teachers' self-ratings of preparedness to actual classroom performance and examining the effect of teacher in-service training, the amount of in-service, and the areas of in-service training on perceptions of preparedness.

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Kindergarten Student's Approaches to Resolving Open-Ended Design Tasks

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Abstract

Research on children's experiences with designing has emphasized cognitive processes, self-efficacy, and outcomes related to designing. However, efforts have been limited towards identifying approaches children use while designing and making decisions related to design. This study, which incorporated a qualitative analysis of children's design portfolios, explored students' decisions in planning and evaluating designs related to children's nursery rhymes. Differences in design approaches, based on teacher, task, and stage of designing, were identified in the analysis. Understanding how children approach and attempt to solve open-ended design problems may assist in improving student design experiences and pedagogical practices in all levels of education.

***Keywords**:* Decision making, Design-based learning, integrated STEM education, kindergarten, open-ended design, primary school

The emphasis on science, technology, engineering, and mathematics (STEM) education in recent years represents a movement towards preparing students for societal contribution in an increasingly technologically advanced world (International Technology Education Association, 2007; National Research Council [NRC], 2012). Those in favor of an increased emphasis on STEM and integrated STEM education cite benefits such as increased abilities in problem solving (Stohlmann, Moore, & Roehrig, 2012), teamwork, collaboration (Savery, 2015), innovation, and creativity (Morrison, 2006). Efforts in broadening STEM participation and education have spanned all grade levels (Honey & Kanter, 2013) and have traditionally been linked with increased preparation of future workforce talent. Overall, the calls for STEM education and workforce preparation have largely emphasized the need for students to be better prepared in navigating open-ended scenarios within design contexts that often require teamwork, creativity, and innovation (Griffin & Care, 2015).

Preparing students for success in open-ended design problems has led to new approaches to education, assessment, and pedagogy (NRC, 2011). Efforts toward understanding how students engage in and with these types of problems have been promising, with key findings related to design cognition (Grubbs, Strimel, & Kim, 2018; Strimel, Bartholomew, Kim & Zhang, 2018) and other student factors (Bartholomew & Strimel, 2018) being highlighted in relation to student capacity with open-ended problem success.

Statement of the Problem

Despite the documented research around STEM education, design, and open-ended problem solving, limited research has investigated the approaches taken by primary school students, specifically those in Kindergarten, when solving open-ended design tasks. Most of the research related to primary school students in STEM education revolves around the benefits of STEM participation for student motivation, self-efficacy, and career interest. However, although some research has emphasized the breadth and depth of cognitive strategies employed by students when engaged in design (Kelley & Sung, 2017; Kelley, Capobianco, & Kaluf, 2015; Strimel, Kim, Bartholomew, & Cantu, 2018), limited examinations of the actual approaches taken by primary school students while solving these types of problems have been presented. Addressing this research gap can be of specific importance because design activities have now become pervasive in elementary school coursework through programs such as *Engineering is Elementary*, *Project Lead the Way Launch*, and *Engineering byDesign*. Although there are some theories about cognitive development indicating that young students may be unable to operate in an open-ended design space (e.g., Piaget's Theory of Cognitive Development), others have pointed out how such a theory can underestimate the development of children because their learning capabilities and biological maturation can vary widely when compared to others their age (e.g., Cohen, 2002; Crossland, 2015; Weiten, 1992). Sutherland (1992) specifically pointed out that Piaget acknowledged this possibility in his later work, which emphasized creating the most appropriate learning environments for children. Considering these cognitive development discussions, we believe that an understanding of how Kindergarteners (ages 5–6) approach and attempt to solve open-ended design problems may shed light on primary school student design decision making and assist in identifying potentially useful pedagogical approaches for improving student achievement in these areas through the scaffolding of design activities and implementation of hierarchical design practices.

Research Questions

Recognizing the emphasis on STEM education and open-ended problem solving for students of all ages and the findings related to cognitive strategies, we determined to investigate how students approach open-ended design tasks. Specifically, we investigated primary school children in Kindergarten with the following research question framing this investigation: What approaches do Kindergarten students use when making decisions in the process of resolving open-ended design tasks within integrated STEM learning contexts?

Integrated STEM Learning in Primary Schools

With a global emphasis on STEM education, school systems have made increasing efforts to implement integrated pedagogical approaches centered on problem-based or design-based learning into their curriculum (Honey, Pearson, & Schweingruber, 2014). STEM integration has not only reached secondary education but has been implemented in primary education as well (Rich, Jones, Belikov, Yoshikawa, & Perkins, 2017). Various findings have emerged from these efforts, including increased self-efficacy (Marra, Rodgers, Shen & Bogue, 2009), increased likelihood of majoring in STEM-related fields (Katehi, Pearson, & Feder, 2009), increases in student autonomy (León, Núñez, & Liew, 2015), and earlier student involvement in STEM coursework (Tyler-Wood, Knezek, & Christensen, 2010; Stohlmann et al., 2012).

Despite these preliminary findings, concerns around the preparation of the educator workforce have been raised (Rich et al., 2017). Currently, the educators working with primary-aged students are often not required to teach integrated STEM nor are they required to obtain an endorsement or any formal education in integrated STEM learning prior to receiving a license (Epstein & Miller, 2011). Research has shown that these educators can be unmotivated to receive STEM training because all areas of STEM do not have equally high standards (Brophy, Klein, Portsmore, & Rogers, 2008). Further, for those educators who do receive STEM training, there often remains a lack of technical background in science, engineering, and technology (Swift & Watkins, 2004). However, notwithstanding these challenges, implementation of STEM education may be feasible and successful at lower grade levels, such as Kindergarten (ages 5–6), because these activities may foster excitement, creativity, and engagement in students (Cunningham & Lachapelle, 2007).

Open-Ended Design and Design Portfolios

One commonly used approach to integrated STEM learning is immersing students in open-ended problems that often involve some element of design (Diefes-Dux, Moore, Zawojewski, Imbrie, & Follman, 2004). These experiences provide students with a design scenario and the accompanying criteria and constraints to guide them as they seek to develop a resolution to an open-ended problem. This type of design-based teaching has been linked with improvement of teacher self-efficacy and learning for elementary school students (Bencze, 2010). However, other evidence may suggest that open-ended design experiences can divert students from recognizing and developing an understanding of the desired concepts of the learning situation, thus reducing their ability to transfer knowledge to other situations (Goldstone & Sakamoto, 2003; Honey et al., 2014; Sloutsky, Kaminski, & Heckler, 2005).

Related to open-ended design problems are design portfolios, which often serve as a means for recording student progress and experiences while designing (Johnson, Mims-Cox, & Doyle-Nichols, 2010). Efforts to track student progress, thinking, and designing while engaged in these problems have also included a variety of media similar to portfolios, such as journals and worksheets (Schallhart & Wieden-Bischof, 2010; Arter & Spandel, 1992). Design portfolios have been implemented across all levels of education (Arter & Spandel, 1992) and have been shown to be successful at a primary level in various activities and environments (Hall & Hewitt-Gervais, 2000). As students work with design portfolios, they may build upon previous knowledge, deepen their understanding of class material, and increase in self-reflection (Jacobs, 2001; Zubizarreta, 2009). Portfolios have also been linked with increases in technical skills, critical thinking, writing, and problem solving (De Fina, 1992; Koch & Burghardt, 2002; Nicolaidou, 2013).

Approaches to Solving Open-Ended Design Problems

Jonassen (2008) broadly describes the approach of design as an iterative process of decision-making with each decision iteration helping to reduce the complexities toward achieving a design resolution. More recently, because design has become prevalent in STEM education initiatives, a wide range of design process models and approaches have been developed and implemented in classroom learning environments (Strimel & Grubbs, 2017). However, research efforts focused on determining the actual approaches students take when solving design problems and the merit of such approaches are limited (Dixon, 2016). Instead, most of the research related to open-ended design involves the use of think-aloud protocols and cognitive strategy identification (Pringle & Sowden, 2017). For example, Kelley, Capobianco, and Kaluf (2015) used think-aloud protocols with primary-aged students and found that the students were able to define the problem, identify criteria and constraints, and generate multiple ideas. Relatedly, Strimel, Bartholomew, Kim, and Zhang (2018) found that the majority of primary-aged students' time in designing was connected to manipulating materials, and limited time was spent defining the problem or applying design criteria. Resnick (1998) found that primary students typically focus on manipulating physical objects while working on open-ended problems.

In related research, outside of think-aloud protocols, Fleer (2000) worked with primary-aged children engaged in designing and used a linear process for design with three steps: planning, making, and evaluating. Fleer explained that *planning* involves brainstorming by writing or drawing out ideas, *making* involves creating the design using various materials, and *evaluating* involves reflecting on the design and determining what could be done to improve.

Methods

We sought to build on Fleer's (2000) research by specifically investigating the approaches students used while designing. We chose to emphasize the planning (Stage 1) and evaluating (Stage 3) periods of design, as defined by Fleer. These stages represented readily identifiable starting and stopping points for the chosen design tasks because the provided portfolios (see Figure 1 for an example) specifically prompted the students in making decisions related to their designs at these stages of their design process. Although the inclusion of an analysis around the making stage (Stage 2) of design would have been ideal, limitations related to time and the large sample size ($N = 55$) precluded efforts in this area.

Fleer's (2000) linear process of design was used for this study because the design activities were constrained by classroom schedules and students completing sections of their portfolios following a prescribed classroom implementation timeline. Although potentially limiting, cooperation by the classroom teachers and schools required the adherence to the timeline and portfolio.

Because our intended research sample involved young students, we elected to collect and analyze student drawings and the accompanying explanations that were created during several open-ended design challenges. Our research process involved: (a) the creation of open-ended design activities, (b) the implementation of these design activities with primary-aged students, and (c) the collection and analysis of student design portfolios to investigate our identified research question. Three teachers were recruited for participation in the study. Two of the teachers taught at one school, and the third taught at a different school. The participating teachers all taught Kindergarten students (ages 5–6) in a Midwestern state in the United States. Demographics were similar in all three classrooms, including student's socioeconomic status (22–35% free and reduced-price lunch) and teacher background with integrated STEM teaching and open-ended design problems (limited experience). All students enrolled in these teachers' classes were recruited for participation in the study based on their teachers' participation.

Primary School Children Design Problems. In an effort to provide the students with design problems that were relevant and engaging, the researchers reviewed available resources for primary school-aged children related to STEM and open-ended design and discussed the curriculum with the participating teachers. After reviewing a variety of resources, the researchers determined to create several open-ended design challenges centered on popular children's rhymes that were scheduled to be covered in the participating class' curriculum (see Table 1).

Table 1
Nursery Rhyme Design Challenges and Criteria and Constraints

Nursery Rhyme	Challenge	Criteria and Constraints
Baa Baa Black Sheep (Yoshikawa & Bartholomew, 2017)	Design a way for the black sheep and its master to separate the wool into three bags.	Creates three equal piles of the "wool."
Itsy Bitsy Spider (Yoshikawa & Bartholomew, 2018a)	Design a way to stop the spider from climbing the water spout.	Water still needs to be able to come out of the spout while restricting access for the spider.
Little Boy Blue (Yoshikawa & Bartholomew, 2018b)	Design a way to wake up Little Boy Blue when the sheep or cattle are wandering.	No power source is available—design must wake up Little Boy Blue.

The researchers first identified a clear problem in each of the chosen children's rhymes (i.e., how can we keep the spider from climbing up the water spout) and then used the problems to frame the criteria and constraints and produce a design portfolio for students to use while designing (see Figure 1).

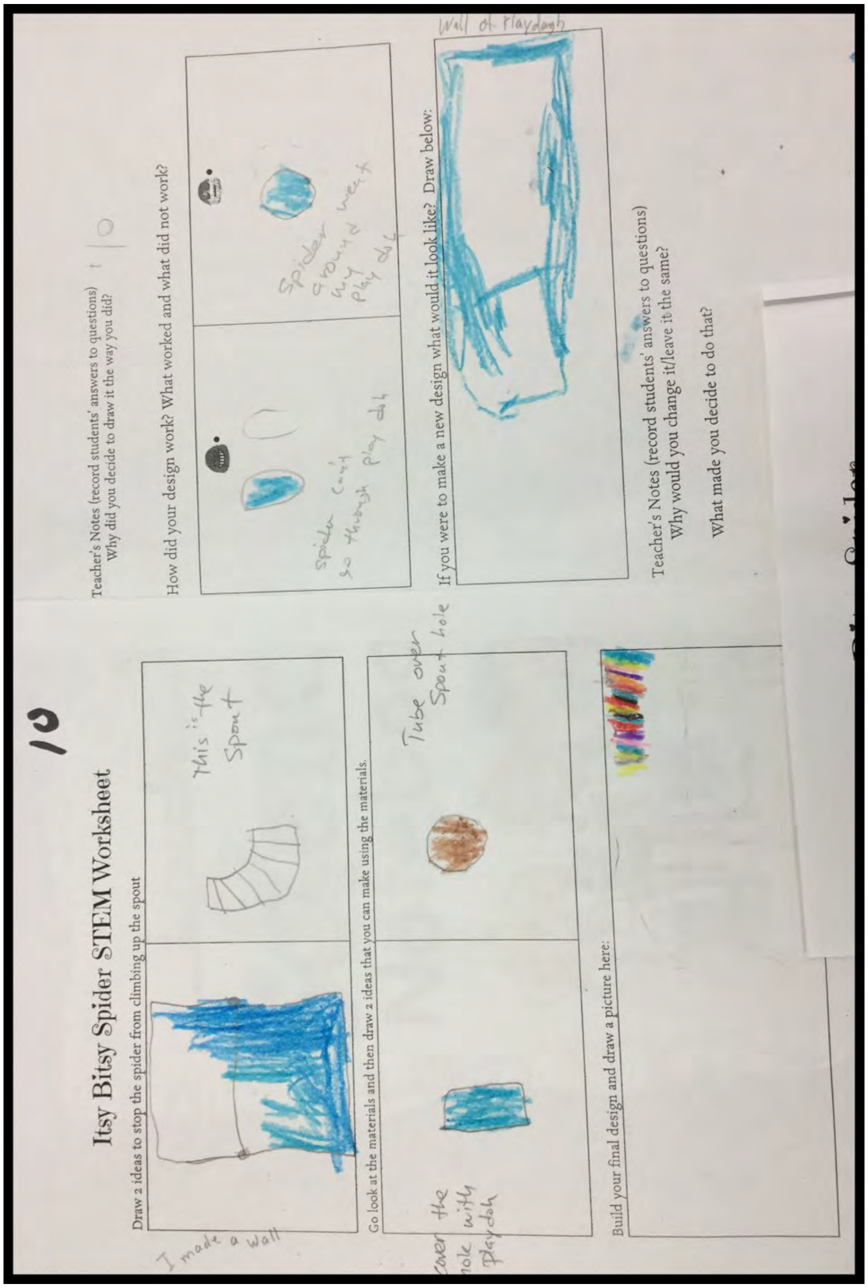

Figure 1. Example of a design portfolio for the Itsy Bitsy Spider task.

The children's rhymes, and associated design tasks, were field-tested with a primary school-aged student in one of the classes to identify any potential revisions necessary to address activity appropriateness. This student engaged in each of the problems while a researcher observed and identified areas needing clarification, adjustment, and direction. Design challenges and portfolios were adjusted following this field-testing and readied for further research. After meeting with the participating teachers, the design portfolio worksheets for each problem were provided to the teachers. Additionally, a variety of items were collected by the teachers for student use in prototyping potential solutions to the design problems. These items were collected from students and included readily available materials such as plastic, paper, cardboard, tape, and glue.

Implementation and Data Collection

Prior to the first design problem, the researchers visited the three classes, explained the research study, and disseminated permission forms. Researchers returned to the classes, retrieved permission forms, and scheduled time with the students (N = 55) and teachers for a 3-week span to introduce each of the three design tasks (one per week). Each design task took approximately 1 hour of class time and was completed individually by the students. During the design task, the researchers followed a script to introduce the problem, guide students through the design portfolio creation, facilitate the prototype creation by students, and take pictures of the student design portfolios and prototypes.

Prior to each lesson, the participating teachers familiarized their students with the associated children's rhyme and disseminated permission forms for participation. During the lesson, a member of the research team recited the rhyme with the students and discussed the design problem included in the rhyme. Students were then given a design portfolio and led through the process of solving the problem and filling out their portfolio by a member of the research team.

Each design portfolio worksheet (see Figure 1) was designed to guide students through different stages of design (e.g., planning, making, and evaluating), and at each step of the process, students were prompted to draw a picture of their ideas, challenges, and successes—this was important because none of these students (ages 5–6) knew how to read or write. Following each opportunity to draw, the students were prompted by a member of the research team to explain their drawings. Because students of this age lack some communication skills (both verbal and graphic), members of the research team asked follow-up questions to students until an understanding of students' intent was reached. This was then recorded by a member of the research team on the portfolios for later analysis (see Figure 2).

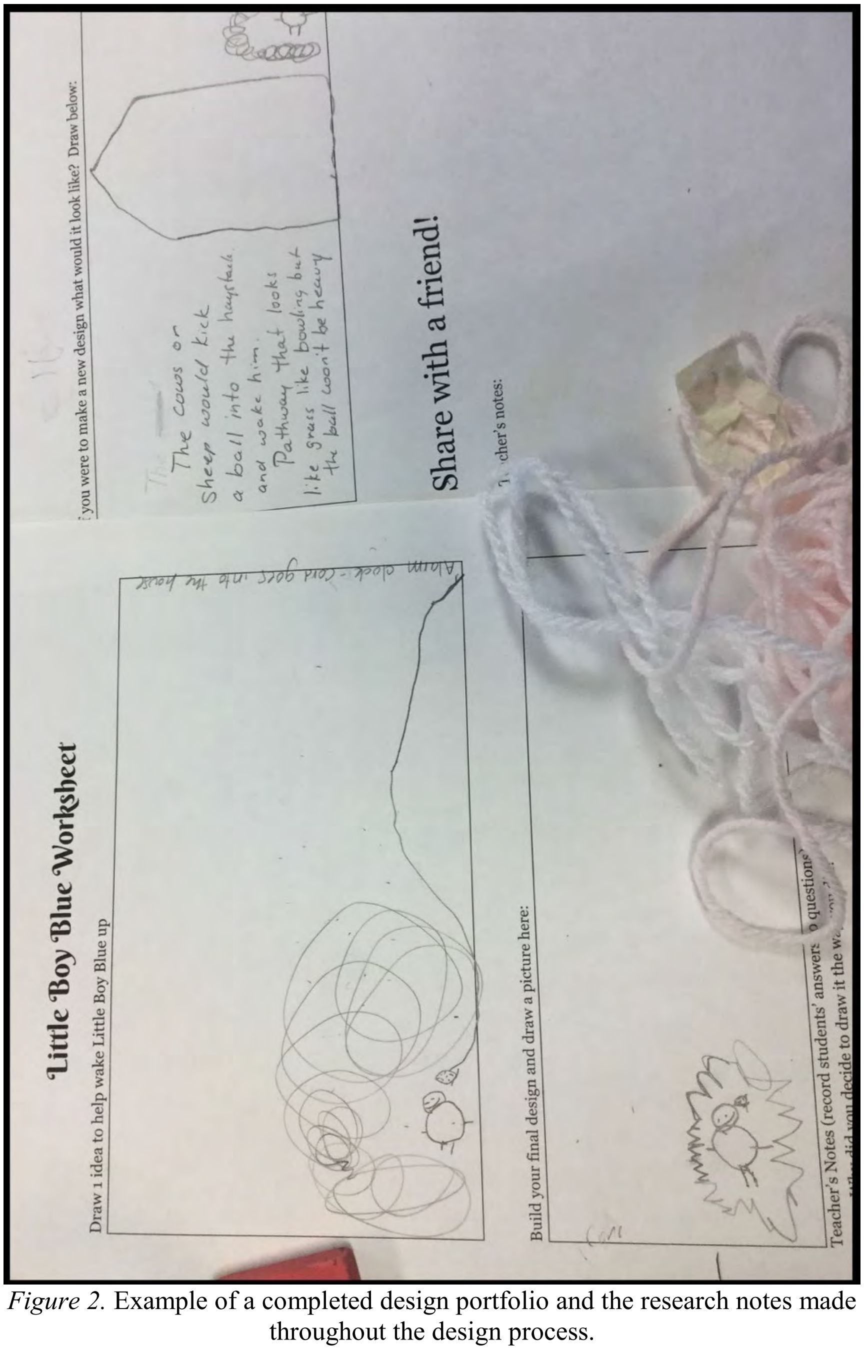

Figure 2. Example of a completed design portfolio and the research notes made throughout the design process.

Students were initially asked to brainstorm and draw ideas to help them solve the problem connected with the nursery rhyme. After the initial brainstorming (e.g., *Planning* phase, see Figure 2), drawing, and notes by the researcher, students were given access to the low-fidelity prototyping supplies and were asked to once again draw what might help them solve the problem—this time focusing on the materials provided. After drawing an idea and explaining their idea to a member of the research team, the students were given access to the supplies and allowed time to create and test their solution prototype (see Figure 3). Following the making and testing stage, the students were invited a third time to draw how they would solve the problem if they were to begin again (e.g., evaluation stage; see Figure 4). As before, these drawings were explained to a member of the research team who recorded the student thoughts on their portfolio.

Figure 3. Example of a student prototype for Baa Baa Black Sheep.

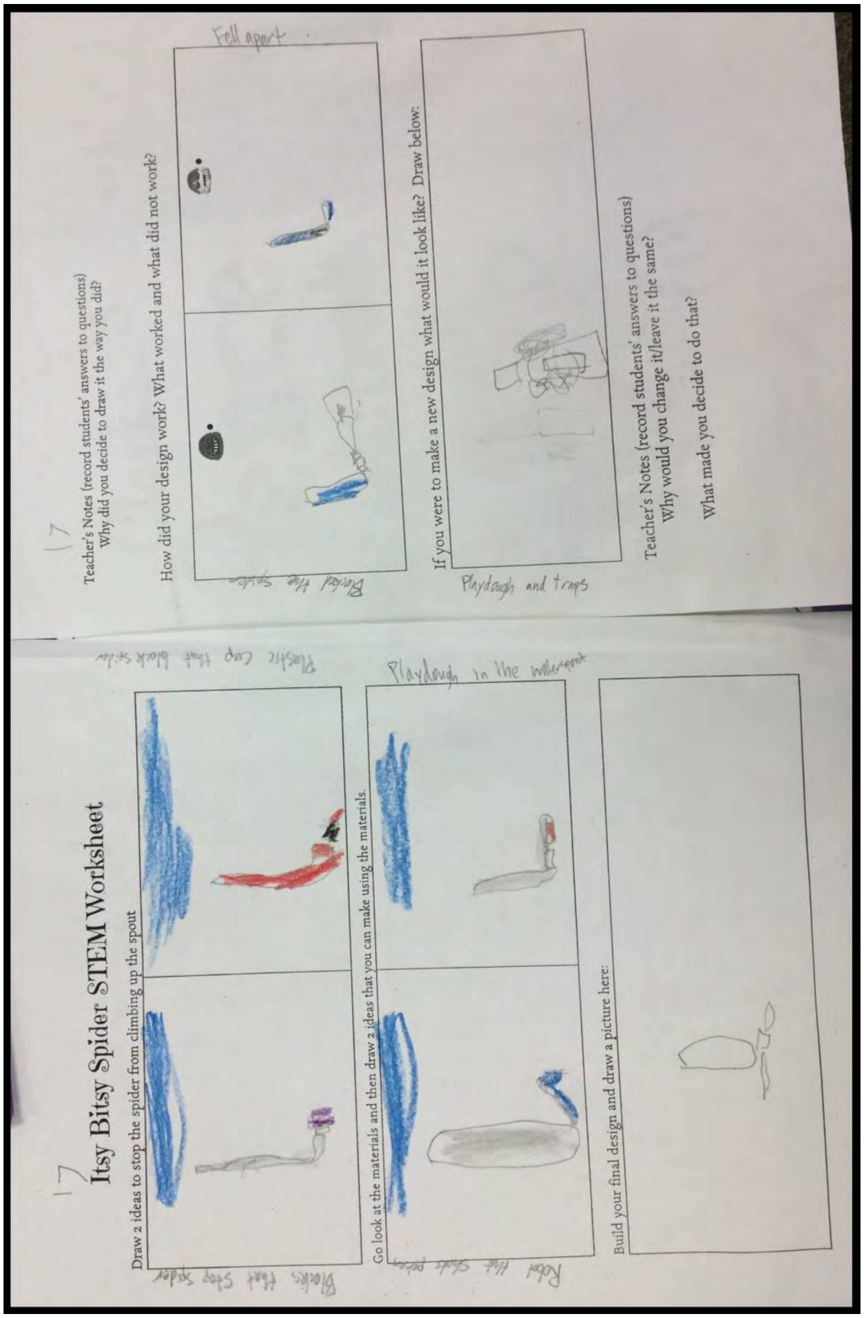

Figure 4. Example of completed portfolio (Itsy Bitsy Spider).

This process was repeated in each of the classrooms with the three tasks. Each of the iterations was conducted during class time and took approximately 1 hour to complete with the students. Following each design task, a picture was taken of the student portfolios and prototypes. The resulting data included 165 pictures of design portfolios and prototypes, collected from 55 participating students, from three open-ended design challenges centered on children's rhymes.

Data Analysis

All images of student prototypes and portfolios were collected and organized according to teacher and design task. After conducting a review of related literature and examining all 165 artifacts independently, the research team, which consisted of three licensed technology and engineering (TEE) teachers, met to discuss potential approaches used during the planning and evaluating stages of design. The researchers followed recommendations of Saldaña (2016) for the holistic coding of qualitative data. This process involved the initial meeting of researchers to identify potential approaches used by students, the generation of a list of potential codes, and then a coding process completed individually by the members of the research team. Following these initial steps, the codes were synthesized by the research team into the following categories:

1. **Invention/Creation**: developing a solution to the problem that emphasized something the student would create that did not already exist,
2. **Application/Innovation**: developing a solution to the problem that emphasized the use of an existing product or products to solve the problem, and
3. **Method/Approach**: developing a solution to the problem that emphasized how the students would solve the problem without explaining how the solution worked.

Following the solidification of the three categories identified above, members of the research team independently viewed each design portfolio, prototype image, and the accompanying descriptions and then assigned one of the initial codes to both the planning and evaluating stages of the design portfolios. After each section of each portfolio was assigned a code independently by two members of the research team, a second meeting was convened to discuss the results. Saldaña (2016) recommends reviewing the results, intercoder reliability, and revising and refining the codes until appropriate codes have been identified and reliability has been achieved. Following the first coding, a relatively low level of interrater reliability was achieved. Discussion amongst the research team led to a revision and identification of four possible codes with specific descriptions, which included:

1. **Black Box:** students offer no explanation as to how the problem is solved but *simply state that the problem will be solved*,
2. **Method/Approach**: students don't specify what they will use to solve the problem but *specify how they will solve the problem*,
3. **Application/Innovation**: students *will use an existing on-the-market product* to solve the problem, and
4. **Invention/Creation**: students will *make something novel* to solve the problem.

Following the revision of the codes, members of the research team independently coded 100% of the planning and evaluating sections of all student design portfolios. Recognizing that many of the student solutions could potentially encapsulate multiple codes, it was determined that the coders would assign only one code at each stage and that the assigned code should represent the code that "best fit" the student's thinking—as determined by the coder. Coders followed a systematic process, questioning first if the solution was an Invention/Creation, then if the solution was an Application/Innovation, and so forth. The coders also noted problematic coding scenarios that could not be easily fit into one code—these problematic sections, of which there were a limited number, were discussed amongst the research team in follow-up meetings until a code was agreed upon. After this process, an interrater reliability was calculated to determine if there was agreement between the researchers assigned codes. There was moderate agreement between the researcher's judgements, $\kappa = .603$ (95% CI, .503 to .703), $p < .0005$. Based on the agreement level obtained through the independent coding of all design portfolios, we determined to proceed with the data analysis related to our guiding research question.

Findings

The findings from this study were taken primarily from the qualitative analysis of pictures of student design portfolios and prototypes. All student drawings and responses were coded holistically by independent members of the research team, and after obtaining a sufficient interrater reliability for the assigned codes, all data were entered into statistical software (SPSS Version 23) for analysis.

The research question guiding our efforts was: What approaches do Kindergarten students use when making decisions in the process of resolving open-ended design tasks within integrated STEM learning contexts? Following the coding of responses, we determined to investigate this question by specifically analyzing the similarities and differences in approaches taken by students according to teacher, design task, and stage of design. In addition to related literature, these specific investigations were conducted based on observations made by the research team and the participating teachers during the design tasks.

Teachers. A one-way ANOVA was conducted to investigate the potential influence of the teacher on the approaches that students used while designing at both the planning and evaluating stages of design. It was noted by the research team that students with different teachers (and thus different classrooms and teaching styles) appeared to gravitate towards different approaches—a decision potentially influenced by their classroom or teacher. An analysis of variance showed that the effect of teacher on approaches used by students in the planning stage was significant, $F(2, 134) = 3.86$, $p = .023$, but the effect of teacher on approaches used by students in the *evaluation* stage of design was not significant, $F(2, 115) = 1.94$, $p = .149$. These findings—that we recognize may be potentially influenced by other variables in addition to the teacher—may suggest that students approached problems differently at the planning stage based on the influence of their teachers. Further, these findings may suggest that different instructional emphases (i.e., teacher emphasis on criteria, creativity, or optimization) may influence the approaches utilized by students while designing.

All student responses, for both the planning and evaluating stages of design, were separated by teacher to further investigate how students approached design in each classroom. The total items coded in each of the identified categories for each teacher are included in Table 2.

Table 2
Student Approaches for Designing by Teacher for All Design Tasks

	Design approach (count, percentage)			
	Black Box	Method/ Approach	Application/ Innovation	Invention/ Creation
Teacher 1	22 (42.3%)	5 (9.6%)	6 (11.5%)	19 (36.5%)
Teacher 2	9 (20.5%)	4 (9.1%)	15 (34.1%)	16 (36.4%)
Teacher 3	0 (0%)	9 (22%)	21 (51.2%)	11 (26.8%)

The students in Teacher 1's class predominantly approached their design task from a Black Box standpoint, stating that they would solve the problem but offering no indication as to how they would accomplish this, or from an Invention/Creation standpoint, proposing to build something new to solve the problem (see Figure 5 for an example).

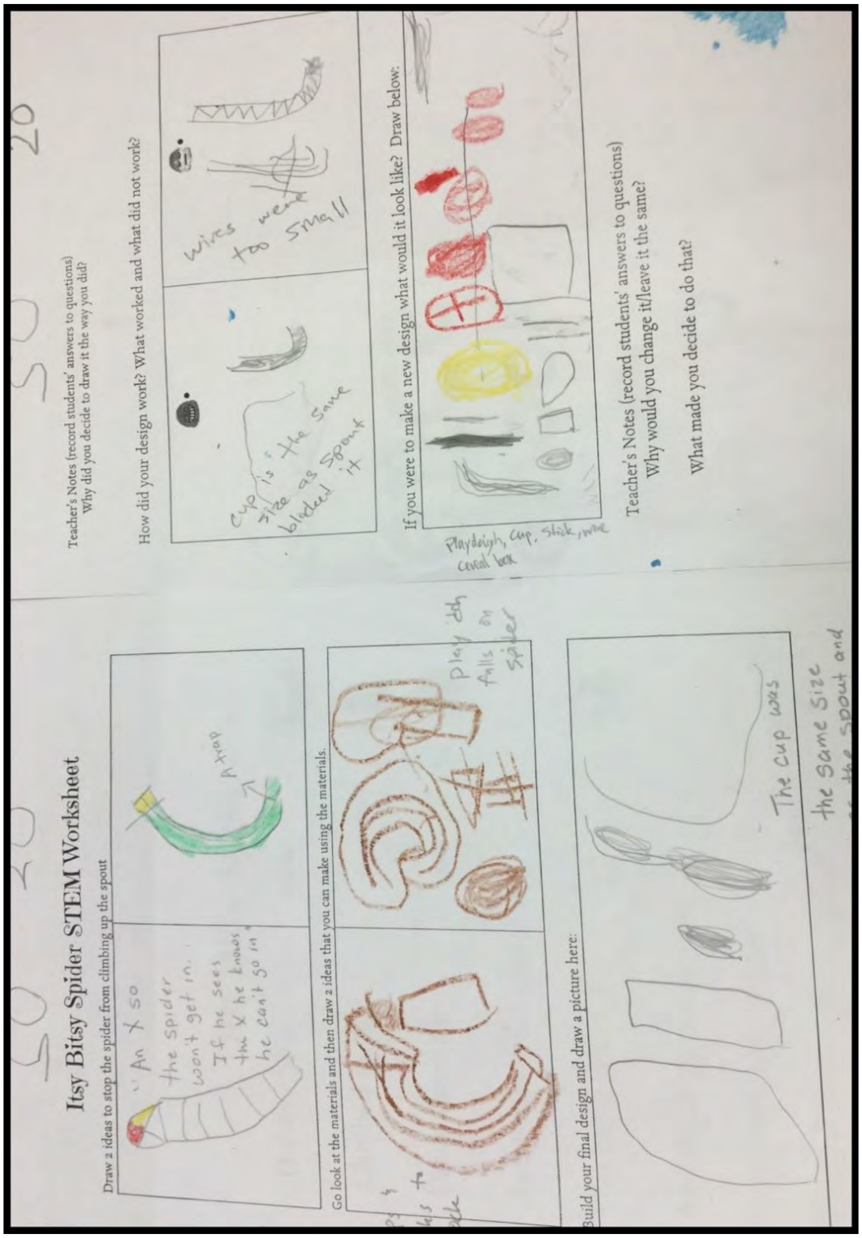

Figure 5. Example of a student portfolio in Teacher 1's class. The first box was coded as a Black Box approach, and the final box was coded as Invention/Creation.

Alternatively, the students in Teacher 2's classroom approached the design tasks differently with an emphasis on either the Method or a Black Box approach. For example, one student explained that they planned to "make a box with three sticks and a headband around it all" for the planning portion, and in the evaluation portion, they changed their design to a box with rubber bands around it to separate the wool.

Finally, although many students in Teacher 3's classroom emphasized Application/Innovation or Black Box approaches, most of Teacher 3's students utilized an approach that revolved around a particular Method to solving the problem. This emphasis on an approach is exemplified by students describing methods of transporting the wool (e.g., using a truck).

Design Task. To investigate the potential effect of different design tasks on the approaches that students used while designing at both the planning and evaluating stages of design, a one-way ANOVA was conducted. The analysis of variance indicated that the effect of the design task on the approaches used by students in the planning and evaluation stages of design was significant. The effect of the task on design approaches used by students during planning was $F(2, 134) = 4.78$, $p = .010$, and the effect of task on the approaches used by students in the *evaluation* stage was $F(2, 115) = 3.58$, $p = .031$. These findings demonstrated a significant difference in the approaches to design by the students based on the assigned design task. Further analysis resulted in the frequencies of each approach used by students (see Table 3).

Table 3
Student Approaches for Designing by Task

	Design approach (count, percentage)			
	Black Box	Method/ Approach	Application/ Innovation	Invention/ Creation
Task 1: Itsy Bitsy Spider	8 (15.7%)	9 (17.6%)	6 (11.8%)	28 (54.9%)
Task 2: Baa Baa Black Sheep	18 (36%)	3 (6%)	21 (42%)	8 (16%)
Task 3: Little Boy Blue	5 (9.1%)	9 (16.4%)	31 (56.4%)	10 (18.2%)

The Itsy Bitsy Spider design challenge involved students designing and prototyping a solution to keep the spider from climbing the water spout while still allowing rainwater to escape. This task was primarily approached by students from an Invention/Creation standpoint. Students offered a variety of solutions that they would create including things such as building a wall, making an object with spikes by the spout, and making a no entry sign for the spout (see

Figure 6).

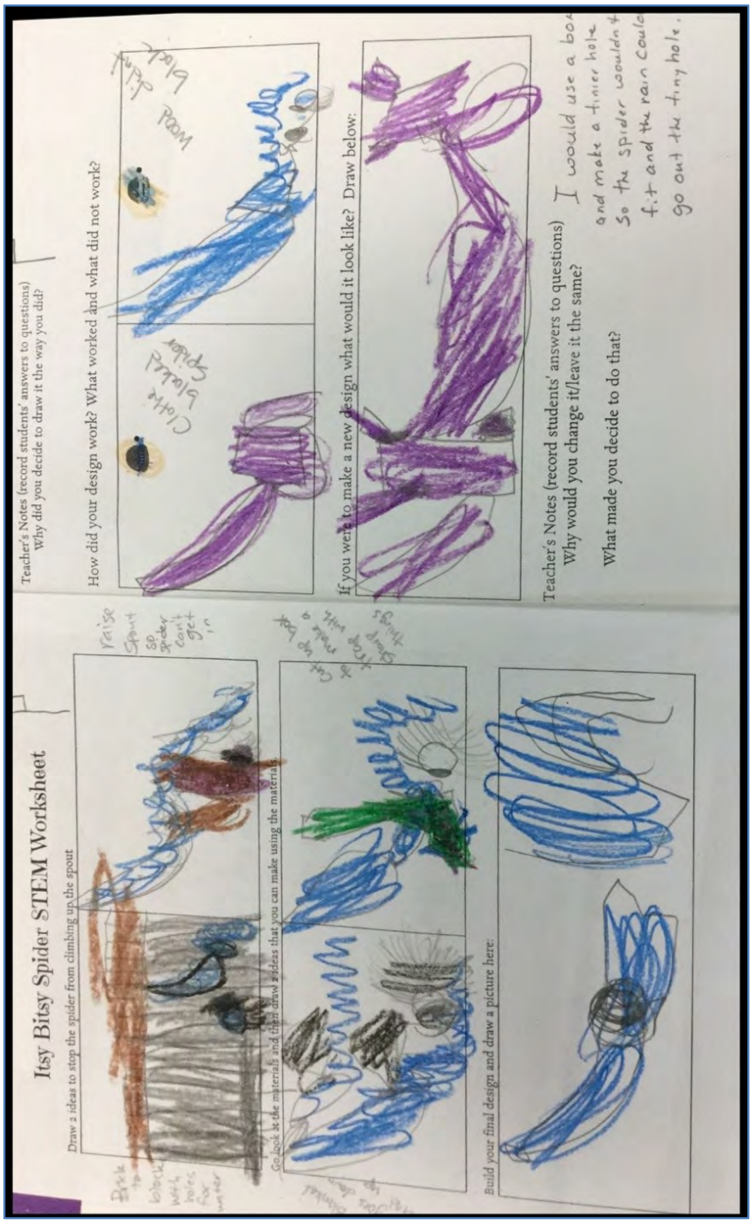

Figure 6. Example of a student portfolio during the Itsy Bitsy Spider task. Both boxes were coded as Invention/Creation.

For the second task, students were tasked with designing and prototyping something to separate sheep's wool. Although some students (36%) took a Black Box approach to solving this problem, offering solutions such as using flowers and boxes, putting them in something to be delivered, and using something made of metal, this challenge was predominantly approached from an Application/Innovation approach (42%) with students offering ideas such as: using a stick for separation, cutting the wool with scissors, and using a knife.

In the third task, the students were tasked with designing and prototyping something to help wake Little Boy Blue so that the cows and sheep would not escape the pasture. Overwhelmingly, the students took an Application/Innovation approach (56.4%) and emphasized the application of existing products to wake Little Boy Blue (e.g., alarm clock or bell).

Stage of Design. Finally, to investigate if design approaches used by primary school children were different at various stages of design (e.g., planning and evaluating), a chi-square goodness of fit was computed to compare the approaches of students during these stages of design. The results indicated a significant interaction between design approach and stage of designing at both the planning ($\chi^2(3) = 13.80$, $p < .05$) and evaluating ($\chi^2(3) = 29.66$, $p < .05$) stages of design. Students were most likely to use either an Application/Innovation-based approach (30.7%) or an Invention/Creation approach (33.6%) at the planning stage. For the evaluating stage, students were most likely to use an Invention/Creation approach to design (44.9%).

Discussion

The findings, related to the analysis of the student work and the potential relationships with several other factors, presented several interesting findings. These will be discussed in turn with potential implications.

Teacher Differences. Previous research suggests that the influence of teachers on students' achievement, attitudes, and experiences is significant (Darling-Hammond, 2000) and that students design experiences can differ based on their teacher (Bartholomew et al., 2017). Although the approaches students used in the evaluating stage of design were not significantly different for each teacher, the approaches students used during the planning stage of design were significantly different. Teachers may be able to significantly influence their students regarding best practices, effective approaches, and positive planning for designing. Identifying the best approaches and training teachers on how to assist their students in incorporating these may result in improved design approaches for their students. Relatedly, we investigated the impact of school on the differences in how students approach design problems but found no significant difference at either the planning or evaluating stages of design based on the students from different participating schools.

Interestingly, the variance in student approaches to designing, based on teacher differences, was not significant at the evaluating stage of design. This finding suggests that, although student initial approaches to design may be significantly influenced by their teachers and classroom experiences, student approaches to designing at the evaluating stage may be influenced by other factors. Of note, the researchers noticed several common "mistakes," "misnomers," and "design flaws" across all classrooms—for example, many students designed a way to keep the spider from going up the water spout but failed to account for the constraint of allowing the water to flow freely through the spout. It is possible that these common "mistakes," across all participating teachers, contributed to a less significant impact of teacher on how students approached design at the evaluating stage of the project. As students fell into similar struggles and challenges, their evaluating responses may have become more "standardized" and less significantly influenced by the differences in their teachers and classrooms. Moreover, it is possible that this finding may be a result of differences in instruction provided to students related to understanding criteria and constraints or the refining and optimization of designs.

Design Task Differences. Three design tasks, all revolving around problems included in children's rhymes, were used with the Kindergarten students in this study (see Table 2). The first problem asked the students to design and prototype a way to keep the Itsy Bitsy Spider from climbing the water spout with the constraint of the design needing to allow the rainwater to flow freely through the spout. For this challenge, students primarily used an approach that revolved around them *Inventing/Creating* something new to solve the problem. This was unique because the other two challenges—Baa Baa Black Sheep, which asked the students to devise a way to separate wool, and Little Boy Blue, which asked students to design a way to wake Little Boy Blue if the cows or sheep went to the meadow or corn—both involved student approaches to design that emphasized the Method/Approach rather than Inventing/Creating.

These differences may be simply a function of the differences in the problem. For example, in the Itsy Bitsy Spider problem, the students had to block a living organism from a certain area; in the second, the students needed to separate an inanimate object; and in the third, the students needed to wake a sleeping individual. Alternatively, it is worth noting that the Itsy Bitsy Spider was the first experience introduced to the students; therefore, it is possible that the differences in approaches were simply a result of the timing, experience, and exposure of the students to the design problems—with students initially approaching problems from an Invention/Creation standpoint and moving to a more Methods-based approach as they gained more experience.

However, the different design approaches revealed in this study may also demonstrate variance in student results for different tasks as a result of the criteria and constraints presented in the given problem scenario. In light of these findings, we recommend that further investigations seek a better understanding of which approach (or approaches) may be best suited for different types of situations rather than which approach (or approaches) are best overall.

Design Stage Differences. The students approached their designing with significantly different approaches at both the planning and evaluating stages of design. At the planning stage the students emphasized both Application/Innovation and Invention/Creation approaches, but the most significant difference was found at the evaluating stage where students primarily used an Invention/Creation approach to design. The significant differences in how students approached the design tasks at each stage may be related to a variety of factors (including many already discussed). We theorize that students emphasized an Invention/Creation approach to design during the evaluation stage of design primarily because they were asked to identify how they would solve the problem if they started over—this question may lead to an emphasis on what they would make or create. However, the students' emphasis on an Invention/Creation approach may be a result of other factors such as their experience—which sometimes included failure, struggles, and other learning experiences—during the design challenges or something else altogether.

Stage of Design. Finally, to investigate if design approaches used by primary school children were different at various stages of design, a chi-square goodness of fit was computed to compare the approaches of students during the planning and evaluating stages of design. The results indicated a significant interaction between approach to designing and stage of designing at both the planning and evaluating stages of design. Students were most likely to use either an Application/Innovation approach (30.7%) or Invention/Creation approach (33.6%) at the planning stage. For the evaluating stage, students were most likely to use an Invention/Creation approach (44.9%).

Conclusion

This study set out to explore approaches used by Kindergartners in solving open-ended design problems through a qualitative analysis of student design portfolios completed during three consecutive open-ended design challenges involving children's rhymes. Our research involved holistic coding (Saldaña, 2016) of student responses during the planning and evaluating stages of design (Fleer, 2000) with four approaches emerging from analysis of the data, including: (1) a Black Box approach wherein the students offered no explanation as to how the problem would be solved, (2) a Method/Approach in which a student focused on a particular method for solving the problem, (3) an Application/Innovation approach that focused on the application of an existing product, and (4) an Invention/Creation approach that focused on creating a new product to solve the problem. The analysis of data included investigating the impact of teacher, design task, and stage of design on the approach (or approaches) used by students during each design task and across all three design challenges.

Despite a teacher script, prescribed design portfolios and problems, and comparability in classrooms, teachers, and students, the analysis revealed a significant difference in how the students approached the design problems based on their different teachers, the different design tasks, and the stage of design in which they were engaged (e.g., planning or evaluating). These findings raise important considerations related to the introduction of design tasks with young students. Namely, those wishing to introduce and use these problems in their classrooms should recognize the potential for students to approach these problems in significantly different ways.

Further, students may attempt to design problems through a variety of approaches that may change from problem to problem, classroom to classroom, and even during the duration of one design problem. We contend that future efforts towards identifying best practices or approaches to design should consider multiple best approaches that may vary based on problem, task, teacher, student, or stage of design. Perhaps there are no best approaches to design that can be broadly applied but a variety of potentially-useful approaches that are dependent on multiple variables related to the designer, task, instructor, and design timeline. Future efforts, with larger variance in students, teachers, or design problems, may shed additional light on these differences and expand our understanding of how primary school children approach these open-ended design challenges.

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Book Review

Khine, M.S. (2017). *Robotics in STEM education: Redesigning the learning experience*. Cham, Switzerland: Springer. ISBN: 978-3-319-57785-2 (Hardback), $99.99, 262 pages.

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Robotics in STEM Education: Redesigning the Learning Experience

Technology and the global market is changing with greater speed—such as driverless cars, automated vending machines, bionic human prosthesis, and farming robots that weed and seed. Despite these changes that will demand new skills for the workplace, public education has remained essentially static. Khine suggests if teachers from the nineteenth century were invited into the classroom, they would have no problem teaching our students because most schools are still using the same practices they have always used in the past, such as not requiring students to acquire critical thinking and reasoning skills, and connect their learning to their lives.

Many curriculum developers and scholars in the field of science, technology, engineering, and mathematics (STEM) ask, "How can we support students in building a deep, integrated knowledge of STEM so that they have the practical knowledge and problem-solving skills necessary to live in and improve the world?" (Krajcik & Delen, 2017, p. 35). Careers that will be available to the next generation workforce will require practical knowledge, the ability to collaborate with others, problem-solving, critical thinking, decision-making, and innovative skills.

The authors in *Robotics in STEM Education: Redesigning the Learning Experience*, provide a collection of current lessons, projects, and ideas that use innovative methods of integrating robotics inside and outside the classroom. The overall purpose of this book is to provide strategies to transform students from being consumers of learning to think deeply about their learning—not only in the STEM field but also across many other disciplines. Ideas for integrating robotics extends into the arts and even into the fields of storytelling and drama. The authors explain the theoretical foundation of educational robotics, connecting robotics education with STEM and other standards, such as the Common Core State Standards. The authors of this text provide educators with a new perspective on the uses and applications of robotics as effective learning tools in the classroom.

Khine and the authors note that STEM education is progressing, and therefore, a redesign is needed to meet the needs of diverse learners, and address issues and challenges, such as creating more enthusiasm among students in the area of STEM. Similar to his past books, Khine gathers a collection of lesson and project ideas from various authors, and each chapter provides the reader with visuals and examples of authentic projects. Khine also discusses pedagogy and cognitive strategies to improve teaching and learning.

This book is organized into three parts. Part I includes Chapters 1-4 and focuses on robotics curriculum and schools; these chapters are based on the benefits of hands-on learning that stems from the constructivism theory. The constructivism theory derives from the constructivist theory of Jean Piaget. Robotics supports this theory since the learner is not just gaining facts to construct in their mind but building knowledge by engaging in the manipulation of a tangible object. The book also makes mention of Paulo Freire's book, *Pedagogy of Oppressed* (1994), where educational practice trains teachers to deliver facts and requires students to be like containers to be filled up by the instructor. Educational robotics is a tool that allows for this inquiry and creative thinking to promote technological fluency or literacy.

Within chapter one is a list of eight mathematics practical standards, English language arts standards, and college and career readiness standards from the Common Core State Standards. The author explains how the use of educational robotics in the classroom addresses some of these standards.

Chapter two contains information on how to teach students to think by using the systems thinking approach. In this scaffolding method, the curriculum is viewed as having many elements and interdependencies within, where students understand and apply the big ideas of STEM. Big ideas link concepts from a wide range of subject fields. Robotics is a learning tool that helps facilitate these ideas, such as computational learning, which many students are reluctant to learn, in part due to their perceptions about the difficulty of computer programming and coding.

Chapter three is primarily based on coding tools, such as Lego Mindstorms, that allows for more visual and hands-on learning that is engaging, and more motivating to students. Within the chapter the author discusses how there is research to support using games as a pedagogical approach to computational skills to improve student understanding. Affordability and accessibility of resources, such as open source academic robotic kits and software, lowers the barriers for all students in high school and undergraduate STEM academics. Students apply and acquire knowledge across many disciplines in the construction of the robot. The Open Academic Robotic Kit (OARKit) already comes with codes and mechanical parts ready for use.

Part two of the text focuses on the influence, support, and alignment of robotics with STEM curriculum. A visual chart and step-by-step explanations are provided on how to conduct a systematic review to analyze all recent research in the field of educational robotics. Educational robotics has allowed teachers to apply mathematics and science concepts in more authentic ways. The tangibility of robotics and their interdisciplinary nature foster the learning of both scientific and artistic concepts. The influence of robotics learning by students is divided into four main categories: “cognitive, conceptual, language, and social (collaboration) skills” (p. 106).

Chapter six is an overview of robotics competitions designed for STEM+C (Computer Science) Education. These competitions promote awareness and interest in the field among students, parents, and the community. They allow students to apply and exercise STEM knowledge as well as other disciplines.

Chapter seven provides us with information about the much-needed skills for the automation industry. Robotics is a major aspect of the new workforce due to growing automation developments. Although some lower skill jobs are being replaced by robots, more jobs are being created by robots, especially in the automotive and manufacturing sectors. To meet this demand, stand-alone training centers, as well as high school and college curriculum, is being developed and implemented. Learning institutions are generating more interest among students in the STEM field, and the cost of implementing these types of courses is becoming more affordable. Modules are available to pre-college and college students. This helps with students transitioning from high school to college in the robotics and the STEM field.

Creative development among children and STEAM education, which includes the arts, is the focus of Part three of this book. The authors provide illustrations and examples of how children interact with educational robots. They note two main creative areas: design and problem solving. Designing involves the conceptual, visual, and tangible creation of the robot. Creativity involves dialogue, understanding, and making of new meanings; it is also the diversity of the way in which the students think or interact culturally with each other and society in constructing new ideas. Creativity is the tangibility of the object, where students are able to hold, play with, and manipulate it. For example, to get more girls interested in robotics and STEM, they may want to make their robot look like more like themselves. The authors explain that the inclusion of all learners in robotics must include the physical look of the object itself. In addition to creativity, problem solving with robots involves critical thinking and idea generation using various methods, such as debating, negotiating, and coordinating.

Chapter ten contends that teachers can use robotics to teach about robotics, or they can use robotics to teach other disciplines. The engineering design process, which is a process engineers use, is explained. As described by the newest acronym, STEAM, which helps promote creativity and expression through technology, educators can go beyond the sciences into arts, culture, social studies, language, dance, and many other fields. The authors explain several interdisciplinary robotics kits, such as *Dances from Around the World*, where children become choreographers, engineers, and stage managers.

This book is recommended for STEM teachers, and particularly engineering and robotics instructors because it provides lesson ideas that align with the curriculum. It also includes recent research specific to educational robotics, which helps educators construct new understandings, and theories. Educational leaders in the STEM field benefit because of its strength of current research findings, and strategies of how to effectively implement STEM, and more specifically, robotics. The authors not only provide methods from the research of successful ways to implement educational robotics, but also warn the reader by listing important factors for successful implementation, such as the role of the teacher as a positive influence, the physical space and learning environment, and the design and variety of the robot itself for inclusion of all students.

Each chapter offers great insight and ideas on redesigning the learning experience by the book chapter authors. Educators may want to follow up with further research that includes student feedback during or after taking a course that utilized educational robotics, and summative assessment data. The book provides an easy to understand and practical compilation of new ideas and perspectives on how to redesign the learning experience in the STEM classroom and beyond.

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At the P-12 grade levels, the goal is for students to develop technological and engineering literacy, regardless of career aspirations, through hands-on, contextual applications of technological and engineering concepts. T&EE students, use a hands-on approach to solve technological problems using problem solving and creativity, while working under constraints, which involves the use of optimization and predictive analysis. At the P-5 grade levels, technology and engineering concepts are integrated into existing coursework such as reading, mathematics, science, and social studies. Typical courses students would take at the 6-12 grade levels in a T&EE program would consist of (a) information and communication technologies, including computer-aided drafting and design, (b) engineering design, (c) construction technology, (d) manufacturing technology, (e) energy, power, and transportation technology, and (f) medical, agricultural, and related biotechnologies. Within these courses, students would utilize troubleshooting, research and development, invention and innovation, and problem solving. The focus of T&EE at the P-12 levels is not to prepare future engineering majors/students, but to provide an education for all students.

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