Zipping to STEM: Integrating Engineering Design in Middle School Science

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This 3-year Innovative Technology Experiences for Students and Teachers (ITEST) project focused on integrating engineering design concepts and practices in the middle school physical sciences curriculum. The goal was to increase students' interest in STEM and expand their access to opportunities to experience integrated STEM activities. Our work focused on middle school students as research shows that interest in STEM decreases through middle school [1]. The planned intervention is based on existing theory and research on motivation, as well as the emerging body of literature on integrated STEM instruction. Research shows that relevance is essential to student engagement in science and mathematics [2]. Research also indicates that there is a link between students' interest and experiences in school and their future educational career choices [3,4] . Therefore, engaging students in engineering activities where they solve real world problems motivates them to learn science and mathematics, and helps them see the relevance to their everyday lives. Increasing middle school students' interest in science in particular is a strong predictor of later STEM career pursuit.

The curriculum was designed around the Soap Box Derby® Mini-Cars that includes the use of computer-aided design (CAD) software, virtual and physical wind tunnel testing, and 3D printing. Eighth-grade middle school science teachers participated in a one-week professional development workshop to learn the software and how to integrate engineering into the force and motion curriculum. They also engaged in ongoing professional development leading up to the learning unit. The students were engaged in using technology (CAD Software, virtual wind tunnel) to design and test a shell for a mini model car, while learning science concepts of forces and motion. This curriculum was aligned with the Next Generation Science Standards in terms of the focus on integrating engineering practices in the science curriculum.

A quasi-experimental pre-test post-test group comparison design was applied to assess the impact of the intervention on students' understanding of engineering design concepts (measured by an engineering concept test with 13 multiple choice items and 2 open ended design tasks), understanding of force and motion concepts (measured by a science concept test), interest in STEM (assessed by the S-STEM survey), and interest in STEM careers (also assessed by the S-STEM survey). We report key findings from the pilot year (Year 2) of this research.

Research questions

The following three research questions were addressed in this paper:

1. Did the treatment (intervention vs. comparison) have a statistically significant impact on post-test ECA M-8 scores, controlling for baseline differences on the pre-test?
2. Did the treatment (intervention vs. comparison) have a statistically significant impact on post-test AAAS forces and motion form scores, controlling for baseline differences on the pre-test?
3. Did the treatment (intervention vs. comparison) have a statistically significant impact on students' interest in STEM and STEM careers, controlling for baseline differences on the pre-test?

Participants

A total of 1520 students across 14 teachers and nine schools in a school district located in the Mid-west were invited to participate in the study. A total of five schools were assigned to the intervention group (n = 582) and five schools were assigned to the comparison group (n = 938). One school had one teacher assigned to the intervention group and one assigned to the comparison group. Eighty-nine percent of students in the school district received free/reduced lunch. A total of 24% of the students identified as African American, 21% White, and 10% Asian Pacific Islander or "other." Nearly half (45%) of the students did not report their race/ethnicity. Thirty-five of the students were girls, 35% were boys, and the remaining 30% did not report their gender.

Intervention

The curriculum was designed to engage students in solving a real-world problem through the use of additive manufacturing [5]. They were asked to optimize a prototype of a Soap Box Derby® Car (mini-car) by using computer-aided design (CAD) software, virtual and physical wind tunnel testing, and 3D printing. After learning general concepts regarding forces and motion, they investigated the factors that impact the performance of a gravity racing car in order to optimize its performance. The students also learned the basics of aerodynamics through investigating the performance of various shapes on a track and in a wind tunnel. Using this knowledge, the students were engaged in using technology (CAD Software, Virtual wind tunnel) to design and test a shell for a mini model car, while applying science concepts of forces and motion. This curriculum is aligned with the Next Generation Science Standards [6] in terms of the focus on integrating engineering practices in the science curriculum.

In addition, eighth-grade middle school science teachers participated in a one-week professional development workshop to learn the software and how to integrate engineering into the force and motion curriculum. The teachers also engaged in ongoing professional development leading up and throughout implementation of the learning unit.

Research design

A quasi-experimental pre-test post-test group comparison design was applied to test the impact of the intervention on middle school students' understanding of engineering design concepts, understanding of force and motion concepts, interest in STEM, and interest in STEM careers.

Instruments

AAAS Science Assessment. Selected items from the AAAS Science Assessment – Forces and Motion [7] was used to assess students' basic understanding of forces and motion concepts. A crosswalk was created to align the selected items to the state standards including the Next Generation Science Standards [6]. There were a total of 18 items with three response choices. Each item was worth one point to yield a possible range of 0 – 18 points earned.

Engineering Concept Assessment-M8. A modified form of the Engineering Concept

Assessment [8] was used to assess students' understanding of engineering design. This modified form, ECA-M8 [9] was aligned to the eighth-grade state standards including the Next Generation Science Standards [6]. The ECA-M8 consisted of 13 multiple-choice items assessing basic understanding of engineering design concepts and one design problem testing the ability to transfer the concepts to a new design problem not previously presented as part of the learning unit.

Two design problem scenarios were developed, one for the pre-test and one for the post-test. Students were presented with five questions related to the design problem. Specifically, students identified the constraints of the problem, explained why or why not these interact, drew two designs that might be solutions, justified the selection of one to prototype, and described how to test the prototype.

***S-STEM survey*.** The Student Attitudes Toward Science, Technology, Engineering, and Math (S-STEM) survey [10] consists of 37 items that are rated on a 5-point Likert-type scales ranging from 1 ("strongly disagree") to 5 ("strongly agree"). The items on the S-STEM are divided into four a priori defined constructs or subscales: math attitudes (8 items), science attitudes (9 items), engineering/technology attitudes (11 items) and attitudes towards 21st century skills (11 items).

Data analyses

We used hierarchical multiple linear regression analyses to evaluate the effect of the intervention on the project outcomes while controlling for background variables. Baseline focal outcome score and then group status (intervention vs. comparison) were entered into the model first, followed by gender, then race, and finally teacher experience (number of years teaching) using forward stepwise entry format.

Impact on students' understanding of engineering design and forces and motion concepts

Two multiple linear regressions were conducted to test whether the treatment (intervention group vs. comparison group) had a statistically significant impact on post-test AAAS and ECA-M8 scores, controlling for baseline differences on the pre-tests. Baseline pre-test score was entered in block 1. Treatment group (intervention or comparison) was entered in block 2. Student gender (boy, girl) was entered in block 3. Student race was entered in block 4. There were five racial categories (African American, White, Asian American, Multiracial, and Other across the 842 students who reported their gender. Three dummy variables were created as summarized in Table 1 collapsing the latter three categories into one group ("other"). Teacher experience was entered in the final block 5.

Table 1: *Dummy Coded Variables for Race (n = 842)*

Variable	Target Group (1)	Reference Group (0)
	n	*n*
African American	367	475
White	319	523
Other	156	686

The regression results for ECA-M8 post-test scores are summarized in Table 2. Variance inflation factor (VIF) values were below 2.0 and ranged from 1.00 to 1.18 across the independent variables. Group status statistically significantly predicted ECA-M8 post-test scores with those in the intervention group scoring higher on the post-test, after controlling for baseline differences on the pre-test accounting for 4.7% of the variability in ECA-M8 post-test scores, $F_{chng} = 24.84$, $R^2_{chng} = .047$, $p < .001$.

Table 2: *ANOVA Model Summary and Change Statistics for ECA-M8 Post-Test Scores*

Block	F	R^2 Change	F Change	*t*	Standardized Coefficient β
Baseline ECA pre-test scores	43.47***	.087	43.47***	4.93***	.225
Treatment group	35.29***	.047	24.84***	5.37***	.251
Student gender	25.42***	.010	5.07*	1.95^{NS}	.084
Student race	17.25***	.016	4.41*	—	—
Other	—	—	—	2.11*	.100
White				2.91**	.140
Teachers' number of years of teaching experience	14.90***	.005	2.82^{NS}	$- 1.68^{NS}$	-.078

Note. **p* < .05, ***p* < .01, ****p* < .001. ^{NS} = not significant.

Group status was the strongest predictor, β = .251, *p* < .001. Student race was also a significant predictor controlling for the other variables in the model with the "other" category scoring higher than African Americans and Whites and those reported as "White" scoring higher than other racial categories.

The students' unadjusted and adjusted mean ECA-M8 [8,9] scores on the pre-test and post-test are illustrated in Figure 1 and reported in Table 3.

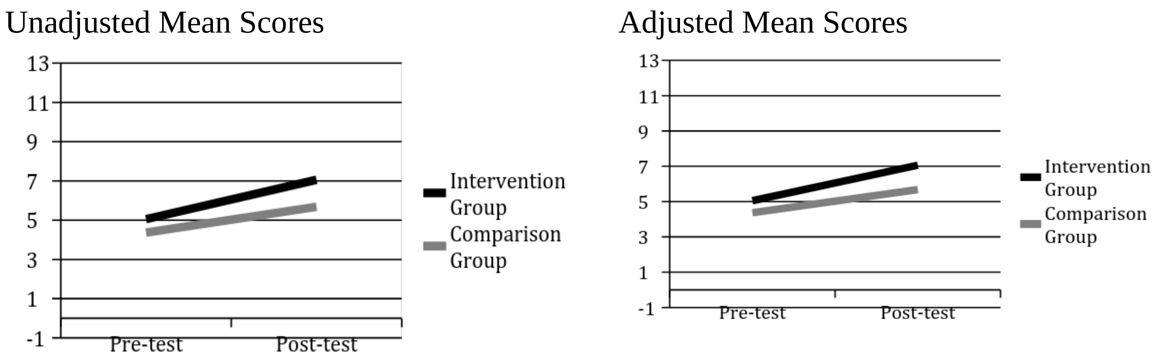

Figure 1: *Unadjusted and adjusted ECA-M8 mean score for the intervention and treatment group on the pre-test and post-test.*

The intervention group had statistically significant higher gains in their scores from pre-test to post-test than the comparison group. The intervention group increased by 2 points, on average, whereas the comparison group increased by 1 point, on average. The intervention group had a higher post-test score of 7.09 (55% correct) than the comparison group who had a post-test score of 5.62 (43% correct).

Each student's essay responses on the Engineering Concept Assessment that target application level have been rated by at least two raters and are in the process of being analyzed.

Table 3: *Descriptive Statistics for Students' Content Test Scores Adjusted for Covariates (n = 459)*

Group		Pre			Post			*Adjusted* Mean Difference
	n	*M (SD)*	*M Adj (SE)*	*CI^{95}*	*M (SD)*	*M Adj (SE)*	*CI^{95}*	
Intervention								
ECA	288	5.05 (2.26)	4.97 (.131)	4.72,5.23	7.06 (2.64)	7.09 (.149)	6.80,7.38	+ 2.12
AAAS	280	6.10 (2.35)	6.02 (.143)	5.74,6.30	8.13 (3.57)	8.15 (.207)	7.74,8.55	+ 2.13
Comparison								
ECA	171	4.37 (2.25)	4.49 (.174)	4.15,4.84	5.68 (2.28)	5.62 (.197)	5.24,6.01	+ 1.13
AAAS	90	4.96 (2.32)	5.21 (.268)	4.68,5.73	7.70 (2.56)	7.64 (.389)	6.87,8.40	+ 2.43

The regression results for AAAS post-test scores are summarized in Table 1.5. VIF values were below 2.0 and ranged from 1.00 to 1.27 across the independent variables. Group status did not statistically significantly predict AAAS post-test scores, controlling for baseline AAAS pre-test scores, $F_{chng} = .190$, $R^2_{chng} = .001$, $p > .05$.

Baseline AAAS scores were the strongest predictor of post-test AAAS scores ($\beta = .193$, $p < .001$) followed by student race ($\beta = -.142$, $p < .05$), controlling for the other covariates in the model. Those classified as "White" scored significantly lower than those classified in the "other" racial categories.

Table 4: *ANOVA Model Summary and Change Statistics for AAAS Post-Test Scores*

Block	F	R^2 Change	F Change	t	Standardized Coefficient β
Baseline AAAS pre-test scores	8.74**	.028	8.74**	3.29***	.193
Treatment group	4.45*	.001	.190^{NS}	.439^{NS}	.027
Student gender	3.03*	.001	.218 ^{NS}	-.465^{NS}	-.026
Student race	3.28**	.022	3.58 *	—	—
Other	—	—	—	.243^{NS}	.015
White	—	—	—	-2.34*	-.142
Teachers' number of years of teaching experience	2.85*	.002	.708 ^{NS}	.401^{NS}	.053

Note. *p < .05, **p < .01, ***p < .001. ^{NS} = not significant.

As illustrated in Figure 2, the students' in the comparison group had higher gains in their scores from pre-test to post-test than the intervention group. The intervention group increased by 2.13 points, on average, whereas the comparison group increased by 2.43 points, on average. The intervention group had a higher average post-test score of 8.15 (45% correct) than the comparison group who had an average post-test score of 7.64 (42% correct). However, this observed difference in AAAS post-test scores was not statistically significant. Also, although the students in both groups increased over time, their scores were below 50%, on average, at post.

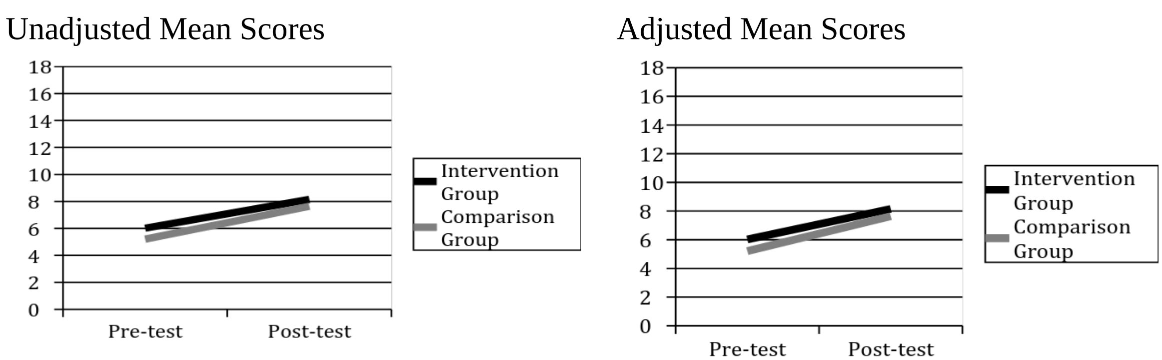

Figure 2: *Unadjusted and adjusted ECA mean score for the intervention and treatment group on the pre-test and post-test.*

Impact on students' interest in STEM and STEM careers

The third research question that our project addressed was whether the intervention improved students' attitude towards STEM, as well as their interest in STEM careers. Table 5 presents means, standard deviations, and standard errors for students' attitudes toward STEM and students' interest in STEM careers at pre-test, as well as at post-test. Inspection of the pre to post changes in the means for students' attitude toward math, science, engineering and technology in general does not appear to show any significant improvement of attitudes. Mean differences in STEM career interests did not vary by group (intervention vs. comparison).

Table 5: *Descriptive Statistics for Students' Attitudes Towards STEM and Their STEM Career Interests*

	Pre			Post			Mean Difference
	M	*SD*	*SE*	*M*	*SD*	*SE*	
Math							
Intervention	3.34	.81	.04	3.36	.82	.04	0.02
Comparison	3.40	.85	.05	3.38	.83	.05	- 0.02
Science							
Intervention	3.48	.68	.05	3.43	.73	.05	-0.06
Comparison	3.34	.69	.03	3.40	.74	.04	0.06
Engineering and Technology							
Intervention	3.48	.81	.04	3.38	.77	.04	-0.10
Comparison	3.35	.77	.03	3.30	.82	.04	-0.05
STEM Career Interest							
Intervention	2.77	.72	.04	2.78	.75	.04	0.01
Comparison	2.81	.70	.05	2.77	.75	.06	-0.04

Multiple linear regression analysis was used to test if the intervention impacted students' attitude towards STEM, as well as their STEM career interest. To this end, four multiple regression analyses (three for STEM attitude subscales and one for STEM career interest) were conducted in blocks as reported under the data analytic strategy section. As can be seen in Table 6, the regression results indicated that the intervention did not significantly predict math attitude after pre-test math attitude was taken into account ($\beta = -.037$, $p > .05$). In fact, the pre-test math attitude was the only statistically significant predictor of post-test math attitude ($\beta = .65$, $p < .001$)

Table 6: *Regression Results for Attitude Towards Math*

Block	F	R^2 Change	F Change	*t*	Standardized Coefficient β
Baseline Math attitude pretest	296.20	.414	296.20	17.07	.646
Treatment group	149.04	.002	1.52	-0.98	-.037
Student gender	99.15	.000	.03	0.06	.002
Student race	60.07	.004	1.27		
Other				1.08	.059

White				1.46	-.008
Teachers' teaching experience	49.952	.000	.04	-0.20	.044

Note. $*p < .05$, $**p < .01$, $***p < .001$. ^{NS} = not significant.

Table 7 presents regression results for science attitude. Again, the intervention was not a statistically significant predictor of science attitude after controlling for pre-test science attitude ($\beta = -.037$, $p > .05$). However, gender and race were found to be significant predictors of science attitude. More specifically, being a girl negatively predicted science attitude ($\beta = -.08$, $p < .05$) but being White ($\beta = .10$, $p < .05$). or Other ($\beta = .12$, $p > .05$) positively predicted science attitude.

Table 7: *Regression Results for Attitude Towards Science*

Block	F	R^2 Change	F Change	*t*	Standardized Coefficient β
Baseline Science attitude pretest	332.80	.454	332.80	17.83	.657
Treatment group	169.01	.004	3.31	-1.46	-.054
Student gender	114.57	.005	3.55	-2.18	-.080
Student race	72.86	.016	5.99		
Other	—			3.08	.120
White				2.53	.099
Teachers' teaching experience	61.32	.003	2.38	-1.54	-.057

Regression results for attitudes towards engineering and technology are presented in Table 8. Similar to the results reported above, the intervention did not significantly predict students' engineering and technology attitude ($\beta = .02$, $p > .05$). Similar to the gender effect reported above regarding science attitude, being a girl was a significant negative predictor of attitude towards engineering and technology ($\beta = -12$, $p < .05$). Table 12 also shows that belonging to White ($\beta = .10$, $p < .05$) and Other ($\beta = .12$, $p > .05$) racial ethnic group was a positive significant predictor of attitude towards engineering and technology.

Table 8: *Regression Results for Attitude Towards Engineering and Technology*

Block	F	R^2 Change	F Change	*t*	Standardized Coefficient β
Baseline Eng and Tech attitude pretest	321.62	.444	321.62	16.63	.626
Treatment group	160.43	.000	0.03	0.60	.022
Student gender	111.66	.011	8.29	-3.30	-.123
Student race	71.68	.018	6.83		
Other	—			3.31	.131

White				2.80	.107
Teachers' teaching experience	59.78	.001	0.64	-0.80	-.030

Note. **p* < .05, ***p* < .01, ****p* < .001. NS = not significant.

Regression results for STEM career interest are presented in Table 9. The intervention did not significantly predict students' STEM career interest after their pre-test interest was controlled. Again, gender and race/ethnicity were significant predictors of post-test STEM career interest. Being a girl was a significant negative predictor of students' STEM career interest (β = -12, $p < .05$). Membership in White (β = .20, $p < .01$) or Other (β = .12, $p < .05$) racial ethnic group was also a significant predictor of STEM career interest.

Table 9: *Regression Results for STEM Career Interest*

Block	F	R^2 Change	F Change	*t*	Standardized Coefficient β
Baseline STEM Career Interest	156.13	.328	156.13	12.02	.542
Treatment group	77.89	.000	0.09	0.53	.024
Student gender	54.01	.009	4.52	-2.65	-.120
Student race	37.99	.038	9.60		
Other	—		—	2.54	.122
White			—	4.20	.202
Teachers' teaching experience	32.32	.006	2.87	-1.69	-.076

Note. **p* < .05, ***p* < .01, ****p* < .001. NS = not significant.

Summary of the results

The findings show an increase in students' understanding of engineering concepts (increase and statistically significant difference between the comparison and intervention group on ECA). There was a statistically significant increase on forces and motion concepts as measured by the AAAS assessment, but this increase was not statistically significantly higher than the comparison group.

There was an increase in students' self-efficacy in engineering from pre to post intervention. However, the mean scores for students' attitudes towards math, science, engineering and technology did not show any significant change. Mean differences in STEM career interests did not show variation by group (intervention vs. comparison).

Acknowledgement

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