AC 2009-1458: A STUDY OF THE IMPACT OF VISUOSPATIAL ABILITY, CONCEPTUAL UNDERSTANDING, AND PRIOR KNOWLEDGE UPON STUDENT PERFORMANCE IN ENGINEERING STATICS COURSES

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A Study of the Impact of Visuospatial Ability, Conceptual Understanding, and Prior Knowledge upon Student Performance in Engineering Statics Courses

Introduction:

Many factors influence the performance of students in their typical first exposure to engineering cirricula, Engineering Statics. An in-depth understanding of these factors is tantamount to successful pedagogue and curriculum design to meet the goals of the engineer of 2020. This study examines the correlation between four factors, visuospatial ability, conceptual understanding, prior knowledge, and student course performance as measured by prerequisite course grades, course grade, and conceptual knowledge gain. Statistical correlation and hierarchical analysis were applied to the results of the Paper Folding Test (PFT), Card Rotations Test (CRT), pre- and post-Statics Concept Inventory (SCI) tests, admission test scores, and prerequisite course grades to examine these relationships.
Although many factors influence student success in an Introduction to Engineering Statics course, their understanding of underlying concepts, knowledge from previous courses, and ability to visualize forces and bodies are certainly significant for success. Conceptual understanding is strongly related to the transfer of knowledge (National Research Council[1]). Stief and Hansen[2] measured a strong correlation between SCI scores and performance on course examinations as well as course grades. They also found that the more abstract concepts of Free-Body Diagrams, Equilibrium, and Static Equivalence discriminated high-performance students from low-performance students.

In addition to knowledge gained in a statics course, transfer of knowledge from other domains such as mathematics and physics would appear to be important to the success of a student in view of the prerequisites for entry into a typical Engineering Statics course. On the other hand, little sophisticated knowledge, other than trigonometry and algebra, is required if the course does not incorporate first and second moments of mass, areas, volumes, etc., thus it is not clear at the present time how important success in prerequisite courses is for success in statics.

Sorby[3] and others have found that 3-D spatial skills are critical to success in engineering. Specifically, visuospatial ability would appear to be an important component for statics performance given that people are required to visualize forces and movements from stationary figures. Prior researchers using standardized tests of spatial ability found that visuospatial ability and conceptual knowledge, among other variables, predicted performance on statics problems (Higley, Litzinger, Van Meter, Masters, & Kulikowich[4]).

Description of Statics Concepts Inventory Instrument:

As described by Stief and Dantzler[5], The SCI test consists of 27 questions that cover the basic concepts of an introductory Statics course. These concepts (and number of questions) are: free-body diagrams (5), static equivalence (3), forces at connections (12), friction limit (3), and equilibrium (4). Free-body diagram questions focus upon representing parts of a system without the complications of force directions or equilibrium considerations. Static equivalence questions probe a student's understanding of equivalent force and moment systems. Forces at connection questions address a student's ability to correctly represent the forces acting at roller and slot connections in the absence of friction. Friction limit questions examine a student's understanding that friction forces as given by Coulomb's friction law are not the actual friction force, but rather the limiting friction force opposing motion. Finally, equilibrium questions deal with force and moment systems that are in equilibrium.

These 27 questions were further divided into nine categories of three questions each by Stief and Hansen[2]. These categories are: free-body diagrams (FBD), action-reaction third law (3LW), static equivalence (SEQ), roller representation (ROL), slot representation (SLT), negligible friction (NFR), problem representation (RPR), friction (FRI), and equilibrium (EQL). SCI data were classified by these nine categories for the purposes of this study.

PFT and CRT descriptions:

The PFT was used to quantify spatial visualization. Each problem in the PFT had 2-D figures depicting a square piece of paper being folded and the last had two small circles drawn on it to show where the paper had been punched through all the thickness at that point. The subject was to pick one of five figures that showed the positions of the holes when the paper was completely unfolded. The subject was given six minutes to complete 20 problems. The total PFT score was adjusted to correct for guessing.

The CRT was used to quantify spatial relations. Each CRT problem set required the subject to view a comparison card, a shape rotated on the vertical axis, and compare it to each of the eight test cards. The subjects were to judge whether each of the eight test cards were the same as (planar rotation) or different from (planar rotation and mirror image) as the comparison card. There were 20 problem sets in total, with a total possible score of 160. The total CRT score was adjusted to correct for guessing.

Experimental Procedure:

Seventy-six students in three sections taught by two different instructors of a Texas Tech University Statics course were recruited to take a standard SCI test administered by Stief[2], and the Paper Folding Task (PFT) and Card Rotation Task (CRT) from Educational Testing Services (ETS) as described by Ekstrom, French, and Harman[6]. Subjects were offered extra course credit if they completed all four tests. The subjects took a pre-SCI test during the first ten days of the course and a post-SCI test during the last week of this course. The same test was used for the pre- and post- examinations. The PFT and CRT tests were administered at the same time as the post-SCI test. Seventy-six students completed both the pre- and post-SCI tests. Several other subjects completed either the pre- or post-tests, but not both. These students either dropped the course during the semester or did not participate in both tests. These data were excluded for the purposes of this study. The tests were administered in a computer laboratory. The PFT and CRT tests were paper and pencil timed tests and the SCI tests were computer administrated with no time constraints. The majority of the subjects completed the SCI test within 30 minutes.

Data Collected and Preparation:

Data collected for each student subject were: course grade, end-of-semester GPA, the difference between the post- and pre-SCI test total scores, the difference between the post- and pre-SCI individual category scores, SAT scores, end of semester credit hours completed, and their letter grades in the prerequisite Mathematics and Physics courses. The data sets were complete for all the subjects except the Mathematics and Physics course grades. Several subjects were transfer students and their Mathematics and Physics course grades were not available.

The grades earned by the subjects in this Statics course were normalized across the three sections to adjust for slight variances in individual instructor grading procedures. The difference between each subject's post- and pre-SCI test scores (i.e., SCI gain) was calculated on a percentage basis for the total test score and each of the nine SCI test categories. The total SCI gain was analyzed for outliers and normalcy. A plot of the data cumulative proportions against that of a normal distribution indicated that the total SCI gain was normally distributed. A scatter plot of this data revealed no outliers.

Data Analysis:

The average grade earned in this course by the 76 participants was 78.7% with a standard deviation of 14.9%. Their average GPA was 3.98 with a standard deviation of 0.63.

The first two columns of Table 1 present the mean scores and standard deviations for students' course grades and overall GPA as well as the SCI post-test scores and gain scores. Gain is defined here as (post-test number correct – pre-test number correct) / number of possible correct answers. For example, if a student got 12 correct on the post-test and 8 correct on the pre-test out of the 27 possible points (i.e., 27 points were possible for the entire test, and 3 points were possible for each of the 9 categories), the percent gain would be 4/27 or 14.8%.

	Mean	Std. Dev.	Mean (Post-Test Score)	Std. Dev (Post-Test Score)
SCI Gain (TOT)	12.1%	15.2%	34.1%	15.3%
Free-Body Diagram Gain (FBD)	-0.5%	29.1%	13.2%	23.1%
Third Law Gain (3LW)	4.4%	35.5%	23.5%	31.0%
Static Equivalence Gain (SEQ)	0.5%	29.1%	19.6%	23.9%
Roller Representation Gain (ROL)	22.5%	40.5%	56.4%	40.4%
Slot Representation Gain (SLT)	17.6%	41.3%	52.0%	35.7%
Negligible Friction Gain (NFR)	14.7%	29.6%	22.5%	24.1%
Problem Representation Gain (RPR)	30.9%	38.8%	54.9%	34.0%
Friction Gain (FRI)	5.4%	32.9%	29.9%	26.5%
Equilibrium Gain (EQL)	13.7%	35.1%	34.8%	29.0%

Table 1. SCI Gain and Post-Test Descriptive Statistics

The last two columns of Table 1 present the mean post-test score and the standard deviations. Inspection of the post-test statistics for the entire SCI test (TOT) indicates that the average score on the post-test was 34.1%. Stief and Hansen[2] reported total SCI post-test scores from 1331 student subjects in 10 different classes at several universities as averaging between 43.0% and 76.0% with standard deviations in the range of 15.2% to 19.0%. The student subjects of this study had lower mean total post-test scores with significantly more variance. Stief and Hansen[2] also reported the Hake[7] normalized total SCI gain score for 6 of the 10 participating classes in their study. These ranged from 0.24 to 0.61. Calculation of Hake's normalized gain score from the data of Table 1 yields a normalized gain of 31.7% which is in the medium-gain classification of Hake. This score is consistent with 5 of the 6 normalized scores reported by Stief and Hansen and is approximately in the middle of their five classes. Although these participants scored lower than those of Stief and Hansen on the post-test, their gain was consistent with the Stief and Hansen participants. Thus, gain appears to be independent of the state of concept knowledge at the time of the post-test.

Inspection of the mean scores of the 9 categories indicates that these students did best at representing forces at various connections and poorest at properly accounting for friction, force-moment equilibrium, and equivalent force/moment systems. Hence, these students did best at understanding concrete things like forces acting at a roller in a slot and poorest at more abstract concepts such as coefficients of friction only represent the relationship between normal and in-direction-of-motion forces at the static/dynamic friction limit. They are still struggling with the concepts of forces and moments and how forces and moments are interrelated.

Comparison of the mean gain score of the 9 categories reveals that students also demonstrated the greatest gain at representing forces at various connections. They also scored the lowest gain in the same categories in which their category mean score was the lowest. In addition, they demonstrated low gain scores in simple free-body concepts and action/reaction forces at body connections. Mean scores in these two categories were in the middle of all the category mean scores. This suggests that students entered this course with a reasonable understanding of simple free-bodies and third law concepts from previous courses like introductory physics. Thus, they were able to score well and did not increase their understanding of these concepts to any great degree.

	GPA	GRD	TOT
GPA	1.000	0.496**	0.290*
GRD		1.0	0.390**
TOT			1.0

Table 2. Pearson's-R Correlation Coefficients for Total SCI Gain, ** - 1% confidence, * -5% confidence

Correlations were performed for the various student performance scores and total SCI gain scores. These are detailed in Table 2. Note that those which have been marked with asterisks are statistically significant. Inspection of Table 2, row 1 reveals that GPA is more strongly correlated with course grade than the total SCI gain over the semester. This is not unexpected since GPA is a weighted average over many courses. Row 2 of Table 2 indicates that course grade is strongly correlated with SCI gain. This is consistent with the findings of Stief and Hansen[2] who found a strong correlation between SCI scores and individual examination scores.

	EQL	ROL	NFR	3LW	SLT	FBD	SEQ	FRI	RPR
GRD	0.326**	0.236*	0.227	0.219	0.197	0.117	0.086	0.082	0.025
TOT	0.427**	0.579**	0.503**	0.425**	0.506**	0.279*	0.216	0.420**	0.459**
EQL	1.0	0.154	-0.024	-0.054	0.176	0.094	-0.028	0.073	0.212
ROL		1.0	0.238*	0.022	0.383	0.130	0.007	0.089	0.085
NFR			1.0	0.403**	0.063	0.034	0.042	0.104	0.188
3LW				1.0	0.059	0.157	0.132	0.141	-0.028
SLT					1.0	0.054	0.026	0.011	-0.010
FBD						1.0	-0.357**	0.036	0.026
SEQ							1.0	0.027	0.078
FRI								1.0	0.184
RPR									1.0

Table 3. Pearson's-R Correlation Coefficients for Category SCI Gain, ** - 1% confidence, * -5% confidence

Correlations between course grade, SCI gain, and the gain of the individual topics contained in the SCI examination are presented in Table 3. These have been arranged in descending (i.e., to the right) correlation between course final score and SCI gain score. There is clearly a strong correlation between SCI gain in overall understanding of statics concepts and the course grade as shown in row 1 of Table 2. This is certainly consistent with expectations. The correlation between gain in equilibrium concepts and course grade is strong (see row 1 of Table 3) and not surprising since the majority of the course is dedicated to force/moment equilibrium analysis. The reasonable correlation between the rollers category gain score and final course grade is most likely due to the strong student performance in this category (see Table 1). Total SCI gain is correlated with practically all the categories as would be expected (see row 2 of Table 3). Correlations between the individual SCI topics (i.e., rows 3-10 of Table 3) do not indicate any particular relationships between the topics.

A linear regression was conducted for the course grade as the dependent variable and the various category gain scores as independent variables to gain insight into the sensitivity of course grades to improved understanding of the various category concepts. The results of this regression are presented in Equation 1. According to this regression,

$$GRD = 0.321*EQL + 0.157*NFR + 0.134*3LW + 0.114*ROL + 0.103*SEQ + 0.080*FBD + 0.071*SLT + \text{lesser terms} \quad (1)$$

where the R^2 is 0.221. This regression equation demonstrates that course grades are most sensitive to gains in understanding force/moment equilibrium and forces acting at connections and body interfaces.

Tables 4 – 6 present the results of correlations between student performance scores, SCI gain scores, and grades in Math 1 – Differential Calculus, Math 2 – Integral Calculus, and Physics 1 –

Mechanics. These are arranged in three different tables because Math 1, Math 2, and Physics 1 grades were not available for all the students,

	GPA	GRD	TOT	MATH 1
GPA	1.00	0.484*	0.099	0.515**
GRD		1.00	0.253	0.298
TOT			1.00	0.195
MATH 1				1.00

Table 4. Pearson's-R Correlation Coefficients for Math 1, ** - 1% confidence, * -5% confidence, n = 43

	GPA	GRD	TOT	MATH 2
GPA	1.00	0.484**	0.306*	0.553**
GRD		1.00	0.386**	0.597**
TOT			1.00	0.326*
MATH 2				1.00

Table 5. Pearson's-R Correlation Coefficients for Math 2, ** - 1% confidence, * -5% confidence, n = 51

	GPA	GRD	TOT	PHYS 1
GPA	1.00	0.483**	0.189	0.592**
GRD		1.00	0.297*	0.418**
TOT			1.00	0.358**
PHYSICS 1				1.00

Table 6. Pearson's-R Correlation Coefficients for Physics 1, ** - 1% confidence, * -5% confidence, n = 53

The strongest correlation occurs between the Statics, Math 2, and Physics 1 course grades. Math 1 does not have a statistically significant correlation with either the Statics course grade or SCI gain. The correlation between Statics and Math 2 grades is somewhat surprising because no integral calculus is used early in this course nor is any included in the SCI. Although it is not clear why this occurs, it is suspected that it has to do with student maturity (Math 2 is a third of fourth semester course) and not actual course content knowledge. Rather, the Statics course depends upon trigonometry and simultaneous solution of one or more algebraic equations. Integration of trigonometry functions is part of the Math 2 course, but this not the manner in which trigonometry functions are used in a statics course.

Most of the questions asked by students while taking a statics course are concerned with visualizing the various angles and triangle sides rather than the mathematics of triangles and angles. These are more of a spatial visualization issue than statics conceptual issue. On the other hand, Physics 1 devotes considerable instruction to visualizing forces and moments acting on bodies to build a conceptual model of the problem. Hence, Physics 1 should correlate strongly with statics concepts and Statics course grades. Similar trends are seen in the correlations between SCI gain scores and course grades.

	Mean	SD
Credit Hours	85.32	23.65
SAT Total	1104.70	159.95
PFT	13.48	4.01
CRT	113.82	29.52

Table 7. Credit Hours Completed, SAT Total, PFT and CRT Descriptive Statistics.

Table 7 displays the descriptive information for credit hours completed, SAT total scores, PFT and CRT. These variables were used as predictors in a hierarchical regression described below.

	PFT	CRT	TOT
PFT	1.00	.574**	.409**
CRT		1.00	.284*
TOT			1.00

Table 8. Person's-R Correlation Coefficients for Visuospatial Ability and SCI Posttest Total Scores, ** $p < .001$, * $p = .007$, $n = 74$.

Correlations were performed for the visuospatial measures and the SCI posttest total score. Table 8 shows the correlation coefficients. The SCI posttest total score was correlated with both the PFT and CRT.

A hierarchical regression was performed to assess the amount of influence each level of the predictor variables would have on GRD. Each level would show or produce the unique variance that is accounted for by the predictors in that level after other variables have been accounted for. Level one consisted of completed credit hours to date, SCI pretest total score, and the SAT composite score. The second level of analysis included the PFT and the CRT. The final level included the TOT (net gain). Therefore, the amount of GRD variance explained by credit hours to date, SCI pretest total score, and SAT composite scores was first assessed. Then the additional amount of GRD variance explained by PFT and CRT scores above and beyond credit hours, pretest total and SAT composite was examined. Finally, after accounting for the prior five predictor variables, TOT was assessed in level three. If PFT or CRT are involved in TOT or if they all share some of the same mechanisms, as suggested by the correlations between the three variables, the hierarchical regression would account for that in level two and the unique, additional GRD variance explained by TOT could be assessed in level three. None of the level one or two predictor variables were able to explain a significant proportion of GRD variance. However, the SCI posttest, entered as level three, was able to predict a significant additional proportion of the course grade variance. The results are provided in Table 9.

	B	$SE\ B$	β
Level 1			
SCI Pretest Total	29.939	21.674	.219
SAT	0.013	0.011	.206
Credit Hours Completed	-0.043	0.089	-.076
Level 2			
PFT	0.374	0.605	.139
CRT	0.022	0.080	.054
Level 3			
TOT	38.498	11.162	.563*

Table 9. Hierarchical Regression for Course Grade, * $p < .001$, $n = 56$.

As predicted, the SCI pretest, SAT total score, and credit hours completed did not account for a significant amount of course performance variance. In addition, course grades were not sensitive to PFT or CRT. This finding was surprising given that TOT was a significant predictor of course performance variance and that PFT and CRT are correlated with TOT.

Conclusions:

The subjects of this study demonstrated the largest gain in conceptual knowledge as shown by the change in their SCI scores in representing forces acting on bodies at connections and other points. They demonstrated the smallest conceptual knowledge gain in more abstract concepts such as force/moment system equivalence, free-body diagrams, and action/reaction concepts. Their overall gain was about 34%, with significant variance. Hence, there was a large difference between the best and poorest subject's change in their knowledge of the concepts of statics.

Correlation and linear regression analysis of the subject's course grade and overall SCI gain indicate a very strong connection between content mastery and conceptual knowledge gain, in general. The force/moment equilibrium and force representation at roller connection correlations with course grade were found to be statistically significant. Linear regression analysis demonstrated that the greatest incremental gain in course performance as measured by the course grade is most sensitive to incremental gains in force/moment equilibrium concept knowledge. The data indicate that course grades are two or more times more sensitive to force/moment equilibrium than to the other factors measured by the SCI. Thus, the most quickly responding improvements in course grades are produced by improving student conceptual knowledge of force/moment equilibrium.

SCI total gain correlations with grades in prerequisite courses were statistically significant for the integral calculus and the physics course that covers mechanics. The correlation with the physics course that introduces students to mechanics is to be expected. But, the correlation with integral calculus was unexpected because very little of the content in this mathematics course is used in the early portions of a statics course. Integral calculus is preceded by several other mathematics courses. Thus, this correlation probably has more to do with their mathematical sophistication and general maturity than the actual content of a specific course like Math 2.

Heirarchical regression analyses indicated that only TOT accounted for a significant amount of variance in course grades. PFT and CRT did not account for a significant amount of variance in course grades. This was surprising given that TOT was highly correlated to both PFT and CRT, and that clusters based on TOT, PFT, CRT, and other variables were able to predict scores on statics problems for Higley et al.[4].

There are several explanations for the non significant findings with visuospatial ability and course performance. It is possible that visuospatial ability only predicts performance on the more difficult problems, as found by Hegarty and Kozhevnikov[8] with mechanical animations. Hegarty and Hozhevnikov also found that low visuospatial ability participants could be separated into two different groups based on their ability to use diagrams to ease load (i.e., over taxing the system). Finally, it is also possible that visuospatial skills are only important for students new to the program, either through low ability students self selecting out of the program as suggested by Sorby[3] or by developing their skills throughout the program.

The authors have repeated this experiment with an additional set of participants since this paper was submitted. The data from this second experiment is currently being integrated with this data for further analysis. Course instructors are now reviewing these findings and developing pedagogies that promote the learning of concepts as well as problem solving.

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