AC 2011-701: COMPARISON OF MECHANICAL APTITUDE, PRIOR EXPERIENCES, AND ENGINEERING ATTITUDE FOR MALE AND FEMALE MECHANICAL ENGINEERING STUDENTS

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Comparison of Mechanical Aptitude, Prior Experiences, and Engineering Attitude for Male and Female Mechanical Engineering Students

Abstract

We investigated ways to measure mechanical aptitude, including: a paper and pencil mechanical aptitude test (MAT), rating of expertise based observation of students doing hands- on tasks, and performance on physics computer games. Male students scored higher then female students on the MAT and physics games at statistically significant levels. Students also completed prior experience and engineering attitude questionnaires. We examined correlations between prior experiences and MAT performance and found activities such as operating machinery, repairing equipment, and using tools to correlate most highly. The prior experience results showed that male students spent many more hours engaging in the activities with the strongest correlations to MAT performance. The attitude survey included questions relating to confidence and enjoyment of figuring out how things work and troubleshooting. Based on the results, the male students had more confidence and enjoyment than female students at statistically significant levels.

Introduction

The representation of women in engineering is quite low relative to other previously male-dominated professions such as law and medicine. Thus, women are a large untapped resource for future engineers. Despite efforts to expose more middle and high school girls to mechanical engineering, the number of women mechanical engineering graduates has been persistently low; in 2009 women received just 11.4% of mechanical engineering degrees in the United States.[1] Viewing the skilled trades as cousins of the engineering professions may help to explain the low numbers of women in mechanical engineering. The percentages of women[2] auto mechanics (1.6%), carpenters (1.5%), and machinists (6.9%) are so low that most of us have never met a woman in one of these professions. One approach to attracting more women may be to market mechanical engineering as being much different than a skilled trade. However, if some of those trade skills are valuable in engineering work, alternative approaches for marketing and educating may be needed.

Feisel and Rosa describe the tension between the practical and theoretical aspects of engineering education.[3] While the emphasis in the early part of the 20th century was on the practical, it shifted to the theoretical in mid-century[4] with the belief that scientifically-trained engineers would create more revolutionary products. With the increased usage of computational tools in engineering, the definition of practical skills has broadened beyond "hands-on" skills. The pendulum has more recently shifted back to the practical with increasing emphasis on project-based learning.[5] The practical-theoretical dimension of engineering education is, by no means, the only one—it doesn't adequately capture curricular elements addressing communication skills and teamwork, for example. Nevertheless, the balance (and integration) of the practical and theoretical remains central to engineering education.[6] Even as engineering work becomes increasingly sophisticated, practical ability and intuition about physical phenomenon remain important. In fact, the NAE identifies "practical ingenuity" as a necessary attribute of the Engineer of 2020.[7]

In addition to grade point average, employers pay attention to practical experience. In surveys of industry representatives, academics, and students, Nguyen found "engineering practice" knowledge and skills (which include "hands-on skills") to be highly valued by industry.[8] As Feisel and Rosa[3] put it: "Engineering is a practical discipline. It is a hands-on profession where doing is the key."

Based on surveys of 406 graduates (who graduated between 1976 and 1985) in mechanical and electrical engineering from two southern California universities, McIlwee and Robinson conclude that mechanical know-how is more important to success on the job than to success in college (where math skills are especially important).[9] "Whether or not they actually build prototypes or tinker with equipment on the job, they need to be able to present themselves as someone who is capable of doing so" (p. 180). They further identify a "tinkering deficit" that puts women at a disadvantage in the workplace.

Spatial visualization and mechanical reasoning are unusual in that there is a measurable gender difference in these skills. Hyde reviewed 46 meta-analyses of gender difference in advancing a gender similarities hypothesis.[10] While most (78%) analyses show differences that are small or close to zero, the differences in mechanical reasoning score and mental rotation score were considered large (with standardized mean differences between males and females of 0.76 and 0.73, respectively).

Research has shown that spatial visualization depends on prior experience and can be taught. Deno investigated the connections between previous experiences and spatial visualization ability.[11] Sorby developed a course and textbook to provide students additional practice in spatial visualization before they took their first engineering graphics course.[12] The course measurably improved spatial visualization skills and grades in subsequent graphics courses. The course also had a positive effect on retention, particularly for female students. Likewise we believe that mechanical reasoning depends on prior experience and can be taught.

Our work has investigated the relationships between mechanical aptitude, prior experiences, and attitudes towards engineering. This paper describes the gender differences we have found in these three areas. The results have implications for the development of curricula that will attract higher numbers of women to mechanical engineering study and ensure their success.

Mechanical Aptitude Measures

Mechanical aptitude was measured in three different ways: paper and pencil mechanical aptitude test (MAT), observations of students doing hands-on tasks, and performance on physics computer games.

The MAT was adapted from a mechanical aptitude practice test that serves as preparation for civil service, military and trade exams.[13] It has questions about gears, pipes, linkages, and other mechanisms.

For the hands-on test, we devised both "easy" and "hard" tasks. The "hard" task involved the measurement of pressure on a pipe rig used in a fluids lab course, and the "easy" task involved the centering of a cylindrical part on a roundness tester. Students were videotaped while doing the tasks, and two raters coded each video. The rates assigned an expertise rating on a scale of 1-4 using the definitions shown in Table 1. To initiate the test, a lab assistant gave the student documentation that stated the task goal and basic instructions to complete the task. Typically, the lab assistant would only become involved if the student asked a question. However, if the student detoured significantly from the lab procedures, the lab assistant intervened. The students were not given any preparation before they arrived. At the start of the task the only information given to the student outside the documentation was location of equipment and safety precautions. Students were randomly selected for hard or easy task.

Table 1: Scoring rubric for assigning an expertise rating

Expertise Score	Definition
4	Primarily self-sufficient, demonstrated high levels of understanding, no major mistakes, one or two seeking questions, and completed the task below average time
3	Relatively self-sufficient, demonstrated understanding of the task, few mistakes, and few seeking questions
2	Slightly self-sufficient, demonstrated some understanding of the task, asked multiple seeking questions
1	Not self-sufficient, did not demonstrate understanding of the task, asked seeking questions frequently

Three physics computer games were tested:

- Bridge Builder
  http://www.learn4good.com/games/simulation/build_bridge_across_canyon2.htm
- Fantastic Contraption
  http://www.freewebarcade.com/game/fantastic-contraption/
- Ball in Cup
  http://www.freewebarcade.com/game/dynamic-systems/

The Bridge Builder activity requires the player to build a bridge to span various canyons cost effectively. Once built, the player can test the structure. The goal of the Fantastic Contraption activity is to build a device that moves an object to a designated location. The player is given various building materials and obstacles. Finally, the Ball in Cup activity requires the player to place various ramps, bolts, crates, and sprints to direct a ball into a cup. All three games had multiple levels with increasing difficulty. To score performance on the game, the number of completed levels after eight minutes was recorded.

Students from a required sophomore course were recruited to participate in the study. Students from five semesters have taken the MAT. Students in the fall 2009 semester completed hands-on tests. Students in the spring 2010 semester completed the physics games. Table 2 outlines the students who have participated.

Table 2: Sample size for each mechanical aptitude measure

Semester	MAT	Hands-On Test	Bridge Builder	Fantastic Contraption	Ball in Cup
Spring 2010	147		36	92	137
Fall 2009	41	30			
Spring 2009	33				
Fall 2008	33				
Spring 2008	61				
Total Women	44	6	7	12	22
Total Men	271	24	29	80	115

The MAT was a constant across all semesters in the study. Table 3 shows the correlations between MAT and the other measures of aptitude. At a significance of $p < 0.10$, the correlation with the hands-on test is significant. The correlations with two of the three physics games are also significant.

Table 3: Correlation coefficients between MAT and other mechanical aptitude measures (*p* value is in parentheses)

	Hands-On Expertise	**Hands-On Time**	**Bridge Builder**	**Fantastic Contraption**	**Ball in Cup**
MAT	**0.332** (0.078)	**-0.411** (0.027)	**0.456** (0.005)	**0.198** (0.055)	0.104 (0.220)

We checked to see if mechanical aptitude is related to academic performance. Table 4 shows the correlations with grade point average, ACT scores, and SAT scores. The academic indicators have some relationship to MAT score but not consistently with the other measures. Note that even the statistically significant correlations (in bold) are low.

Table 4: Correlation coefficients between mechanical aptitude measures and academic indicators (grade point average and ACT scores)

	MAT	**Hands-On Expertise**	**Bridge Builder**	**Fantastic Contraption**	**Ball in Cup**
GPA	**0.122** (0.038)	-0.039 (0.847)	0.157 (0.382)	-0.053 (0.619)	**-0.158** (0.071)
ACT English	**0.156** (0.017)	-0.053 (0.796)	0.0015 (0.994)	**0.274** (0.019)	-0.016 (0.870)
ACT Math	**0.263** (0.000)	0.082 (0.690)	0.102 (0.583)	0.179 (0.121)	0.127 (0.179)
ACT Reading	0.046 (0.485)	-0.128 (0.535)	0.105 (0.581)	0.041 (0.728)	-0.092 (0.340)
ACT Science	**0.220** (0.001)	0.134 (0.513)	0.180 (0.340)	**0.244** (0.038)	0.104 (0.280)
ACT Comprehensive	**0.186** (0.004)	-0.037 (0.858)	0.055 (0.774)	**0.240** (0.041)	0.012 (0.902)

The mechanical aptitude measures were compared by gender. Table 5 shows the average and/or median scores for the female and male students. The paper and pencil test as well as the physics computer games show a statistically significant difference between the male and female students. The hands-on test expertise and time do not show differences. Keep in mind that the sample size for the hands-on test was small with 24 men and 6 women participating. Table 6 shows a comparison of the academic performance indicators by gender. Of these, only the ACT reading score shows a statistically significant difference between the male and female participants.

Table 5: Comparison of mechanical aptitude measures by gender with scores of statistically significant difference (p<0.1) shown in bold

Measure		**Female**	**Male**
MAT (max=16)	avg	**9.6**	**11.2**
	median	**10**	**12**
Hands-On Expertise (max=4)	avg	2.00	2.08
	median	2	2
Hands-On Time (minutes)	avg	33.58	32.31
	median	33.25	32.85
Hands-On Time (normalized)	avg	0.151	-0.038
	median	-0.270	0.102
Bridge Builder (no. of levels)	avg	**1.57**	**2.34**
	median	**1**	**3**
Fantastic Contraption (no. of levels)	avg	**3.00**	**3.69**
	median	3	3
Ball in Cup (no. of levels)	avg	**7.09**	**8.10**
	median	**7**	**8**

Table 6: Comparison of academic performance indicators by gender with scores of statistically significant difference (p<0.1) shown in bold

Indicator		**Female**	**Male**
GPA	avg	3.24	3.09
	median	3.21	3.12
ACT English	avg	24.9	23.8
ACT Math	avg	27.3	27.4
ACT Reading	avg	**26.3**	**24.8**
ACT Science	avg	25.7	26.3
ACT Comprehensive	avg	25.4	26.0

Prior Experiences that May Contribute to Mechanical Aptitude

Understanding the influence of student prior experiences on hands-on ability could help provide the foundation for creation of learning experiences that would increase a student's hands-on ability. Over the course of three years, students took prior experience questionnaires. In the spring and fall 2009, students completed a 147-question prior experience questionnaire (PEQ1), and in spring 2010 students completed a 13-question PEQ (PEQ2). The data include responses from a total of 315 students though not all students completed all items. We then looked at correlations between MAT scores and all PEQ1 and PEQ2 responses.

The PEQ1 was adapted from an existing Spatial Experience Inventory.[11] Questions relating more specifically to hands-on experiences were added. Questions were also deleted or combined to reduce the time needed to complete the survey. Questions were grouped into several chronological categories: pre-school years experiences (PS), elementary school years experiences (ES), middle school years academic experiences (MS), high school years academic experiences (HS), middle and high school years non-academic experiences (M/HS), and post high school academic experiences (postHS). Respondents indicated the extent of their participation on a four-point scale. For most of the questions the scale choices were: never, seldom, occasionally, and frequently. For the questions that involved course work, the choices were: no courses, one course, two courses, and more than two courses.

The PEQ2 was developed to shorten response time and to collect more detailed information on hours students spent performing a specific task during a given time frame. The first question for each prior experience asked whether the respondent had ever participated in the activity; it required an answer of yes, no, or I don't know. The second question for each prior experience asked students to provide detailed information as to the time period they had the experience and for how many years, weeks per year, and hours per week. An initial draft of the revised PEQ was piloted at another university to 40 sophomore level undergraduates in mechanical engineering. The final version of the PEQ2 was shortened to 13 questions. The questions selected for the final version met one or more of the following requirements: a high correlation value between PEQ2 and MAT at the piloting university, high correlation for both genders between PEQ1 and MAT performance at our university, and a high correlation between PEQ1 and hands-on task expertise rating for both genders at our university.

Table 7 lists the prior experiences that correlate most highly with MAT score. Some themes are apparent in Table 7: working with tools, outdoor activities, and instrumental music. Note that while the p values indicate significance, the correlation coefficients are all quite low. This is likely because many activities contribute to mechanical aptitude and not just one or two.

Table 7: Positive correlations between MAT score and prior experiences with $p<0.05$ (PEQ1 N=156, PEQ2 N=147)

Activity	**PEQ1/PEQ2**	**Correlation Coefficient, *r***	**Significance, *p***
M/HS: used hand tools	PEQ1	0.290	0.0002
M/HS: target shooting	PEQ1	0.284	0.0003
M/HS: canoeing	PEQ1	0.259	0.0011
M/HS: repaired equipment	PEQ1	0.243	0.0023
postHS: repaired automobiles, toys, bicycles, equipment, motorcycles etc.	PEQ2	0.271	0.004
M/HS: used power tools	PEQ1	0.229	0.0041
HS: woodworking courses	PEQ1	0.223	0.0052
M/HS: repaired bicycles	PEQ1	0.212	0.0079
M/HS: archery	PEQ1	0.208	0.0090
postHS: electronics courses	PEQ1	0.207	0.0103
M/HS: carpentry projects	PEQ1	0.201	0.0118
postHS: read blueprints	PEQ2	0.337	0.014
HS: small engines courses	PEQ1	0.191	0.0167
M/HS: repaired automobiles	PEQ1	0.190	0.0178
postHS: Tech classes	PEQ2	0.206	0.019
M/HS: operate machinery	PEQ1	0.185	0.0242
M/HS: instrumental music	PEQ1	0.172	0.0318
M/HS: marching band	PEQ1	0.170	0.0337
M/HS: hunting	PEQ1	0.167	0.0375
M/HS: knot tying	PEQ1	0.165	0.0393
HS: repaired automobiles, toys, bicycles, equipment, motorcycles etc.	PEQ2	0.184	0.042
HS: metalworking courses	PEQ1	0.160	0.0465

Correlations between prior experiences and MAT were also examined by gender. Tables 8 and 9 list the prior experiences with highest correlation to MAT for the male and female students, respectively. The tables have a number of overlapping activities, but they also reveal some differences between the female and male students. For example, the female list (but not the male list) includes post high school classes in manufacturing technology, pneumatics/hydraulics, and metalworking. The male list (but not the female list) includes activities related to hunting, engines, and automobiles.

Table 8: Positive correlations between MAT score and prior experiences with $p<0.05$ for male students (PEQ1 N=138, PEQ2 N=124)

Activity	PEQ1/PEQ2	Correlation Coefficient, r	Significance, p
M/HS: target shooting	PEQ1	0.268	0.0015
HS: woodworking courses	PEQ1	0.246	0.0037
M/HS: used hand tools	PEQ1	0.237	0.0051
M/HS: canoeing	PEQ1	0.230	0.0068
postHS: repaired automobiles, toys, bicycles, equipment, motorcycles etc.	PEQ2	0.264	0.008
M/HS: used power tools	PEQ1	0.215	0.0112
postHS: Tech classes	PEQ2	0.54	0.012
post HS: electronics courses	PEQ1	0.204	0.0175
M/HS: archery	PEQ1	0.203	0.0169
M/HS: repaired equipment	PEQ1	0.196	0.021
M/HS: marching band	PEQ1	0.190	0.026
postHS: used power tools	PEQ2	0.204	0.034
Total hours: repaired automobiles, toys, bicycles, equipment, motorcycles etc.	PEQ2	0.194	0.042
HS: small engines courses	PEQ1	0.168	0.0486

Table 9: Positive correlations between MAT score and prior experiences with $p<0.1$ for female students (PEQ1 N=18, PEQ2 N=23)

Activity	PEQ1/PEQ2	Correlation Coefficient, r	Significance, p
post HS: mfg tech courses	PEQ1	0.750	0.0079
M/HS: camping	PEQ1	0.605	0.0488
HS: physics courses	PEQ1	0.584	0.0592
ES: instrumental music	PEQ1	0.553	0.0172
M/HS: operate machinery	PEQ1	0.525	0.0975
post HS: hydraulics/pneumatics courses	PEQ1	0.461	0.0625
post HS: metalworking	PEQ1	0.451	0.0691
M/HS: read blueprints	PEQ1	0.444	0.065
ES: worked puzzles	PEQ1	0.427	0.0771
M/HS: scouting	PEQ1	0.407	0.0934
MS: construction courses	PEQ1	0.403	0.0969

Next, we examined the differences between male and female students for the prior experiences that correlate most highly with MAT. Table 10 shows the experiences in this group with a statistically significant difference. Note that the male students have much higher participation levels in these relevant prior experiences. These dramatic differences in prior experience may help to explain the difference in MAT score.

Table 10: Items of statistically significant difference between men and women (note that the Mann-Whitney values are adjusted for ties)

Activity or Measure	PEQ		Male	Female	*p*-value	Test for Difference
MAT		N	273	42	0.0000	t-test
		Mean	11.2	9.6		
Total hours: worked construction	PEQ2	N	120	23	0.0000	Mann-Whitney
		Median	72	4		
Total hours: repaired	PEQ2	N	120	23	0.0000	Mann-Whitney
		Median	326	29		
postHS: repaired	PEQ2	N	120	23	0.0001	Mann-Whitney
		Median	72	4		
Total hours: used power tools	PEQ2	N	120	23	0.0002	Mann-Whitney
		Median	483.5	82		
Total hours: target shooting	PEQ2	N	120	23	0.001	Mann-Whitney
		Median	35	4		
M/HS: used hand tools	PEQ1	N	138	18	0.0012	Mann-Whitney
		Median	frequently	occasionally		
M/HS: repaired equipment	PEQ1	N	138	18	0.0018	Mann-Whitney
		Median	occasionally	never		
M/HS: target shooting	PEQ1	N	138	18	0.0263	Mann-Whitney
		Median	seldom	never		

Engineering Attitude

Student attitude affects performance.[14] Understanding the influence of student attitudes could lead to improved learning experiences that help students improve their hands-on skills. In spring and fall of 2009, students completed a 50-question engineering attitude survey (EAS1), in addition to the MAT and PEQ1. In the following spring, students completed an altered attitude survey, EAS2, and the MAT. EAS1 was the Pittsburgh Freshmen Engineering Attitude Survey.[15] EAS2 was a modified shorter version of EAS1. EAS1 questions with low correlation to MAT were removed. Six questions were added from a tinkering self-efficacy questionnaire to better capture differences in hands-on self-efficacy.[16] In total the EAS2 was shortened to 35 questions. Table 11 shows the attitude questions with the most significant differences between male and female students. Note that the male student responses on average reflect more confidence in and enjoyment of hands-on activities.

Table 11: Attitude items of statistically significant difference between male and female students

Attitude		Male	Female	*p*-value	Test type
I have the knowledge and technical skills to create mechanisms or devices.	N	119	23	0	Mann-Whitney
	Median	4	3		
I enjoy figuring out how things work.	N	119	23	0.0054	Mann-Whitney
	Median	5	4		
I can troubleshoot technical problems.	N	119	23	0.0001	Mann-Whitney
	Median	4	3		
When I look at something I cannot imagine how it works.	N	119	23	0.0314	Mann-Whitney
	Median	1	2		

Conclusions and Future Work

Male students scored higher in mechanical aptitude measures then female students. This is consistent with the findings of Hyde (2005). Our survey results have identified prior experiences that correlate most highly with mechanical aptitude. Male students engage in these activities at a much higher level than female students, thus offering a likely explanation for the lower female mechanical aptitude scores. Finally, our results show that women report lower confidence and enjoyment in questions related to mechanical and tinkering skills.

This investigation relied heavily on the MAT, which is an aptitude test directed at the skilled trades. It may not be the best test for identifying the physical intuition that is most important for mechanical engineers in the workplace. Our future work includes the development of a new test with high reliability and validity. Students come to engineering school with a wide range of mechanical aptitude. The prior experiences that have been identified as high correlators with mechanical aptitude provide guidance on experiences to add to a mechanical engineering curriculum.

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