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Undergraduate Students' Materials Science and Engineering Self-Efficacy: Assessment and Implications

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Abstract

Prior work has shown that student achievement and persistence within undergraduate programs can be linked to individual beliefs. The purpose of this study was to create a materials science and engineering self-efficacy scale to predict student achievement in both materials science and engineering courses and within the programs of participating undergraduates. We performed an exploratory factor analysis to determine which items to include in the materials science and engineering self-efficacy scale and then analyzed the predictive validity of the scale for academic achievement. The materials science and engineering self-efficacy items were then embedded in a larger survey that also included demographic items. Participants whose data were used within the exploratory factor analysis (n = 97) and the predictive validity (n = 176) phases of this study were recruited from a southeastern university. Students in an introductory materials science and engineering course showed significant differences in gains in self-efficacy from the beginning to the end of the semester. Although at the beginning of the semester, male students had statistically higher item mean scores for five of the eleven survey criteria, no significant differences between the genders were observed by the end of the semester. Students who failed or withdrew had a significantly lower mean score and item mean differences than did all other students. Regression analysis, however, did not indicate that overall materials science and engineering self-efficacy was a significant predictor of the course grade. This study quantified the change in response rates between data collection via electronic surveys completed outside of the classroom and via paper surveys completed in the classroom.

Introduction

Undergraduate engineering degree programs are designed to prepare students for careers as engineering professionals who have an in-depth understanding of their own discipline and its relationship to basic science (e.g., physics and chemistry) and other engineering disciplines (e.g., mechanical, civil, electrical). Under the guidance of ABET, engineering departments have often developed undergraduate programs in which students enroll in courses both within their own department and in engineering courses external to their discipline. Not until their final two years of their college degree program do undergraduate students have a significant number of their courses taught by faculty from their degree programs.

To improve the academic achievement of students within these general engineering courses, the authors are seeking to understand student self-efficacy related to subject matter within these general engineering courses. Research on students' *self-efficacy* (SE), or the beliefs they hold in their academic capabilities (e.g., *Can I do this?*) has been commonly investigated in the mathematics and science domains of K-12 academics. Self-efficacy has also been shown to be related to the choices students make, how much effort students put forth, how well they perform, and whether they persist in the face of difficulty.[1] Although researchers have shown that undergraduate students' achievement and persistence within undergraduate programs can be linked to individual students' beliefs, less is known about how self-efficacy is related to student success (academic achievement such as grades) in large service courses at the university level.

Because most undergraduate engineering students in their first two years take a materials science and engineering (MSE) service course that centers on understanding the fundamental relationships between the structures, properties, and processing of various materials, the authors used content from this course to develop a skills-based self-efficacy measure designed to explore undergraduates' beliefs that they can perform the tasks in this specific field. The purpose of this study was to create a materials science and engineering self-efficacy scale (MSE-SE) to help predict student achievement in both MSE courses and within the broader engineering program. It is anticipated that the collected results could be used to improve student persistence and success in engineering disciplines, particularly in the first two years of engineering study before undergraduates specialize in mastering the engineering major they came to school to pursue.

Research Objectives

The objective of this study was to create a self-efficacy scale for introductory level MSE knowledge and then to investigate the psychometric properties of the scale items (mean, skewness, kurtosis, and inter-item correlation) and explore the scale's factor structure. We then attempted to determine (a) any changes in materials science and engineering self-efficacy during the semester; (b) any significant difference in the level of materials science and engineering self-efficacy by students in different demographic groups (e.g., gender and major); and (c) any associations between materials science and engineering self-efficacy and student achievement outcomes (e.g., course grade, engineering grade point average (GPA), and cumulative GPA).

Experimental Methods

Phase 1: Item Development

Twenty-two discrete items were designed to assess student self-efficacy related to the initial material science and engineering knowledge they were expected to learn over a one-semester course. The items were developed using the outcomes on instructors' syllabi and from the objectives outlined in the required course textbook, *Materials Science and Engineering: An Introduction (8th edition),* written by William D. Callister and David G. Rethwisch. This text is currently required in many engineering programs across the U.S.

Phase 2: Exploratory Factor Analysis

To establish the validity of our instrument, engineering undergraduates enrolled in a sophomore level materials course from a public, land-grant research-intensive university completed an online survey in the spring of 2013. The materials science and engineering self-efficacy items were embedded in a larger survey on student motivation, which also included demographics. For these self-efficacy items, students used a 6-point Likert-type scale (1 = *completely uncertain*; 6 = *completely certain*) to assess their own level of certainty in performing the engineering activities they learned in class. Cronbach's alpha was used to examine internal consistency of the items in the scale, and bivariate correlations were used to examine concurrent and predictive validity. IBM SPSS Statistics version 21 was used to conduct exploratory, descriptive analyses of all data, specifically to determine the item means, standard deviations, frequency distributions, outliers, skewness, and kurtosis.[2] The data were checked for univariate and multivariate outliers to ensure that the assumption of normality was met. The psychometric properties of the initial pool of items were then determined through an examination of skewness (< |3.0|) and kurtosis values (< |10.0|)[3], inter-item correlations (≥ .30), and item-scale correlations (≥ .30).[4] Items that did not meet the criteria values were removed.

Items from the MSE-SE scale were subjected to an exploratory factor analysis (EFA) using the maximum likelihood method of factor extraction to determine the factor structure.[5] Screen plots of eigenvalues associated with each factor were used to identify the number of factors to include in the factor analysis, with the position of discontinuity indicating the specific number.[6,7] Loadings in the factor structure matrix (≥ .40) were evaluated to refine the criteria generated in the factor analysis.[8] If an item was removed from the scale, all remaining items were used in a new factor analysis. After each factor analysis, the Cronbach's alpha coefficient was used to evaluate the internal consistency of the scale items.[5]

Phase 3: MSE-SE Reporting over Semester & Regression of Scale with Achievement

To determine whether students' MSE-SE significantly changed during the semester, undergraduate students enrolled in a sophomore level materials course were asked to complete two surveys–one at the beginning and one at the end of the fall 2013 semester. Electronic surveys initially sent out during Week 1 to the beginning of Week 5 were considered to be Time Point 1 (TP1). Participants were again asked to take the survey. All responses collected between Week 15 and Week 18 were considered Time Point 2 (TP2). The semester only spanned 16 weeks and after the conclusion of the class the survey was left open to increase the number of participants who wished to complete the survey but previously had no time to do so. To augment the low response rate in fall 2013, a paper copy of the survey was distributed to students at the beginning (first day of class) and end (during Week 15 of a 16-week semester) of the spring 2014 semester.

Data from the paper surveys were manually entered, anonymized, and then checked for entry errors by separate researchers. In addition, academic achievement was used to evaluate the predictive validity of the MSE self-efficacy scale. The achievement data (final course grade for the MSE sophomore level course, cumulative grade point average, and engineering-course specific grade point average) were obtained from the university's Office of Institutional Research and course instructors. The data were cleaned and descriptive statistics (e.g., means and relative frequencies) were calculated at the item and scale levels. Correlations at both the item and scale levels were then calculated. Using only the data collected during spring 2014 to understand the predictive ability of the scale, we initially calculated the mean scores of each item at both TP1 and TP2 and the mean item differences between TP1 and TP2, and the mean scale difference between TP1 and TP2. To explore mean differences in MSE self-efficacy, we then performed *t* tests by gender and by class standing (upper and lowerclassmen), and an analysis of variance (ANOVA) between majors.

Results and Discussion

Phase 1: Item Development

The initial pool of twenty-two items that were developed is listed in Table 1. These items are associated with learning objectives typically used for introductory MSE courses.

Table 1: Original items developed for potential inclusion in the MSE-SE scale.

Item Code	Original Item
MSE-1*	I can explain the difference between primary and secondary bonding in materials.
MSE-2	I can predict a material's physical and mechanical behavior based on the type of bonding present in the material.
MSE-3	I can understand the basic concepts of material qualities (e.g., hardness, ductility).
MSE-4	I can understand how material qualities (e.g., hardness, ductility) are measured for all materials.
MSE-5*	I can describe the difference in atomic/molecular structure between crystalline and non-crystalline materials.
MSE-6*	I can describe the difference between a crystal structure and a crystal system.
MSE-7	I can identify effects of structure on mechanical properties of solids.
MSE-8	I can demonstrate the effect of materials microstructure on the engineering properties of materials.
MSE-9	I can explain to others the relationships between microstructure and properties.
MSE-9b*	I can explain the relationships between a material's microstructure and properties.
MSE-10	I can identify effects of defects on mechanical properties of solids.
MSE-11*	I can explain how imperfections affect the behavior of materials.
MSE-12*	I can understand kinetic processes in materials.
MSE-13*	I can describe atomic mechanisms of diffusion.
MSE-14*	I can understand the fabrication and processing of engineering materials.
MSE-15*	I can understand the relationship between the processing of a material, its structure, its properties, and its performance in a given application.
MSE-16	I can describe how materials are processed to alter their microstructure, properties, and their applications.
MSE-17	I can interpret a phase diagram.
MSE-18	I can identify phase transformations.
MSE-19*	I can apply the lever law to predict the phases that are present and their amounts.
MSE-20	I can describe the different matrix systems (e.g., polymer, metal, ceramic).
MSE-21	I can make competent design decisions using my knowledge of materials structure and properties.
MSE-22*	I can select materials for different applications based on the constraints of the given applications.

*Item retained in final scale

Phase 2: Exploratory Factor Analysis

EFA was used to determine which items to include in the final MSE-SE scale. Not all students who completed the survey in spring 2013 at TP1 answered all of the items related to MSE-SE. For the electronic surveys, we only considered participants who answered most or all of the MSE-SE items (see Table 2 for the specific participant demographics). For participants who answered a majority of the MSE-SE items (but not all items), missing data were imputed using an average of the other MSE-SE items. After the data set was finalized, we used the Kaiser-Meyer-Olkin (KMO) measure to confirm sampling adequacy. A KMO with a value greater than 0.60 indicates that a factor analysis can be used with the current data set;[5, 9] our value of 0.90 exceeded the cutoff. We next used Bartlett's test of sphericity to discern an adequate correlation of every item used in the scale with the other scale items.[5] The results were significant ($p < .05$), indicating that factor analysis could be used because of a definite correlation of variables.[5]

Items flagged during the EFA were reviewed by all authors and the items were reduced due to unclear wording or redundancy. MSE-2 was removed because of redundancies with MSE-1 and to reduce the length of the final MSE-SE scale. MSE-3 was also removed for unclear wording (i.e., because of the initial use of the term qualities rather than properties). Because MSE-7 and MSE-8 were examining the same concepts as MSE-9, they were removed from the scale. MSE-10 was similar to MSE-11 and hence removed. MSE-16 was removed as it was similar to MSE-15. After discussion, both MSE-17 and MSE-18 were eliminated because these concepts were emphasized in general chemistry classes. MSE-20 was also taken out of the scale because some of the course instructors did not believe the reflected content that was adequately covered during the course (time constraints in certain sections of the course prevented equal coverage of this topic) by all instructors. Finally, MSE-21, which was similar to MSE-22, was removed to reduce the scale length. Table 3 shows the means, skewness, and kurtosis for the retained items in the scale, and Table 4 shows the inter-item correlation for those items. The inter-item correlations were all above .30 except for MSE-1 with MSE-19 and MSE-22. Based on observing factor loadings, the final scale of 11 items was determined to be unidimensional. After conducting the EFA, the Cronbach's alpha coefficients were computed to measure the reliability of our instrument.[4, 5] The final scale had a Cronbach's alpha of .94, which was further confirmed in later iterations of the scale (spring 2014 TP1, $\alpha = .93$ and spring 2014 TP2, $\alpha = .90$).

Table 2: Participant demographics at various time points in each semester of survey administration.

	Spring 2013		Fall 2013				Spring 2014			
	Time Point 1		Time Point 1		Time Point 2		Time Point 1		Time Point 2	
Number of Participants (n)	97		81		29		243		185	
GENDER	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Male	69	71.1	54	66.7	18	62.1	175	72.0	131	70.8
Female	28	28.9	27	33.3	11	37.9	68	28.0	54	29.2
RACE/ETHNICITY										
Caucasian White	86	88.7	69	85.2	25	86.2	200	82.3	154	83.2
Asian/Pacific Islander	4	4.1	7	8.6	3	10.3	8	3.3	6	3.2
African American/Black	2	2.1	2	2.5	0	0.0	25	10.3	16	8.6
Hispanic/Latino/Chicano	4	4.1	0	0.0	0	0.0	5	2.1	5	2.7
American Indian/Alaskan Native	0	0.0	0	0.0	0	0.0	1	0.4	1	0.5
Middle Eastern	0	0.0	3	3.7	1	3.4	0	0.0	0	0.0
Other	0	0.0	0	0.0	0	0.0	1	0.4	1	0.5
No Response/Prefer Not To Answer	1	1.0	0	0.0	0	0.0	3	1.2	2	1.1
CLASSIFICATION										
Freshman	0	0.0	5	6.2	1	3.4	45	18.5	37	20.0
Sophomore	51	52.6	66	81.5	24	82.8	174	71.6	129	69.7
Junior	40	41.2	10	12.3	4	13.8	21	8.6	17	9.2
Senior	6	6.2	0	0.0	0	0.0	3	1.2	2	1.1
MAJOR										
Bioengineering	12	12.4	33	40.7	14	48.3	31	12.8	24	13.0
Industrial	27	27.8	6	7.4	1	3.4	80	32.9	55	29.7
Materials Science	12	12.4	13	16.0	5	17.2	8	3.3	6	3.2
Mechanical	44	45.4	29	35.8	9	31.0	122	50.2	98	53.0
General	1	1.0	0	0.0	0	0.0	1	0.4	1	0.5
Other	1	1.0	0	0.0	0	0.0	1	0.4	1	0.5

Table 3: Descriptive statistics of the MSE-SE items used with spring 2013 sample (*n* = 97).

	M	*SD*	Skewness	Kurtosis
MSE-1	3.15	1.47	0.19	-0.77
MSE-5	3.23	1.45	0.01	-0.92
MSE-6	2.81	1.38	0.46	-0.36
MSE-9	2.63	1.33	0.42	-0.66
MSE-11	2.95	1.32	0.13	-0.66
MSE-12	2.98	1.27	-0.02	-0.83
MSE-13	2.54	1.27	0.47	-0.49
MSE-14	3.13	1.42	0.32	-0.68
MSE-15	3.06	1.46	0.28	-0.95
MSE-19	2.21	1.20	0.82	0.05
MSE-22	2.86	1.34	0.30	-0.65

n = 97

Table 4: Inter-item and item-scale correlations of the MSE-SE items using spring 2013 data.

	r-total	MSE-1	MSE-5	MSE-6	MSE-9	MSE-11	MSE-12	MSE-13	MSE-14	MSE-15	MSE-19
MSE-1	.59	-									
MSE-5	.73	.62 **	-								
MSE-6	.75	.48 **	.72 **	-							
MSE-9b	.83	.49 **	.65	.76 **	-						
MSE-11	.84	.56 **	.58 **	.61 **	.71 **	-					
MSE-12	.82	.51 **	.60 **	.60 **	.69 **	.78 **	-				
MSE-13	.77	.44 **	.54 **	.64 **	.72 **	.67 **	.72 **	-			
MSE-14	.84	.56 **	.61 **	.60 **	.69 **	.83 **	.79 **	.63 **	-		
MSE-15	.83	.62 **	.60 **	.57 **	.65 **	.82 **	.73 **	.65 **	.88 **	-	
MSE-19	.66	**.28** **	.45 **	.60 **	.73 **	.52 **	.56 **	.68 **	.46 **	.46 **	-
MSE-22	.64	**.23** *	.43 **	.47 **	.58 **	.59 **	.57 **	.50 **	.65 **	.58 **	.66 **

n = 97

Phase 3: MSE-SE Reporting over Semester & Regression of Scale with Achievement

Undergraduate engineering students were recruited to complete this survey at both TP1 and TP2 during the fall 2013 term. An adequate response rate was obtained at the beginning of the term with the electronic surveys (*n = 81*); however, only 29 of these students completed the survey again at TP2 (Table 5). As a result of the low response rate, the authors elected to administer the same survey questions via paper survey in students' classrooms during the spring semester of 2014. This approach yielded 247 completed surveys at the beginning of the semester (93.9% response rate). The paper survey also reduced the variability in the participants' response times and enhanced the total aggregate of responses, with 185 students completing surveys at both TP1 and TP2. For the electronic survey (spring 2013 and fall 2013), TP1 included all data collected between weeks 1 and 5 while the paper surveys contained only data collected on the first day of class. The same effect was seen during the collection of TP2, where the electronic surveys were left open from week 15 to 18 to increase participation during spring 2013 and fall 2013.

Table 5: Participant response rates for fall 2013 (electronic surveys) and spring 2014 (paper surveys).

	Spring 2013	**Fall 2013**		**Spring 2014**	
	Time Point 1	Time Point 1	Time Point 2	Time Point 1	Time Point 2
Total students enrolled in course	177	359	359	263	263
Number of Participants (*n*)	97	81	29	243	185
Response Rate (%)	54.8	22.6	8.1	92.4	70.3

After collecting data for TP1 and TP2 in both the fall 2013 (n = 29) and spring 2014 (n = 185), we considered merging the data into one large data set. The mean item values for the items at TP1 were largely different, with those collected during spring 2014 (paper surveys) being much lower than those collected in fall 2013 (electronic surveys). We hypothesize that this difference is perhaps (a) due to the survey administrator's comments to participants that the survey would cover course material that had not yet been taught (which did not occur during electronic administration); and (b) because of a longer collection period for the paper surveys.

The MSE-SE item means and standard deviations at TP1 and TP2 are shown in Table 6. Results of the paired samples t test for all items using spring 2014 data showed a significant increase in self-efficacy between TP1 and TP2. This increase was expected as the items were written to include course content and align with course objectives. Item MSE-19 had the lowest mean score for both TP1 and TP2, indicating that the participants did not feel confident in their skills related to using binary phase diagrams. In future versions of the survey, the wording of this item should be changed to, "I can apply the lever rule to predict the phases that are present and their amounts," to be technically accurate. However, the impact of this wording change should not change the participant response levels and the authors do not believe it will change the results reported in this manuscript.

Table 6: MSE-SE item means and standard deviations at TP1 and TP2 in spring 2014.

Items	Time Point 1 (n = 243)		Time Point 2 (n = 185)	
	M	*SD*	*M*	*SD*
MSE-1	2.49	1.15	4.33	1.10
MSE-5	2.88	1.29	4.68	1.01
MSE-6	2.23	1.11	4.26	1.20
MSE-7b	2.32	1.16	4.52	1.01
MSE-11	2.80	1.23	4.83	1.02
MSE-12	2.67	1.27	4.19	1.13
MSE-13	2.29	1.20	3.62	1.25
MSE-14	2.79	1.31	4.45	1.12
MSE-15	2.75	1.33	4.69	0.95
MSE-19	1.82	1.07	3.57	1.67
MSE-22	2.66	1.28	4.50	1.07

We next considered the influence of gender on engineering student self-efficacy, which has already been shown to be a factor of importance in self efficacy studies.[10, 11] Brainard and Carlin[10] attempted to identify the factors affecting the retention of women in engineering and cited that one of the most frequently perceived barrier for first-year students and sophomores is lack of self-confidence. When Brainard and Carlin probed students' confidence in math and science, they found that the cohort of students had a drop in self-confidence over their freshman year and then a growth through the completion of their senior year. We expected to observe that males had statistically higher reported self-efficacy at both TP1 and TP2. In our data (in all cases), males did have higher reported self-efficacy for each item at TP1. However, these gender differences were not always statistically significant. At TP1, when considering male versus female participants, we found a significant difference between the means of the following five items: MSE-9b, *"I can explain to others the relationships between microstructure and properties"*; MSE-11, "*I can explain how imperfections affect the behavior of materials";* MSE-14, *"I can understand the fabrication and processing of engineering materials";* MSE-15, *"I can understand the relationship between the processing of a material, its structure, its properties, and its performance in a given application"*; and MSE-22, *"I can select materials for different applications based on the constraints of the given applications."* There was also a difference in the gains made over the course of the semester. When we compared the changes between item means for TP1 and TP2, there were also significant differences in gains obtained by male and female participants for items MSE-11, MSE-14, MSE-15, and MSE-22. However, there were no significant differences between males and females at the item or scale levels at TP2 (the end of the semester).

We next looked at mean differences as a function of class standing and major. When considering the influence of class standing, we observed a difference between lowerclassmen (freshman and sophomore level students) and upperclassmen (junior and senior level students). Specifically, at TP2, upperclassmen reported significantly higher self-efficacy for MSE-1, "*I can* *explain the difference between primary and secondary bonding in materials;"* and MSE-15, "*I can understand the relationship between the processing of a material, its structure, its properties, and its performance in a given application."* The reasons for this difference maybe that the upperclassmen were taking courses that provided mastery experiences aligned with materials science (such as a course on biomaterials). Another factor may have been increased awareness by the upperclassmen of how the material was needed to complete the fundamentals of engineering exam. When considering the differences between majors, we found significant mean differences for items at either TP1 or TP2. Specifically, bioengineering students had a significantly higher mean score than mechanical or industrial engineering students at TP1 for MSE-5, "*I can describe the difference in atomic/molecular structure between crystalline and non-crystalline materials."* However, at TP2 there was no longer a significant difference between the mean values for MSE-5 for different majors, indicating that over the duration of the course initial differences by major in self-efficacy are no longer significant. At TP2, there was a significant difference between mechanical and industrial engineering student mean responses for item MSE-12, *"I can understand kinetic processes in materials."* More study is needed to understand these differences.

We initially expected that self-efficacy would predict achievement. Our results did not validate this expectation with the end-of-the-semester course grade nor cumulative GPA. Regression analyses were run with the achievement variables (course grade, cumulative GPA, engineering GPA) as the dependent variables and the MSE-SE scale mean score at TP2 and mean difference as the independent variables. In all cases, the R squared values were very small (< 0.1 in all cases) and therefore the model does little to explain the variation in achievement. Because the cumulative grade GPA of participants in this study was a weighted average of all their completed courses (most of which were unrelated to the materials science and engineering self-efficacy items in our survey), it was not surprising that this achievement measure did not correlate with the final MSE self-efficacy scale. We would now anticipate the cumulative GPA should align better with general academic self-efficacy rather than a specific scale like the MSE-SE scale. The MSE-SE scale also did not predict the participants' final grades within a foundational course focused on MSE knowledge. One reason might be that the course grades were progressively assigned. The syllabi of each course instructor showed that grades were calculated from a weighted average of midterm exams, homework, final exam, quizzes, and other course requirements at many time points between the start and end of the semester. Regressions showed that our measurement of MSE-SE at TP2 was not predictive of the course grade. Future work should include an analysis of comprehensive final exam grades with the MSE-SE means at TP2.

In addition to being interested in predicting achievement, we also explored whether the MSE-SE scale could be used to predict retention. We ran an ANOVA using course grade as the grouping variable. In this test, we combined all students who either withdrew from the course or received an 'F' as a final course grade ($n = 17$ at TP1 and $n = 3$ at TP2). At TP1, there were no significant differences between any item means for students achieving a specific course grade. However, at TP2, students who failed or withdrew had significantly lower mean scale score and mean difference than all other students. The number of respondents in this category at TP2 is a limitation and reflects the difficulty of recruiting students who withdraw for a survey.

Ideally, self-efficacy scales could be used to help faculty assess course and program effectiveness in addition to tracking student achievement. Though the gains made by students who participated within the materials science course were significant between TP1 and TP2, it was not possible to predict whether the gains in materials self-efficacy would have effects beyond the MSE course. It would be beneficial for faculty to be able to understand how the self-efficacy gains made by students in individual courses longitudinally fluctuate after the course. We were unable to identify longitudinal studies for self-efficacy surveys that examined how mastery experiences were related to changes in self-efficacy over time. This should be undertaken as future work.

Conclusions

We developed a scale to measure the self-efficacy of students in an introductory MSE course. After examining psychometric properties, we determined that 11 items out of the initial 22-item scale were appropriate to include in the final scale. There was no strong correlation between the mean scale score and the mean difference with academic achievement outcomes (course grade, cumulative GPA, engineering GPA). Although survey data from the beginning and the end of the semester indicated a significant difference between mean item scores for all participants, male students had statistically higher mean values for five of the eleven items on the survey at the start of the semester. By the end of the semester, however, the female students appeared to have closed the gap, as there were no significant differences between genders at this time point. Students who either failed or withdrew were found to have significantly lower mean scores and mean item differences than all other students. Regression analyses failed to validate overall MSE self-efficacy (mean score) as a significant predictor of course grades. We also recommend the administration of surveys via paper format to increase student response rates.

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