

2006-155: CRITICAL THINKING SKILLS OF ENGINEERING STUDENTS: UNDERGRADUATE VS. GRADUATE STUDENTS

Elliot Douglas, University of Florida

Elliot Douglas is an Associate Professor in the Department of Materials Science and Engineering at the University of Florida. His educational research interests lie in the areas of critical thinking and active learning techniques.

Critical Thinking Skills of Engineering Students: Undergraduate vs. Graduate Students

Abstract

Critical thinking among engineering students is an important issue, yet there is little known about the differences between undergraduate and graduate students. This study provides initial data comparing the critical thinking skills of engineering undergraduate and graduate students. Twenty five students were administered the California Critical Thinking Skills Test. The only difference observed between the groups was that the graduate students completed fewer questions within the time limit compared to the undergraduates. Qualitative data shows differences between the groups in the way they approached the test. The results suggest that there are important differences in the way undergraduates and graduate students approach tests, and that the use of timed instruments may not be appropriate to measure complex thinking skills.

Introduction

Development of critical thinking skills is generally recognized as an important aspect of undergraduate education. An internet search reveals a large number of colleges and universities, both public and private, comprehensive and liberal arts, that explicitly call for the development of critical thinking skills as part of their mission statement. Two examples are those of Clemson University, which states, "In all areas, the goal is to develop students' communication and *critical-thinking skills*, ethical judgment, global awareness, and scientific and technological knowledge,"¹ and Missouri Valley College, which states, "The College's liberal arts heritage focuses on scholarship, *critical thinking* and academic excellence to prepare the students to become members of a responsible citizenry."² (Emphases added.) Within engineering in particular, ABET 2000 has guided engineering programs to develop a set of educational objectives, many of which include the ability to engage in critical thinking as one of the desired skills (see for example ³⁻⁶).

While many papers in the engineering education literature claim to address critical thinking, for the most part these reports simply discuss critical thinking as a general concept, with no attempt to define or measure it. The few that do have examined critical thinking skills as related to different aspects of engineering education, and so no comprehensive view of the critical thinking skills of engineering students can be obtained.

In one study, Polanco et al. used the Spanish version of the California Critical Thinking Skills Test as one measure to determine the effectiveness of a problem-based learning curriculum in the first two years of the engineering curriculum at a Mexican university.⁷ No difference in overall score or in any of the sub-scores was observed between the students who had participated in the new curriculum and the control group. However, there is no indication of the sample sizes, demographic description of the groups, or even the definition of what constituted the control group, making the usefulness of this study limited.

Critical thinking skills were measured for minority engineering students who had failed in the first year at predominately white institutions and were enrolled in a special support program at

other schools.⁸ Using measures based on analysis of written essays, the authors found that higher critical thinking skills tended to be correlated with negative college experiences, with some effect caused by the type of institution (predominately white or minority). The authors do note several issues that may affect the generalizability of the results: the students were all “at-risk”; the sample size was small (79 students at three different institutions); and the critical thinking measures used were developed for the liberal arts curriculum.

Hager et al. administered the Cornell Critical Thinking Test, Level X (for senior high school and early undergraduates) to engineering students in their first month of study at an Australian university, and attempted to correlate the results to students’ self-reported study habits.⁹ The only correlation they found was a negative one between critical thinking skills and achieving study strategies (strategies used to obtain good grades); no correlation was found between critical thinking and either surface study strategies (memorization, unreflective correlation of concepts and facts, etc.) or deep strategies (relating new concepts to prior knowledge, re-organizing the content, etc.). The authors identify several potential drawbacks to the study: the Level X test may not be at the appropriate level for these students, and they may not have yet developed effective study strategies. It should also be noted that self-reporting of those strategies may introduce error.

Whitmire attempted to correlate self-reported gains in critical thinking skills with a number of other variables across a large number of undergraduate students.¹⁰ Among the findings were that engineering students tended to report higher gains in critical thinking than students in liberal arts or business. In addition to the obvious problems with using self-reported gains in critical thinking, this study also does not report differences by year of study. Two comprehensive reviews of the literature have shown the general trend that critical thinking skills increase throughout a student’s years in college.^{11,12} Thus, even if students are able to accurately self-report gains in critical thinking, any actual increases for the engineering students will be minimized by averaging across all respondents from freshmen to seniors.

To date, these are the only studies we have identified that attempt to specifically measure critical thinking skills of engineering students. As can be seen from this review, these studies have focused on different aspects of the issue, and in several cases have important flaws. A comprehensive overview of critical thinking in engineering can not be obtained from the available literature, which is somewhat surprising given its perceived importance among educators, legislators, and accrediting agencies. Here we describe a study that uses results from a quantitative critical thinking instrument and an informal qualitative investigation to describe the way in which a group of undergraduate and graduate students approach the quantitative instrument. This was intended to be an exploratory study to probe some of the issues associated with critical thinking, rather than a true experimental design that would allow generalizability to a larger population. As such, it provides some insight into differences in the way the students that were a part of this study think, and suggests a number of paths for further investigation.

Theoretical Framework

A number of definitions of critical thinking based on specific skills exist.¹³⁻¹⁶ While the list of skills in each of these studies is slightly different, there are many commonalities, suggesting that

there is a relatively stable framework to define critical thinking skills. Less work has been done to define critical thinking specifically within the context of engineering. Lunt and Helps apply the broad definitions of critical thinking as specifically applying to engineering problem-solving.¹⁷ Similarly, Mina et al. examine the objectives of engineering programs, especially problem-solving, in light of John Dewey's philosophy of critical thinking, and argue that engineering education should be substantially revised to focus more on inquiry by the students.¹⁸ Cloete also focuses on problem-solving heuristics as a means to teach students to think critically.¹⁹

For this study we adopt the definition of critical thinking as defined by the Delphi report.¹⁴ In 1988 and 1989 a panel of experts was convened to identify the skills and dispositions associated with critical thinking. The vast majority of these panelists were experts in philosophy, psychology, or education; only four of the 46 participants were from "technical" fields (physics, economics, zoology, computer science). The resulting "Delphi Report" defines critical thinking as "purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation, and inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or contextual considerations upon which that judgment is based." It then goes on to list specific skills and sub-skills as follows:

1. Interpretation, consisting of categorization, decoding significance, and clarifying meaning.
2. Analysis, consisting of examining ideas, identifying arguments, and analyzing arguments.
3. Evaluation, consisting of assessing claims and assessing arguments.
4. Inference, consisting of querying evidence, conjecturing alternatives, and drawing conclusions.
5. Explanation, consisting of stating results, justifying procedures, and presenting arguments.
6. Self-Regulation, consisting of self-examination and self-correction.

The report provides descriptions and examples of each of these skills and sub-skills. It also emphasizes that the particular list generated by this panel is not necessarily definitive; other means of classifying critical thinking skills are possible, and may be more appropriate depending on the context. This particular definition is useful because it is the most recent of the definitions, represents a broad consensus of opinion, and has been specifically operationalized in an available instrument, the California Critical Thinking Skills Test.

Methodology

The California Critical Thinking Skills Test (CCTST) Form 2000 was used to measure critical thinking ability. The CCTST uses the definition of critical thinking from the Delphi Report as its conceptual framework. There are three versions of the instrument, each of which consists of 34 multiple choice items. Form 2000 is a modified version of the original Forms A and B that includes more items that involve analysis of diagrams and charts. For all versions, the total number of correct answers is used as an index to measure overall critical thinking skill. Validity of the CCTST has been established through the face validity of the individual items,²⁰ and through criterion reliability in comparison to other measures of academic performance.²¹ The test manual reports correlation coefficients of Form A with the more widely used Watson-Glaser

instrument of approximately 0.5. Comparable data is not available for Form 2000, but the manual does report correlation coefficients between Form A and Form 2000 of approximately 0.9. Reliability of Form 2000 is reported as approximately 0.8, slightly higher than either Form A or B.

The CCTST Form 2000 was administered to 12 graduate students in Materials Science and Engineering who had passed the PhD qualifying exam, and 13 undergraduate juniors in Materials Science and Engineering at the same institution. Participants were limited to students in the Materials Science and Engineering Department, and to students whose prior education was primarily in the US, in order to reduce variability in the sample and increase the likelihood of finding differences between the two groups despite the small sample size. Undergraduate students were recruited by a general advertisement through email, and the first 13 responses were accepted as participants. This approach was not effective with the graduate students (only one graduate student responded to the general email), and so graduate students were recruited by specifically inviting individuals selected randomly from the population of students who met the qualifications. The CCTST was administered several different times and the test manual procedures were followed in all cases. The most important aspect of the procedure for this study is that there was a 45 minute time limit for completing the instrument. Participants were paid \$20 for participating in the study.

Subsequent to administering the CCTST, participants were contacted by email and asked to reflect on their experience taking the instrument. A total of 8 undergraduates and 10 graduate students responded. Codes were developed out of the responses by identifying major themes articulated by the students.

Results

Table 1 provides the descriptive statistics from the CCTST for the two groups. Surprisingly, the undergraduates scored higher than the graduate students, scoring on average 3 points higher. As it is usually interpreted, this difference would imply that the undergraduates are more skilled at critical thinking than the graduate students. However, further analysis reveals that the difference is caused by the graduate students answering fewer questions within the time limit. A total of 12 of the 13 undergraduates were able to complete the instrument within the time limit, while only 3 of the 12 graduate students were able to complete it. Table 1 shows that on average the graduate students answered 3 fewer questions than the undergraduates. When the percentage of correct items out of the total number of items answered is calculated, the difference between the two groups is eliminated, with both correctly answering approximately 70% of the items.

Table 1: Results from the CCTST. Numbers are the mean responses.

	Undergraduate students	Graduate students
CCTST index ^a	24.15	21.17
Number of items answered ^a	33.92	30.92
Percentage of items correct ^b	71.23	68.70

a: Difference between the two groups is significant at $p < 0.05$.

b: Percentage of correct answers out of the total number answered.

In order to understand the difference in the ability of the two groups to complete the instrument, the students were asked to reflect on their experience. The only guidance they were given was that there was a desire to explain a surprising difference in the ability of some students to complete the instrument. Table 2 shows the general codes developed from the responses, and the number of responses that could be identified with each code. It should be noted that in Table 2 a single participant's response may be coded in more than one category.

Some clear distinctions between the two groups emerge from Table 2. Six graduate students commented on some aspect of the difficulty they had in analyzing the items and the time they spend trying to select an answer (codes 1 and 2):

...several of the questions could have been answered in more than one way depending on how the paragraphs were read... I remember marking at least four or five questions that seemed to have more than one correct answer. Knowing that there could be only one correct, I spent a great deal more time with these questions than expected. (Graduate student).

Table 2: Coding of participant responses to the request to reflect on their experience of taking the CCTST. The numbers indicate the number of each group who provided a response that could be coded in that category.

	Undergrad	Grad
1. Hard to choose answers, spent time deciding.		3
2. Questions were complicated, needed to read carefully		3
3. Tried not to stay with any question too long, made best educated guess.	3	
4. Long time since I took a written test.		3
5. CCTST was similar to high school or undergrad experience.	2	
6. Surprised when time was up.		2
7. Use of test-taking strategies.	1	2
8. Different attitude towards exams or ability to think as grad vs. undergrad.		4
9. Hard to choose answers, no indication of strategy.		2

I remember many of the questions required accurate "book-keeping" of the situations described. I know that on numerous questions I had to reread the descriptions, sometimes more than twice. (Graduate student).

In complete contrast, three of the undergraduates commented on taking an opposite approach (code 3):

On the ones that I couldn't figure out an answer immediately I simply made an educated guess based on what I knew. I left the test thinking it had several challenging problems that could really confuse you if you tried to spend a bunch of time on them. (Undergraduate student)

Another clear distinction was in how they saw their recent experience with exams affecting their performance (codes 4 and 5):

I feel that the test was remarkably similar to the SAT reading comprehension section... Also I have been enrolled in some classes that have had a basis of reading and writing, which I think helped. I felt that the test was based on knowledge that I had learned throughout high school. (Undergraduate student)

At the onset of the exam, I realized that it had been years since I had taken a "standardized test" such as the SAT or GRE. I had to remind myself of the time limit and to pace myself. (Graduate student)

Another theme that emerges comes from the graduate students who commented on how their thinking has changed since they were an undergraduate (code 8):

I have found that learning does not stop with studying, but often connections are made while taking the exam. I can't say I enjoy taking exams, but I have developed a newfound "respect" for them. As an undergrad I would take the exam, answer the questions the best I could at the time, and leave without another thought. I looked at it as the last step before the break. It seems in graduate school, I'm more apt to take my time reading the questions and thinking through my answers, not just scribbling the first thought and moving on. Of course this does not necessarily mean I get more questions correct, but I do put more thought into my work. (Graduate student)

...there is an actual metamorphosis that we make from being an undergraduate to a graduate student. From being an undergraduate, the curiosity to learn new things and time you spend on expanding your mind is not as mature as when you are a graduate student. I feel that becoming a graduate student, compels me to delve deeper into understanding what is going on and why. When the test was administered, I feel like I was driven to take this test seriously and try to analyze what these questions/problems were relaying. So basically when I was an undergraduate I didn't feel like I took things as "serious" as I do, nowadays. (Graduate student)

Discussion

The initial quantitative findings were quite surprising. We expected that the graduate students would have higher overall scores on the CCTST, on the basis that graduate students who are conducting engineering research would be more likely to need to use critical thinking skills such as analysis, interpretation, etc., than undergraduates. However, the finding that graduate students had more difficulty completing the instrument is consistent with other results from the literature. In a study that allowed students to take as much time as needed to complete the CCTST Form A, it was found that longer completion times were correlated with higher scores.²² This tended to support the authors' "slow and careful" hypothesis, namely that an important disposition towards critical thinking is the tendency to carefully analyze situations, while those who are quicker are being less careful and tend to make mistakes. The "smart and fast" hypothesis, that brighter students can finish the test more quickly due to higher innate intelligence, was not supported.

On the one hand, the “slow and careful” hypothesis seems to explain the differences between the two groups, as evidenced by the qualitative results. There is a striking difference between graduate students, who stated that they took their time to carefully analyze the questions, and undergraduates, who stated that they would make their “best guess” if there was not a clear answer. These statements also seem to suggest a different overall approach to test-taking by these two groups of students. In this context, we first note that both groups seemed to recognize that these types of standardized tests are more familiar to the undergraduates than the graduates. Second, several graduate students commented on a major qualitative difference in their thinking compared to when they were undergraduates. This remains a relatively unexplored area; we are familiar with only one study that examined differences in critical thinking between undergraduates and graduates.²³

However, the “slow and careful” hypothesis can not completely explain the results, as the two groups answered the same percentage of questions correctly. Again, we might expect graduate students to be able to correctly answer a higher percentage of questions than the undergraduates. Our results, that there was no difference in the percentage correct, is consistent with the results of King et al.²³ They used three measures of critical thinking, two of them multiple choice instrument similar to the CCTST (Watson-Glaser and Cornell Critical Thinking Test), and the Reflective Judgment Interview (RJI), in which subjects are presented with a dilemma and asked to provide arguments in favor of one of the points of view. While graduate students scored higher on all three measures, the difference disappeared for all but the RJI when academic ability was controlled for. The difference may be related to the way in which critical thinking is defined for each of the instruments. The two instruments in which the groups scored the same use a specific skills definition, while the RJI uses a general definition. Thus, it may be that undergraduates and graduates are equally adept at using specific skills, but that the ability to combine these skills to deal with complex issues is a higher level of thinking that undergraduates are not as adept at doing. If this is true, it would explain the lack of a difference in the percentage of correct answers found in our study. King et al. also point to the difference between recognition tasks and production tasks in explaining the difference.

While the combined quantitative and qualitative results seem to provide a clear explanation of the differences between the two groups, other possibilities exist. In particular we note that there was a difference in the way the two groups were recruited. Undergraduates volunteered in response to a general advertisement for participants. Although the same approach was attempted for the graduate students it was unsuccessful, and so graduate students were subsequently randomly selected from the eligible population. It may be that the undergraduates who volunteered tended to be the more motivated, higher academic ability students. This could potentially lead to the undergraduate sample scoring higher than would a random sample. Unfortunately, data to compare the academic abilities of the two groups was not collected, and so the possibility of this effect can not be discounted.

Conclusions

The results of this exploratory study suggest that our understanding of how to measure critical thinking is incomplete. Does an objectively scored instrument adequately access the deep thinking skills that are associated with critical thinking? In our study, the type of thinking

described by the graduate students does not seem to have been reflected in the quantitative scores. The results show evidence for a qualitative difference in the type of thinking that occurs in the two groups, rather than a quantitative difference in ability to use specific critical thinking skills.

This study raises a number of questions regarding the measurement of critical thinking skills. From the undergraduate comments, it appears that the instrument may reflect the ability to take a test, rather than critical thinking ability. This could relate to either the fundamental nature of the test (multiple choice), and/or the use of a limited time for completion of the instrument. The CCTST, and similar objective instruments, are all intended to be administered within a limit time. By doing so, timedness becomes part of the operationalization of critical thinking, even though time is not a part of any of the definitions. This study suggests that the use of timed instruments for the measurement of critical thinking needs to be carefully considered, especially when comparing two groups that differ qualitatively in their thinking abilities, as in this study. The effect of time may be less pronounced when the difference in ability is a matter of degree rather than type, for example in comparison of freshmen and juniors.

Another aspect of critical thinking that must be considered is that of generalizability. The question of the generalizability and transferability of critical thinking skills has been a matter of debate. A series of essays edited by Norris provides the range of philosophical perspectives on this issue.²⁴ The question is generally framed as to whether general critical thinking skills can be taught and then transferred to a discipline-specific context, or whether it is necessary to teach critical thinking skills within a specific context in order for them to be used in that context. All critical thinking instruments are general in nature, not tied to any specific subject. Thus we must question whether these results reflect the inability of critical thinking skills to be generalized. Perhaps engineering graduate students would exhibit greater critical thinking ability than undergraduates on engineering tasks, but they are unable to transfer those skills to other content domains.

Overall, this study raises a number of intriguing questions for further study. The use of the CCTST provides an interesting context within which to explore how students approach critical thinking tasks. By better understanding how students think when confronted with a critical thinking problem, we can better interpret results from measurement instruments and ultimately guide students to be better critical thinkers.

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