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The Effects of an Engineering Design Module on Student Learning in a Middle School Science Classroom

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Abstract. Eighth grade students often experience difficulty concretely representing learning objectives in a physical science course. In order to determine the effect of engineering design modules, advanced manufacturing machines were employed including 2D and 3D fabricators to create tangible objects from computer-aided designs. Students completed the *Waves and Sound Assessment* prior to participating in the digital fabrication activities, and again after the hands-on activities. We also aimed to examine differences in learning based on sex. Major findings for the 13 males and 8 females were that both males ($p < .01$) and females ($p < .01$) gained a large amount of knowledge over the course of the two week-long unit on waves and sound. Large effect sizes for the open-ended questions and multiple-choice questions were found in both males ($d = .83$) and females ($d = 1.48$). There were no significant differences in scores between sexes at either the pretest or the posttest time period for the open-ended or multiple-choice questions. Findings indicate advanced manufacturing activities were effective for both boys and girls in fostering gains in science content knowledge related to waves and sound concepts.

Keywords: digital fabrication; advanced manufacturing; physical science; middle school

Introduction

The need to improve K–12 education in science, technology, engineering, and mathematics (STEM) subjects has been generally agreed upon for several years (National Research Council (NRC), 2009). Groups and agencies calling for improvements and changes include the U.S. Department of Education, the National Science Board, and the National Academies (Livingston, 2008; NSB, 2007; NAS, NAE, 2011). Generally, the goal is to improve STEM education programs so that future generations are more qualified for employment in the rapidly growing technology fields.

The U.S. National Assessment of Education Progress reports roughly 75% of U.S. eighth graders are not proficient in mathematics or science when they complete 8th grade (President's Council of Advisors on Science and Technology (PCAST), 2010). Employers report job applicants lack needed skills in these subject areas to succeed in the work place (National Governors' Association (NGA), 2007). The problem is not just a lack of proficiency but also a lack of interest among American students in STEM content areas and careers (PCAST, 2010). STEM education is seen as a key component to overcoming the challenges facing this nation in an increasingly interconnected and competitive world (NGA, 2007). The general consensus is that an improvement in K–12 STEM education will help meet these needs.

The skills acquired in STEM content areas during the middle school years lay the foundation for a successful career in the STEM workforce (Woolley, Strutchens, Gilbert, & Martin, 2010) as many STEM occupations require competencies in science, mathematics, technology, and problem solving. Because the future is changing at such a rapid pace, it is crucial to focus on the development of middle school students (George, Stevenson, Thomason, & Beane, 1992). Without the proper scaffolding, more advanced study is impossible.

The presence of engineering in K–12 classrooms is important because of the implications engineering education has on the future of STEM education (Brophy, Klein, Portsmore, & Rogers 2008). Implementing engineering education in K-12 schools may improve student learning and achievement in STEM subjects; increase student awareness of engineering and the work of engineers; boost youth interest in pursuing engineering as a career; and increase the technological literacy of all students (Brophy et al., 2008). Advancement in engineering education may even be a key for a more coalesced and effective K–12 STEM education system in the United States (NRC, 2009).

Literature Review

Using design-based learning experiences in middle school STEM classrooms can provide real-world context to otherwise abstract and difficult STEM concepts, potentially helping students retain what they learn more effectively (NRC, 2009). Current research studies regarding hands-on learning experiences have shown improvement in student learning and achievement in mathematics and science (Akinoglu & Tandogan, 2007. Design-based learning has also proven to enhance students' interest in STEM subjects (NRC, 2009). Educators and administrators are interested in this hypothesis because of the lack of significant improvements from other means to improve STEM achievement and interest in K-12 education (NRC, 2009).

Engineering Design. Engineering design is an open-ended problem-solving process with specific constraints and goals. Over several iterations, students create, test and refine solutions until they have satisfactorily met the required specifications. This process provides key relevance because most real-world problems are not well defined (Dym, Agogino, Eris, Frey, & Leifer, 2005).

The ratification of the Next Generation Science Standards (NGSS) is indicative of the emerging view of national education leaders that engineering design is an integral and complementary part of scientific literacy (Cajas, 2001). In fact, the NGSS place engineering design on the same level as scientific inquiry. The rationale emphasizes the value of engineering in solving meaningful problems and providing opportunities for students to deepen their understanding of science by applying the knowledge they gain in a real-world context (NGSS, 2013). These national standards indicate teaching science through engineering design may be a worthwhile endeavor.

Enabling students to reason scientifically is one of the key elements in successful science teaching (Chinn & Malhotra, 2002). Traditionally however, science teaching has used pedagogical methods such as lectures, readings, worksheets, and demonstrations to impart facts and rudimentary skills to the science student (Silk, Schunn, & Cary, 2009).

Theoretical knowledge alone does not provide students with the skills necessary to translate that knowledge into solving real-world problems (Horwitz, 1995). High school students who scored well on question-and-answer tests of electrical circuits could not build or troubleshoot physical circuit models. Building, testing, and refining real models can close the gap between theoretical and applied knowledge and increase scientific understanding. The National Research Council (2009) purports that a classroom should be an environment in which more emphasis is given to knowledge that is useful. Engineering design is an approach that offers the ability for teachers to implement the NRC's recommendation. It provides students the opportunity to explore science concepts through the construction of models in a relevant context (Silk et al., 2009).

Engineering design curricula may have several benefits including engaging students in science reasoning. Using engineering design may help students better realize the usefulness of scientific knowledge in solving real-world problems (Fortus, 2005). When students participate in problem-solving in a relevant context they are more likely to engage and question the results of the experiment, rather than accepting what the books says even if their data results are contrary to the book (Benenson, 2001). Engineering design activities also provide opportunities to model difficult concepts with physical representations. This requires students to take into account physical limitations that may not be apparent with images in a book and providing a real-world representation of the concept being learned so that other students can learn from and critique the model (Roth, 2001). This model requires teachers to allow students to direct their own experimentation. It also requires that both teachers and students be willing to accept and even embrace failures during the iterative process (Smith, 2015).

Digital Fabrication. The rapid development of low cost, easy to use digital fabricators has allowed schools to adopt these advanced manufacturing machines in many classrooms (Bull & Groves, 2009). Digital fabrication is being used to promote higher order thinking and problem solving skills in middle school students by allowing students to conceptualize an idea and then realize the idea in a physical form (Bull & Groves, 2009).

Digital fabrication involves automated conversion of a digital design into a physical object through a computer-controlled fabrication system. The Society of Manufacturing Engineering (SME) concludes that personal digital fabrication will offer "revolutionary changes for both manufacturers and the everyday consumer." The Society lists personal fabrication as one of the key *Innovations that Could Change Engineering*, noting that the U.S. Department of Education has identified innovations of this kind as vital to future prosperity.

Other findings have shown that by fabricating artifact based on scientific concepts, students can demonstrate a fuller understanding of the science principles being studied (Hmelo, Holton, & Kolodner, 2000). For high-risk urban middle school classrooms implementing the engineering design process significant content gains were reported in the science classroom (Silk et al., 2009).

Achievement Gap. It is often assumed that girls are less likely than boys to perform well in mathematics and science classes and are more likely to lose interest in STEM subjects in the middle grades (Kahle, Meece, & Scantlebury, 2000). In many cases, though, empirical research is not definitive and in some cases no differences are observed (e.g., Pine et al. 2006). Furthermore, the gender gap may not involve the same causation among different ethnicities (Kahle et al., 2000).

The gap in STEM interest and achievement between boys and girls has been the subject of several research studies (Choi & Chang, 2009). Although previous studies have demonstrated that male students perform better in STEM areas than female students, Choi and Chang (2009) reported that recent studies have shown mixed results. As Knezek, Christensen & Tyler-Wood (2011) argued, the gender gap is less of an ability gap than a gap in perceptions of science careers.

While girls often score higher on math achievement in the classroom than boys, it is the opposite for standardized math scores (Liu, 2008). These gender differences related to math types of scores have been attributed to females thriving in the social aspect of the classroom while standardized tests are typically given in a more impersonal environment. Including social aspects in science and mathematics activities may be a more effective learning environment for girls. Fewer than 10% of engineers in the United States are female (Hirsch, Carpinelli, Kimmel, Rockland, & Bloom, 2007).

Many women are relatively uninformed about STEM fields and many are thought to have a higher attraction to career fields perceived as being of service to society (Hirsch et al., 2007). Other studies have found that traditional technology and engineering courses are not taught in a style that will appeal to females (Weber, 2012) yet when these types of courses incorporate engaging, real-world activities, both males and females are engaged (Mitts & Haynie, 2010; Weber & Custer, 2005).

Challenges Faced. Despite the national and international focus on STEM education, our understanding of how K-12 students learn science through engineering design is still limited. Engineering design is difficult to learn, teach, and assess, and there is not yet a large body of studies that have explored this topic (Katehi, Pearson, & Feder, 2009). The National Academy of Engineering report, *Engineering in K-12 Education,* concludes that existing science curricula do not fully take advantage of the connections between engineering and the other STEM subjects (Katehi et al., 2009).

The difference in the results and time constraints of implementing an engineering design in a diverse population can be significant (Kuhn & Dean, 2008). Li, Klahr, and Siler (2006) found that students from affluent homes could design an experiment within two days while students from less affluent homes could take up to three weeks depending upon the classroom and school. The population in which research is conducted must be accounted for when determining the effectiveness of the intervention (Lee, Deaktor, Hart, Cueva, & Enders, 2005).

With these challenges in mind, Fortus, Dershimer, Marx, Krajcik, and Mamlok-Naaman (2004) found significant gains in students who engaged in design-based learning in science classrooms. These students constructed scientific knowledge through hands-on activities that encouraged them to problem solve and demonstrate their knowledge gains. Other findings have shown that by fabricating models of a scientific concept, students demonstrate a deeper understanding of the science being studied (Hmelo, Holton, & Kolodner, 2000).

Research Questions. The relatively recent emergence of the importance of engineering education in K-12 has exposed several key questions for educators, policy makers, and researchers to consider. How should engineering be taught in K–12 schools? What instructional materials, curricula, and instructional methods are currently being used to teach engineering education? Has current implementation of engineering in K-12 schools improved student achievement in STEM subjects or increased interest and awareness in STEM careers (NRC, 2009)?

This study builds upon previous research which indicates engineering design projects may reduce the achievement gap among students while boosting standardized test scores in science subjects (Cantrell, Pekcan, Itani, & Velasquez-Bryant, 2006) by testing the following questions:

1. What effect does participation in an engineering design module on waves and sound have on middle school student's content knowledge of science, mathematics and engineering concepts?
    a. Do male and female students differ in their levels of competence gained in science, mathematics and engineering content after participation in an engineering design module?
    b. Do students in separate classes differ in their levels of competence gained in mathematics and engineering content after participation in an engineering design module?

Methods

This study executed a quasi-experimental design with a one group pretest-posttest design (Campbell & Stanley, 1966). Quantitative research methods were used to measure and examine data to explore the research questions.

Participants. This study was conducted as a pilot in a middle school located in a mid-Atlantic state. The population was comprised of 48.4% African American, 40.9% White, 6.7% Hispanic, and 4% Asian/Pacific Islander students. Fifteen percent of students speak English as a second language. Twenty-nine percent of the students have been identified as gifted and 14.7% are classified as special education students. Students in three eighth grade science classes served as participants for this study.

A total of 54 students in three different classrooms participated in this engineering design module. However, due to absence caused by a multitude of reasons including sickness, discipline, and familial circumstances, only 21 were present for each day of instruction and completed the pretest and posttest (13 males and 8 females).

The teacher for each of the three sections is a veteran public school teacher with 27 years of experience that includes teaching physical science at the middle and high school levels. His philosophy of teaching embraced project-based learning, and he is an advocate of STEM initiatives that encouraged students of all backgrounds to become involved in STEM subject areas.

Intervention

Overview. The engineering design module was comprised of five 90 minute block classes in an eighth grade physical science course over the span of two weeks. Teams of students were given the task of building two speakers. One speaker was to be designed to play low frequencies, referred to as the subwoofer. The second speaker was to be designed to play higher frequencies and was called the tweeter.

Students learned progressively more about the behavior and manipulation of waves throughout the five lessons. Each of these lessons included hands-on activities utilizing several advanced manufacturing machines such as 2D and 3D fabricators to create tangible objects from computer-aided design software. Using advanced manufacturing tools allowed students to test their designs and make the necessary changes to create more effective models. In building, testing, and refining the speakers, the students engaged in the engineering design process.

Digital fabrication. Digital fabrication is a process that creates tangible physical objects from digital designs. The digital design can be created on a tablet or computer using a myriad of software-based solutions. Digital fabrication offers many options for the classroom educator to implement project-based learning while building skills in subject areas such as mathematics, science, and engineering.

Advanced manufacturing machines such as 3D printers and die cutters can be coupled with technology such as 3-dimensional computer design software, computers and tablets and sound level meters. The die cutters us a small razor to automatically cut out shapes of all kinds on 2-dimensional materials such as paper and cardstock.

The CAD (computer aided design) software allowed students to design and draw objects on the computer using real dimensions and preview their object before fabrication. This provided the students with the opportunity to use real software to design something that would come to life, just like an engineer would. The students then used this model on the software and sent it to the die cutter so that it could cut it out to the correct specifications set by the students so that they were ready to fabricate a working model.

An example of digital fabrication in this experiment was when students created the cone for their speakers. They began by drafting rough design dimensions onto paper before using the FabLab Model Maker software to draw the cone on the speaker. The digital design was exported to the Silhouette CAMEO which cut the cone from cardstock paper.

Software and hardware. FabLab Model Maker (Aspex, London) was the primary computer aided design (CAD) software program students used to design the speakers. This particular software was chosen because of the built in hardware support for 2D and 3D fabricators. Microsoft Excel was used to develop the frequency response graphs which students used to measure the efficacy of each subwoofer and tweeter.

The 2D fabricator employed was the Silhouette CAMEO die cutter. Generic decibel meters were utilized by students while creating frequency response curves. AFINIA 3D printers were also introduced to the students. However, incorporating the 3D printer into the five lessons became non-viable due to time constraints. Students utilized the 3D printer later in the semester to improve their speaker design but data and observations from that extension are not included in this paper.

The students also used a sound level meter to test the loudness or amplitude of their speaker. This allowed the students to capture an intangible concept and map it in relation to their speaker design. The sound level meter brought a reality to the idea of volume so that they could see what their speaker could do.

Curriculum. The learning objectives of this unit included learning the properties of soundwaves while building, testing and refining a set of working speakers using advanced manufacturing technologies.

Day one. Students created a pre-designed paper speaker using the FabLab Model Maker software to test and compare with commercial speakers using low, mid, and high tones to enhance their understanding that different speaker designs are used to functionally play different tones more efficiently. This speaker became the base design from which changes, modifications, and adaptations were made to fulfill the design specifications for the subwoofer and tweeter speakers.

Day two. Students explored some of the properties of waves including wavelength, amplitude, frequency and period using various commercial and improvised tuning forks. Students further studied this phenomenon by building a pendulum dispensing paint mechanism. By pulling paper underneath the paint dripping pendulum as it swung, students created sine waves from which they identified the properties of a wave.

Day three. Students, on day three, explored the features of the FabLab Model Maker software. They practiced making different shapes and cutting them using the Silhouette CAMEO.

Day four. Refinement began in earnest on day four. Students used pencil and paper to draw, document, and justify planned changes. The designs created included metric measurements for each speaker part to be fabricated. Teams then created digital designs using the FabLab Model Maker software and fabricated their designs using the Silouette CAMEOs.

Day five. Upon completion of the construction of the speakers, students began testing their designs. Using an online tone generator, students would play specific pre-determined frequencies through each speaker. Students would record the loudness of the speaker at each frequency using a decibel meter. These measurements were entered into an Excel spreadsheet and a graph was created to display the frequency response for the speaker. By combining the frequency response graph for a tweet and a subwoofer, teams were able to determine the range and peak frequencies for their speaker pair.

Instrumentation

Eighth grade students in three different classes of a physical science course took the *Waves and Sound Assessment* prior to participating in the unit. The assessment consisted of multiple-choice and open-ended questions designed to evaluate participants' understanding of sound and sound waves. Included items were retrieved from the following sources:

- The International Mathematics and Science Study (TIMSS);
- Prentice Hall Physical Science Concepts in Action (Wysession, Frank, & Yancopoulos, 2011) by Pearson Education;
- The physical science curriculum framework (8th grade) published by the Virginia Department of Education;
- Albemarle County Public Schools' Physical Science Matrix; and
- STEM educators affiliated with the University of Virginia.

The assessment was not validated through formal measurement testing; however content area experts in science, mathematics, and instructional technology provided iterative feedback during the development of the assessment tool.

Two blinded raters scored all of the pre-assessments. One rater was a former high school technology educator with knowledge of the core scientific principles associated with sound waves and sound. The other rater was a former high school science teacher. Participants' responses received a correct or incorrect notation for all of the multiple-choice items (0 = Incorrect, 1 = Correct). Open-ended questions were rated according to a general rubric that evaluated the presence or absence of scientific understanding of sound and sound waves. The ordinal scale for evaluating open-ended items included the following levels:

- 5 Points: All items are addressed. Full inclusion of science principles. Explanations include proper terms and usage throughout response.
- 4 Points: Response is thorough, missing one element to response to provide complete understanding of science concepts.
- 3 Points: General conceptual understanding. Missing elements to providing a full response that addresses all science principles. Misconceptions may still exist.
- 2 Points: Response is vague and addresses a common understanding, while providing some instances of misconceptions.
- 1 Point: Blank response or no relation to the question asked. Full misconception in response.

The pre-assessments were scored by the two raters and the average measure intraclass correlation coefficent was .903 with a 95% confidence interval from .847 to .938, $p < .001$. A post hoc power analysis was conducted using the software package, *GPower* (Faul, Erdfelder, Buchner, & Lang, 2009). The sample size of 20 was used for the statistical power analyses and the alpha level used for this analysis was $p < .05$. The post hoc analyses revealed the statistical power for this study exceeded .99. Thus, there was more than adequate power.

The same assessment was re-administered after the 5-day unit. Pre to post knowledge gains were compared using paired *t* test; students were then grouped by sex for pre-post knowledge gain comparisons. Finally, the knowledge gains were compared between the sexes. All alpha levels were set *a priori* at 0.05. Cohen's *d* was used for effect size calculation (Cohen, 1988) and were interpreted as small = .2, moderate = .5, or large > .8.

Results

The multiple-choice items that were scored as 0 for incorrect and 1 for correct were totaled for the TotMC label (possible range of 0 – 13). The open-ended rated items were averaged for a label of OpenAvg (possible range of 9 – 45). The participants were paired and a paired *t*-test was run on the means and sums pre-post. As shown in Table 1, both indicators of content knowledge showed significant gains ($p < .01$) with large effect sizes.

Table 1: Paired Sample Analysis of Content Knowledge Gains, Pre to Post

		Mean	N	Std. Dev.	Sig.	Effect Size
Pair 1	Pre OpenAvg	19.50	20	4.199		
	PostOpenAvg	29.75	20	9.640	.0005	1.38
Pair 2	PreTotMC	6.05	20	2.625		
	PostTotMC	8.65	20	2.641	.0005	0.99

Gender Comparisons. Independent sample *t*-tests were used to compare the mean scores of the 13 males to those of the 8 females in this group of students, as shown in Tables 2 and 3, no significant ($p < .05$) differences in scores by gender for the open-ended questions or the multiple-choice questions, at the pretest or the posttest time period, were found. Gender-specific analyses of the indices confirmed that both males and females gained a large amount of knowledge over the course of the week-long unit on waves and motions. The effect size for males from pre to post on the open-ended questions was ES = 1.28 (Cohen's d = 29.4-18.8/Pooled SD) while the effect size for females pre to post was ES = 1.48 (30.4-21.5/Pooled SD). With regard to multiple-choice questions, the effect size for males pre to post was ES = .83, while for females the pre to post gain was ES = 1.45. All would be considered large gains according to guidelines provided by Cohen (1988). The similar pre-post gains in content knowledge by males and females are graphically illustrated in Figure 1 and Figure 2.

Table 2: Analysis of Open-ended Content Scores by Gender

		N	Mean	Std. Deviation	Sig
	Male	13	18.77	4.531	
PreOpenAvg	Female	8	21.50	3.625	
	Total	21	19.81	4.332	.166
	Male	13	29.38	10.813	
PostOpenAvg	Female	7	30.43	7.721	
	Total	20	29.75	9.640	.824

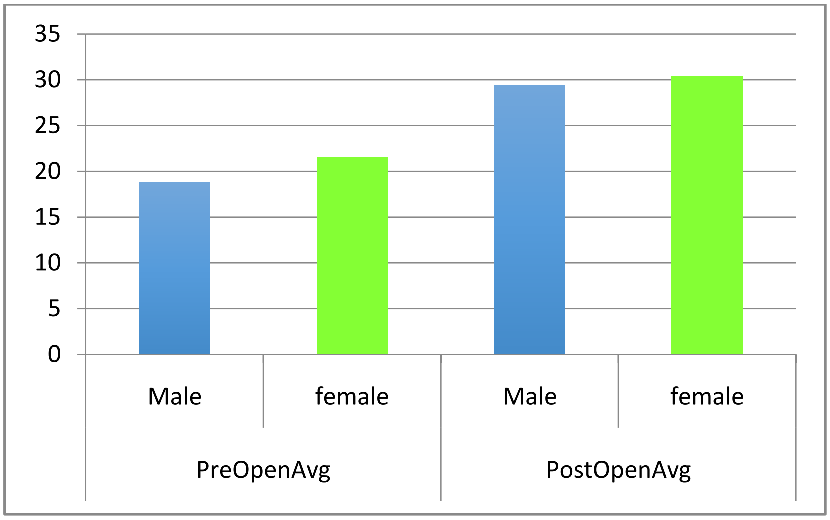

Figure 1: Pre and post comparisons by gender for open-ended content scores.

Table 3: Gender Comparisons for Multiple Choice Content Scores

		N	Mean	Std. Deviation	Sig
	Male	13	5.69	2.983	
PreTotMC	Female	8	6.88	1.727	
	Total	21	6.14	2.594	.323
	Male	13	8.08	2.783	
PostTotMC	Female	7	9.71	2.138	
	Total	20	8.65	2.641	.194

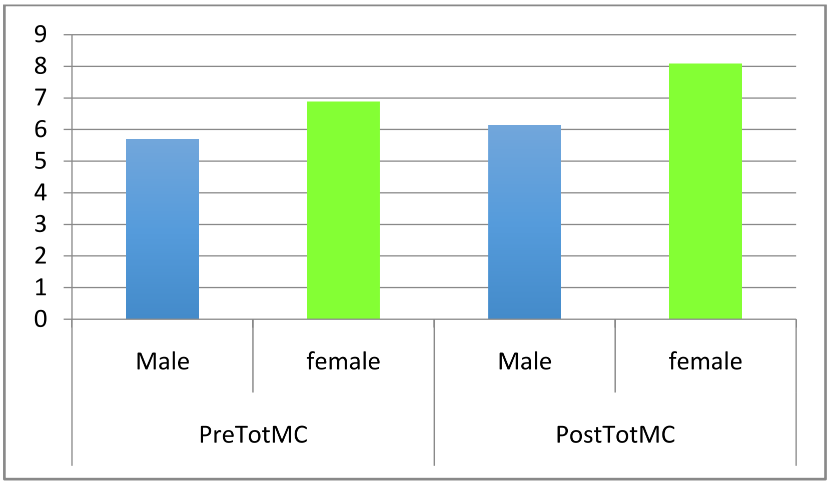

Figure 2: Pre and post comparisons by gender for multiple-choice question scores.

These findings led to the following conclusion regarding research question 2: Both male and female middle school students completing a digital fabrication unit exhibited large gains in content knowledge. No conclusive ($p <$ .05) evidence was found to indicate that males versus females began at differing levels of content knowledge, nor that they differed in the extent of knowledge gain.

Comparisons Among Classes. A one-way analysis of variance by class was completed for the three eighth grade classes on their open-ended questions at pretest and at posttest times (see Table 4). There were small numbers of fabrication activity participants in each group but the differences between classes was found to be significant ($p < .05$) at the pretest and at the post test times. With regard to gains, Class 2 gained approximately five points from pre to post, while Class 1 and Class 3 each gained approximately 8 content points. The pre to post effect sizes were: ES = 1.27 for Class 1; ES = .54 for Class 2; and ES = 2.50 for Class 3. Class 2 exhibited a moderate gain (Cohen, 1988) while for Class 1 and Class 3 the gains were very large (Cohen, 1988). These and other trends are graphically displayed in Figure 3.

Table 4: One-way Analysis by Class on Open-Ended Questions

		N	Mean	Std. Dev.	Sig.
PreOpenAvg	Class 1	8	20.00	3.59	
	Class 2	3	13.67	3.22	
	Class 3	10	21.50	3.69	.014
	Total	21	19.81	4.33	
PostOpenAvg	Class 1	8	28.75	9.00	
	Class 2	3	18.33	11.85	
	Class 3	9	34.44	6.33	
	Total	20	29.75	9.64	.030

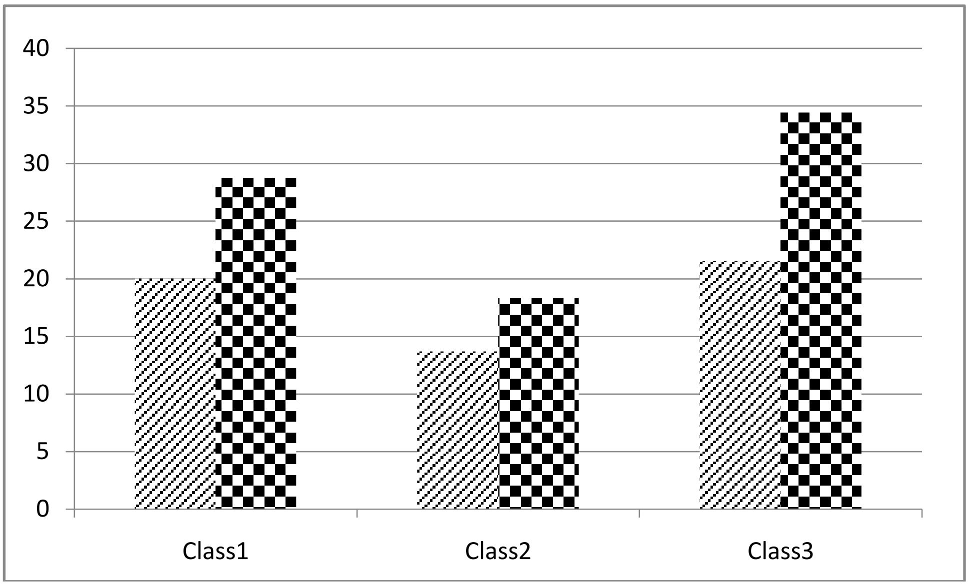

Figure 3: Pre-post open-ended questions by class.

One-way analysis of variance by class was also completed for the three eighth grade classes on their multiple choice questions at pretest and at posttest times (see Table 5). There were small numbers of fabrication activity participants in each group but the differences between classes were found to be significant ($p < .05$) at the pretest and at the post test times. With regard to gains, the pre to post effect sizes were: ES = 1.06 for Class 1; ES = 2.90 for Class 2; and ES = 1.49 for Class 3. Class 2 exhibited an extremely large gain (Cohen, 1988) from its pretest low starting point (1.67) while for Class 1 and Class 3 the gains were very large (Cohen, 1988). These and other trends are graphically displayed in Figure 4. Note that the effect size for class 2 could have been somewhat inflated by the very small sample size of n = 3. However, it is also possible that Class 2 truly had lower content knowledge at the pretest time, and that this class exhibited higher gains in basic knowledge commonly assessed by multiple choice questions.

Table 5: Oneway Analysis by Class for Multiple-Choice Questions

		N	Mean	Std. Dev.	Sig.
PreTotMC	Class 1	8	6.75	1.83	
	Class 2	3	1.67	.58	
	Class 3	10	7.00	2.11	
	Total	21	6.14	2.59	.001
PostTotMC	Class 1	8	9.13	2.59	
	Class 2	3	4.33	1.16	
	Class 3	9	9.67	1.41	
	Total	20	8.65	2.64	.003

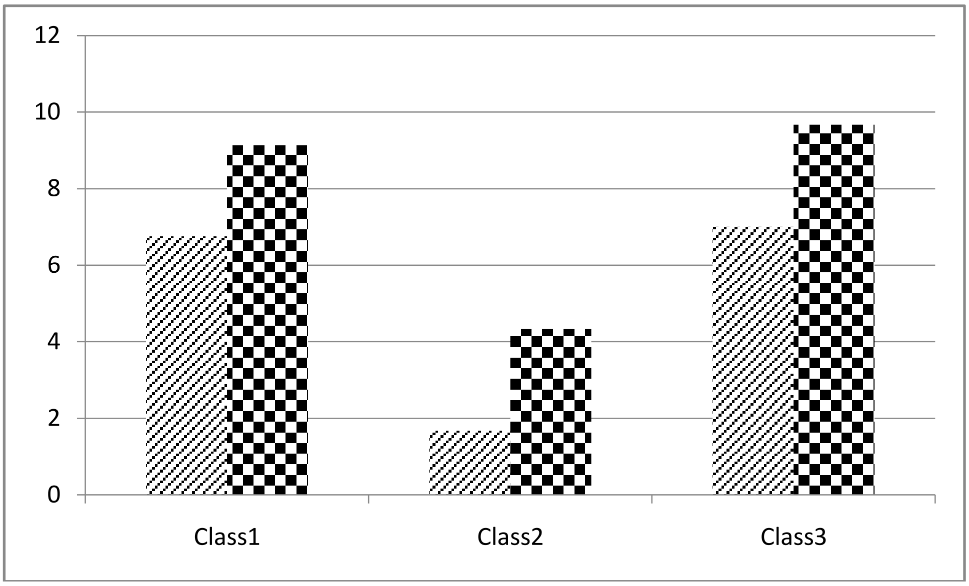

Figure 4: Pre-post multiple-choice items by class.

These findings led to the following conclusion regarding research question 3: There were significant (p < .05) differences among middle school students in three classes completing digital fabrication units in their levels of competency in content knowledge of mathematics and engineering. These differences existed at pre-test time, posttest time, and in the extent of gain. In particular, Class 2 began with scores much lower than Class 1 or Class 3 on open-ended and multiple-choice tests, and remained in that relative position at the post test time. However, while Class 2 exhibited the smallest gain among the three (ES = .54) on the open-ended questions, it exhibited the highest gain among the three (ES = 2.90) on the multiple-choice questions. This may be a reflection of the lower versus higher cognitive skills commonly assessed by multiple-choice items versus open-ended items, respectively.

Discussion

The dual methods employed for assessing content gain in this study generally reinforced each other, resulting in similar conclusions regarding the significance (p < .05) and magnitude (moderate to large effect) of the gain. Effect size indices are especially important in examining the data from this study as all pre-post measures resulted in effect size gains (Cohen's d) greater than ES > .3, the point at which gains would normally be considered educationally meaningful (Bialo & Sivin - Kachala, 1996). These findings have cross-validated the multiple choice test item portion of the study with the much more time-consuming human-rater scoring of open-ended questions, implying that future studies without extensive human-rater resources might be able to rely on well-formulated multiple choice tests alone.

Student participation in activities that promote engineering design principles while teaching science and mathematics concepts may improve both achievement as well as interest in a STEM career. The students in this study gained a significant (p < .05) amount in their content knowledge related to the waves and sound curriculum. On site observations indicated that this activity enhanced student enthusiasm for and engagement in learning. In future studies direct measurement of attitude change as well as gains in content knowledge might be warranted to address the issues regarding the lack of proficiency and interest among American students reported by PCAST (2010).

Findings from this study are consistent with previous research indicating that fabrication coupled with engineering design projects may reduce the achievement gap among students in science subjects (Cantrell et al., 2006). Fortus, Dershimer, Marx, Krajcik, and Mamlok-Naaman (2004) found significant gains in students who engaged in design-based learning in science classrooms. Similar to findings from previous research (Fortus, et al., 2004) these students constructed scientific knowledge through hands-on activities that encouraged them to problem solve and demonstrate their knowledge gains.

Although the educationally meaningful (ES > .3) content gains found in each of three classrooms provides evidence of the ability to replicate the positive impact of the *Waves and Sound* curricular unit, the possibility still remains that students without these activities might have exhibited similar gains. Replication of this study with suitable comparison group data – such as pre- and posttest data from comparable students who did not experience digital fabrication activities – is warranted.

Conclusions

K–12 engineering education may improve student learning and achievement in science and mathematics; increase awareness of engineering and the work of engineers; boost youth interest in pursuing engineering as a career; and increase the technological literacy of all students (Brophy et al., 2008). Advancement in engineering education may even be a key for a more coalesced and effective K–12 STEM education system in the United States (NRC, 2009)

Eighth grade students involved in an engineering design unit using advanced manufacturing tools were found to have measurably large content gains ($p < .01$, ES > .8) (Cohen, 1988) on multiple-choice test items and open-ended test questions featuring waves and motion, the focus of their intervention curricular unit. No significant ($p < .05$) differences were found by gender. Some differences ($p < .05$) were indicated among the three treatment classes. Additional research is needed to isolate the reasons for these differences. Replication studies are warranted to reconfirm these findings in the context of a strong comparison group.

These collective findings led to the following conclusion regarding research question 1: Middle school students completing a digital fabrication unit focused on waves and sounds do indeed gain in content knowledge of science, mathematics and engineering concepts.

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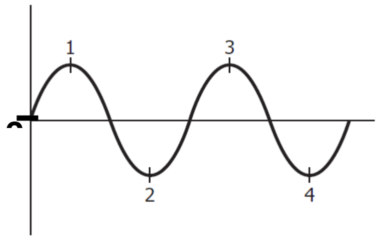
Appendix

Sound Unit Assessment. *Instructions:* The following assessment is designed to find out what you know about waves and sound. Do not worry if you do not know all of the answers. If you do not know or cannot guess, leave choices blank or write "I don't know" on the lines. Please try to choose the best answer from the choices, and write what you do know about waves and sound on the lines.

Use the diagram of the wave below to answer questions 1-3.y



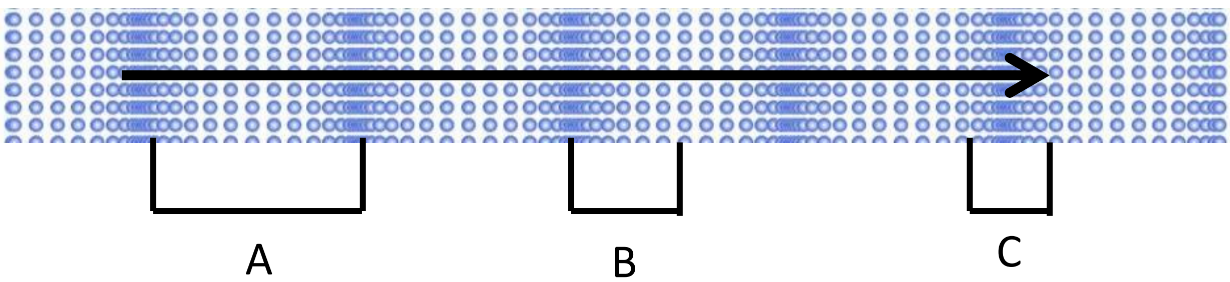
1. The wavelength is best descr between:
    a. points 1 and 2.
    b. points 1 and 4.
    c. points 2 and 3.
    d. points 2 and 4.

How confident are you in your response to question 1?
1-not confident (a guess), 2-pretty confident, 3-very confident

2. The amplitude of the wave is best described as:
    a. the vertical distance between points 0 and 1.
    b. the vertical distance between points 1 and 2.
    c. the horizontal distance between points 2 and 3.
    d. the horizontal distance between points 2 and 4.

How confident are you in your response to question 2?
1-not confident (a guess), 2-pretty confident, 3-very confident

Use the wave below to answer questions 4-6.



3. The wavelength is depicted by
    a. A
    b. B
    c. C

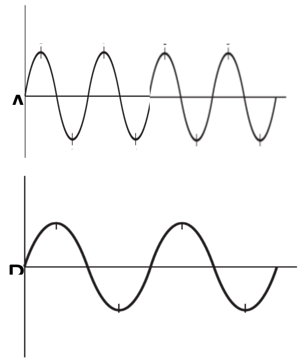
How confident are you in your response to question 3?
    1-not confident (a guess), 2-pretty confident, 3-very confident

4. Circle an area where the amplitude is highest.

How confident are you in your response to question 4?
    1-not confident (a guess), 2-pretty confident, 3-very confident

5. a. List three similarities between longitudinal (compression) waves and transverse waves.
    b. List two differences between these two types of waves.

6. Which of the waves below has the higher frequency? **Need to know what the axis and scale.**
    a. A
    b. B



Explain why you selected the

7. How are the frequency and wavelength of a wave related?
    Explain your thinking.

8. A sound that you hear is caused by an object vibrating, which then causes: **Could swap with bell jar question.**
    particles to move to your ear through material (a medium).
    b. particles to move to your ear through material (a medium) or through nothing (a vacuum, such as outer space).
    c. energy to move to your ear through material (a medium).
    d. energy to move to your ear through material (a medium) or through nothing (a vacuum, such as outer space).

How confident are you in your response to question 10?
    1-not confident (a guess), 2-pretty confident, 3-very confident

9. A sound wave is transmitted through air, glass, and water. If the vibration starting the sound wave begins at the same instant for all three materials, rank the order in which the sound would travel fastest (from 1-fastest sound to 3- slowest sound).

___ Air
___ Glass
___ Water

Explain your thinking.

10. Your science teacher challenges you to design a speaker cone that transmits sound at specific pitch (frequency).
    a. What effect, if any, will increasing the size of a speaker cone have on the sound you hear? (Consider whether the sound will be louder or softer, higher or lower pitch, etc.)
    Why do you think so?
    b. What effect, if any, will increasing the size of a speaker cone have on the wavelength of the sound produced? Why do you think so?
    c. How would you design the speaker cone? (Describe the steps you would take or the process you would use.) Why would you do it this way?
    d. How will you know if your design is successful? Explain your thinking.