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Critical Thinking Activities –A case study for enhanced performance and retention in Fluid Mechanics

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ABSTRACT

CONTEXT

In engineering education there is a need for a more cohesive approach to conceptualize and (better) understand critical thinking (Ahern et al., 2019). Teaching of critical thinking skills should be based on a shared understanding, and practices and pedagogies that enhance student outcomes. Encouraging students to draw conclusions through deducing or inferring answers to questions and then reflecting on the quality of the reasoning helps to develop conceptual constructs (Ralston & Bays, 2015). We hypothesize that by providing students with opportunities to examine problems in a variety of contexts, a better learning environment and retention of complex course content may be possible.

PURPOSE OR GOAL

In this study we assessed the efficacy of a Critical Thinking Activity (CTA) in an undergraduate Fluid Mechanics course by i) evaluating student performance in the CTA and final grade, and ii) the students' perception of how the CTA impacted their learning as a learning tool. This study investigates whether the implementation of a CTA can improve students' critical thinking as described by their performance in the course overall.

APPROACH OR METHODOLOGY/METHODS

The underlying assumption of this study was to engage students in higher-order thinking skills by relating the (theoretical) content of a 2nd year Fluid Mechanics course to a real-life experience. By specifically targeting and developing problem solving skills. The CTA linked theory to practice through a contemporary situation in which the connection to Fluid Mechanics concepts discussed in the classroom might not have been so obvious to the student. The IDEAL model was chosen to promote the problem-solving skills of students.

ACTUAL OR ANTICIPATED OUTCOMES

The motivation to implement the CTA in Fluid Mechanics was to encourage students to review their learning, apply insights gained by this reflection and to think critically about the fundamental concepts taught in the course. Despite the apparent difficulty in defining and measuring the process of critical thinking, the sample size of the pilot class provides a good record of how strategies and activities designed to encourage the process of critical thinking have positively impacted student performance and their learning experience.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

The CTA not only enhanced student knowledge and understanding of concepts, but also enhanced the evidence of learning and their overall performance in the course. The consistency of acknowledgement across the cohort independently confirms the impact of the CTA on the student experience and their performance. This corroborates the use of CTA's in classes to achieve better learning outcomes. The adaptation of these CTA's to other engineering classes in an effort to confirm the outcomes and enhance the investigation of these through longitudinal studies is recommended.

Introduction

The significance of "critical thinking" is known to many educators, but it has been diversly conceptualized. Historically the literature has characterized critical thinking simply, as one or more skills, mental processes, or sets of procedures (Bailin et al., 1999) which led to the view that critical thinking could be taught simply by practicing or demonstrating it. However, some studies argue that critical thinking must be characterized in terms of specific performance criteria in which critical judgment is developed through applying knowledge in many contexts, and that improvement is made through frequent feedback and evaluation with respect to the quality of thinking demonstrated (Abrami et al., 2008; Behar-Horenstein & Niu, 2011) and through the meaningful and constructive interpretation of information (de Acedo Lizarraga et al., 2012).

In engineering education there is a need for a more cohesive approach to conceptualize and (better) understand critical thinking (Ahern et al., 2019). Teaching of critical thinking skills should be based on a shared understanding, and practices and pedagogies that enhance student outcomes should be applied. For example, by encouraging students to draw conclusions through deducing or inferring answers to questions and then reflecting on the quality of the reasoning (Ralston & Bays, 2015) conceptual constructs can be developed. These cannot be learned by drill and practice but require opportunities for reflection and feedback. In addition, we suggest that by providing students with opportunities to examine problems in a variety of contexts more involved thinking is required and that this encourages the development of critical thinking skills.

In this study we explore the development of critical thinking skills through the implementation of a Critical Thinking Activity (CTA) in a 2nd year Fluid Mechanics course. We investigate how the CTAs affected students critical thinking by analyzing how the CTA contributed to student performance. Some studies (Kong et al., 2014), have used specific tools, such as the California Critical Thinking Skills Test (CCTST) or the Watson–Glaser Critical Thinking Appraisal (WGCTA) whilst other studies have used indicators such as demographics to measure the impact of learning activities on critical thinking. In this study we assessed the efficacy of the CTA by i) evaluating student performance and the resultant impact of this on their performance in the course overall, and ii) students' broad perceptions of how the CTA affected their performance. The broad research question guiding this study is: "Does the implementation of a CTA improve critical thinking as reflected by students' performance in the course overall?" Outcomes from this research will provide insight into authentic problem-solving activities and will subsequently shed light on ways the CTA can be used to enhance the student learning experience.

Methodology

Fluid Mechanics course

The compulsory second-year course Fluid Mechanics course chosen for this study is often considered one of the most difficult in the engineering curriculum by students. Equivalent to two units within an engineering curriculum of 64 units taught over 4 years it is prerequisite to courses in later years of the curriculum. The syllabus and content is equivalent to Fluid Mechanics courses at other institutions such as fluid dynamics, fluid statics, Bernoulli's principle, energy and momentum equations, dimensional analysis, flow and friction in conduits etc. With a student cohort often between 100 and 200 students, the course includes 65 contact hours, split up into approximately 40 hours of lectures, 13 hours of tutorials and 12 hours of laboratory work. Assessment is a combination of summative and formative assessment including an end-of-semester examination and work throughout the semester (see Table 1). Each of the three CTAs was worth 1% of the total mark and based on a bonus scheme, meaning participation was voluntary. Thus, the combined CTAs could contribute to an additional 3% of the total grade. Student performance in this course over the years has generally been normally distributed.

Table 1: Test statistics for various statements related to critical thinking questions

Assessment Items	Weighting [%]
4 Laboratories (Pressure readings / Manometers, Friction in pipes, Lift and Drag forces, Momentum equation)	30
Tutorials (solving problem sets)	No weighting
Mid-term Exam (quiz style)	10
Final Exam (long and short answer questions, calculations)	60
Bonus Scheme: Critical Thinking Activity (CTA) x 3	3x 1% each

Critical thinking Activity

The holistic learning process in the Fluid Mechanics course involves theoretical concepts being introduced during the lectures, developed further during the tutorials through collaboration and peer mentoring, with the application of important concepts and theories being practiced by students during the laboratories. Although higher-order thinking skills such as "analyze"," evaluate" and "create" from Bloom's revised taxonomy (Krathwohl, 2002) were integrated with coursework and assessment items, the additional implementation of CTA as based on a bonus scheme (1% per CTA, three CTA in total) was targeting the process of solving an authentic real-world problem.

The underlying assumption of the CTA was that students would engage in higher-order thinking skills by relating the (theoretical) course content to a real-life experience. By specifically targeting and developing problem solving skills the CTA linked theory to practice through a contemporary situation in which the connection to Fluid Mechanics might not be obvious to the student. The IDEAL model (Bransford and Stein, 1993) was chosen to promote the problem-solving skills of students (Bhadargade & Joshi, 2020; Gusau & Mohamad, 2020).which is aligned with core elements of the development of critical and creative thinking (Nazzal and Kaufman, 2020). The structure of the CTA is outlined in Figure 1 and has many commonalities with other models such as the Four Stage Model of Creative Problem Solving (Cropley, 2015).

Identify: In the first Step, students were required to identify and define the problem, the catalyst for this was an everyday situation such as the example of a flyboard and the use of water jets for recreational sporting activities. This was one of the most challenging steps for students as the connection to the course content was made deliberately opaque (expressed in Figure 1 as the first step where observation is needed to identify the problem which is one of the most critical steps of the CTA as it is supposed to inspire curiosity).

Define: In the second Step, students had to select a strategy or concept from fluid mechanics that would enable them to solve the problem or identify whether it could be solved, for example the momentum equation, the hydrostatic equation, the Bernoulli principle etc. or a combination thereof.

Explore: In the synthesis phase (third and fourth step) students were required to calculate or execute their selected strategy. In Fluid Mechanics this often means students must perform calculations from the available data and

Act: as the fourth step, extract meaning from their results that answers the initial question or problem as identified in Step 1.

Look back and evaluate: In final step. students were required to evaluate their result, i.e., is it meaningful and/or within expectations and physical limits and how would the result change if the boundary conditions were to change.

Feedback Loop: On completion of the CTA students were required to submit short responses (maximum length ~1.5 -2 pages) online with equations and diagrams to support their arguments. Integral to this process was an opportunity for students to resubmit a second attempt (Take 2) after their initial response (Take 1). Students received feedback within 2-3 days from a tutor on the initial submission (Take 1). This feedback included comments indicating how their solution could be improved by pinpointing where an assumption was either missing, incorrect or could be enhanced. Based on this feedback, students were able to re-submit a revised solution within 3 days to improve the marks received in Take 1 by incorporating responses to feedback and from their reflection on their answers in Take 1. Only the better score of the two submissions counted towards their final grade. Critical to this resubmission process was the timeliness of feedback (less than 72 hours) that enabled students to reflect on their answer while still “fresh in mind”. This provided an opportunity to build a stronger connection between theorical concepts, the strategy they chose to solve the problem and to respond to the feedback through the process of reflection.

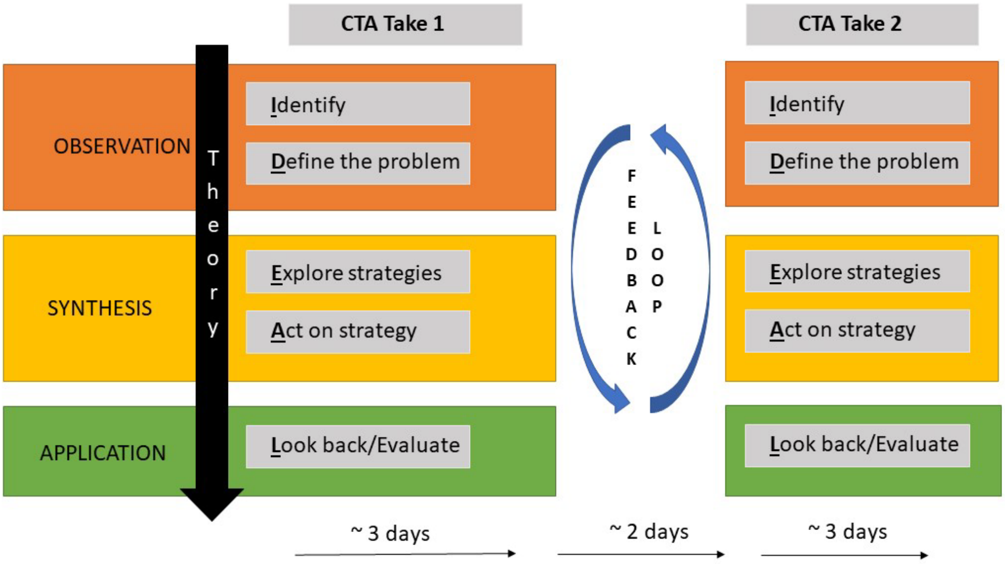

Figure 1: Structure of the Critical Thinking Activity

<u>Example CTA 1</u>

And example of the CTA (here of the CTA# 1: Momentum Equation) in Fluid Mechanics and marking rubric is outlined below.

Flyboarding has become a popular water sport fun activity worldwide. The design allows the rider to climb out of the water up to heights of h ~10 m above the water surface or simply remain stable in the air. This is achieved by the underfoot propulsion from two jets. Discuss the forces that are involved to lift a rider out of the water and use the concept of control volume and momentum flux for a flyboard.

Figure 2: Structure of the Critical Thinking Activity

Table 2: Example of the (generic) Marking Rubric of a CTA

Score (8 max)	Description
2/8	Very limited and/or erroneous response containing some correct information. Wording is vague or imprecise
4/8	Response is correct but written as a list of simple observations without drawing connections between different aspects of the problem OR correctly identifies some important connections but includes significant errors. Text may include grammatical and punctuation mistakes, wording may be imprecise or ambiguous
6/8	Response is correct and draws important connections between different aspects of the problem. Text is fairly clear but may include minor grammatical and punctuation mistakes, wording could be more precise.
8/8	Exceptional response (predictive), response is correct, and draws important connections between different aspects of the problem. The response is concise and precise, and the significance beyond this specific problem is clear. Text is clear and easy to read, free from grammatical and punctuation mistakes. Ideas flow logically.

Example answers for each marking score in the rubric was provided to tutors and training sessions for giving adequate feedback based on the responses were also held prior to the CTA. Other topics covered in the CTA with were “Velocity and energy losses in pipes” (CTA #2) and “Dimensional analysis” (CTA # 3).

Methods of Analysis

Investigating the effect of the CTA required an approach that provides an in-depth understanding of the outcomes of the study and places these into context. This case-study utilizes an experimental research approach, examining both quantitative and qualitative data. Critical thinking can be developed through the implementation of specific pedagogical interventions (Tiruneh et al., 2014) and it is suggested that the use of both quantitative and qualitative assessments provide a more accurate way to measure students’ critical thinking (Behar-Horenstein and Niu, 2011).

A survey was conducted to gather qualitative data and gather insights on the approach used to solve the CTA (refer to Table 3 for details) and its alignment with the IDEAL model. The survey was designed to ensure anonymity, and participants were asked to rate their responses on a 5-point Likert scale ranging from 1 ('strongly disagree') to 5 ('strongly agree').

For quantitative data analysis, students' performance data in the CTA Takes and final exam grades were utilized. The analysis aimed to compare the marks of the CTAs for each problem, examining whether there was an improvement in marks between CTA Take 1 and Take 2. Additionally, it aimed to estimate the impact of the CTA Takes on the final grades. This analysis was performed for all CTAs by reviewing the mean distributions of all four takes. The Pearson Correlation Coefficient was then used to explore the relationship between the marks in the CTAs and the overall grades. This helped determine if the number of attempts in the CTAs had a significant effect on the students' final performance.

To accomplish this analysis, the data, organized in a Microsoft Excel Spreadsheet, was exported to the Statistical Package for Social Sciences (SPSS) Version 29. The dataset was cleaned by removing students with scores of 2 or less in all three takes. The mean distribution was computed to provide insights into the students' progression in learning as a result of participating in the CTAs. Additionally, the Linear Regression coefficient was employed to estimate the impact, offering an explanation of the extent to which the Takes in the CTAs influenced the students' overall performance grades.

In evaluating the students perception of their overall experience in participating in the CTAs, a chi-square test was performed, to test the association between the “Final Grade”, “participation in one (CTA_1), two (CTA_2), or all three CTA (CTA_3)” and “CTA Score,” This was done to establish if there was any significant relationship between the three variables. The values for each statement represent the chi-square test statistic. Higher chi-square values indicate a greater deviation from the expected distribution, with the degrees of freedom for each statement reported at 4. The p-values for each statement indicate the level of statistical significance. Values "<.001" suggest that the results are statistically significant at a very high level of significance ($p < 0.001$).

Results

Qualitative

Table 3 shows test statistics (the chi-square and associated p-values) and assesses the relationship between the statements and critical thinking questions. Higher chi-square values of Q1, Q2, Q5, and Q6 (highlighted in green) suggest a stronger association between their experiences and the critical thinking questions and suggest that these questions have a stronger impact on the overall student experience compared to the other questions in the table. Thus, the responses to these specific questions are more closely related to the students' overall experience than the responses to other questions. It implies that these aspects covered by questions 1, 2, 5, and 6 have a greater influence on shaping the students' perception of their experience. Questions 3 and 7 also showed stronger relationship (light green) compared to questions 4 and 8 (beige).

Table 3: Test statistics for various statements related to critical thinking questions. The number of response was n=71

Student Experience Q1-Q8	Mean	Std. Deviation	Chi-Square	df	Asymp. Sig.
Q1: I attempted to discover the main ideas in the question.	4.07	0.7	130.27	4	<.001
Q2: I asked myself how the question related to what I already knew.	4.07	0.7	59.67	3	<.001
Q3: I thought through the meaning of the question before I began to answer it.	3.67	0.9	48.40	4	<.001
Q4:I used multiple thinking techniques or strategies to answer the question.	3.31	0.9	36.27	4	<.001
Q5: I selected and organized relevant information to solve the question.	3.93	0.9	89.73	4	<.001
Q6: The critical thinking strategy helped me to better understand fluid mechanics concepts	3.99	0.9	51.07	4	<.001
Q7: I would recommend Critical Thinking Questions for other subjects	3.97	0.9	46.27	4	<.001
Q8: Critical Thinking Questions should weigh heavier in the overall assessment	3.55	1.2	13.73	4	0.008

The mean ratings are above 3 (Q1-Q8) indicating that, on average, students mostly agreed or strongly agree with the statements presented in the questions. Additionally, the low p-values (<.001) imply that there the students' responses are not random and can be considered representative of their actual experiences. It is also worth noting that Question 8 received a relatively lower mean rating compared to the other questions (3.55). Furthermore, the chi-square test for question 8 yielded a p-value of 0.008, which is below the 0.05 threshold. This indicates a significant association between the students' rating for Question 8 and the overall assessment. Therefore, it suggests that students believe that critical thinking questions should be given more weight in the overall assessment. The statement "Critical Thinking Questions weigh heavier in the overall assessment" has a p-value of ".008," which indicates statistical significance at the 0.008 significance level.

Quantitative

Results indicate (Table 4) that a higher proportion of students that did not participate (39%) in any of the critical reflection (CTA_0) activities performed more poorly than those who participated in at least one CTA (CTA_1) activity (24.4%), or two activities (CTA_2, 17.6%). Only 2 out of 51 students who attempted all three CTAs (CTA_3) got a marginal pass, whilst the vast majority passed with grades 4 and above. A significant proportion of the students who did not attempt or participate in the CTA exercises performed poorly in their final examination (42.9%). The results also show that there is a correlation between the amount of CTA to overall performance in the course: 75.4% of all students who participated in one CTA activity passed their final examinations, 79.4% passed who took two CTAs activities. 96% passed of those who tool all three CTAs of which a high proportion received at least a Distinction in their final grades. Two students who participated in the CTAs but only received a marginal pass, achieved also only an average of 3 marks in CTAs they participated in. This may indicate a way of identifying struggling students early in the course before the final assessment.

The Pearson chi-square test statistic was recorded at 49.470, with 15 degrees of freedom (df). The p-value for this test was less than 0.001, indicating a highly significant result suggesting that there is a significant association between the variables being examined. The likelihood ratio chi-square test statistic was also recorded at 60.454 (df= 15). The p-value was less than 0.001, suggesting strong evidence against the null hypothesis. Additionally, the linear-by-linear association chi-square test statistic was 37.192, with 1 degree of freedom. The p-value was less than 0.001, indicating a significant linear relationship between the variables.

Table 4: Ratios of students' participation in CTA activities by Performance

CTA Takes	Performance (Final Grades)						Total No. of Students
	Fail (0)	**MP (3)**	**Pass (4)**	**Credit (5)**	**Good (6)**	**Distinction (7)**	
CTA_0	0.39 (30)	0.039 (3)	0.273 (21)	0.169 (13)	0.104 (8)	0.026 (2)	77
CTA_1	0.244 (11)	0 (0)	0.244 (11)	0.378 (17)	0.111 (5)	0.022 (1)	45
CTA_2	0.176 (6)	0.029 (1)	0.294 (10)	0.235 (8)	0.118 (94)	0.147 (5)	34
CTA_3	0 (00)	0.039 (2)	0.196 (10)	0.333 (17)	0.196 (10)	0.235 (12)	51
Total	0.227 (47)	0.029 (6)	0.251 (52)	0.266 (55)	0.13 (27)	0.097 (20)	207

Discussion and Conclusion

Problem solving approaches allow engineering students to experience the roles and processes they will experience in the real world and encourage the development of critical thinking skills. The use of authentic learning experiences situates students in an environment in which learning objectives are aligned with real-world tasks. The rationale behind the implementation of the CTA in Fluid Mechanics was to encourage students to review their learning when confronted with a real-world scenario, apply insights gained by this reflection and to think critically about the fundamental concepts taught in the course.

From our results and the feedback obtained we conclude that the CTA improved the learning experience during the course expressed through the improvements in the overall performance of students. We hypothesize that the impact of the CTA on student learning was sustained and carried through to the final exam leading to an overall better performance of students. Successful completion of the CTA is directly related to the ability of problem-solving activities to contribute to the development of sustained critical thinking skills in students.

Based on our findings we recommend the use of CTA in undergraduate courses due to the importance of providing students with authentic real-world learning experiences. and the impact that problem solving strategies can have on students' ability to think critically. However, when making any changes to instructional pedagogies there are a number of issues that exist. Firstly, incorporating activities such as the CTA should be considered from a course wide perspective or even across a program of study. Students may resent activities that are added ad-hoc and without significant alignment to the course learning outcomes and other activities therein. Secondly, resourcing issues are also manifested in activities such as this and careful consideration must be made to the workload of all teaching staff in the course – including the feasibility of tutors implementing the specified marking regime. A significant feature of 'quality' feedback is its timeliness (Chen et al., 2019; Sopina & McNeill, 2015). In an effort to provide the feedback required to stimulate students to think critically about their responses and resubmit the CTA, marking was effectively required twice. Therefore, special attention needs to be considered for large cohorts and any staff involved in marking, as it can be quite challenging to maintain the necessary time frames.

We recommend that as part of any further research the implementation of CTA should be encouraged and monitored in other (engineering) courses. By benchmarking CTA against the intended learning outcomes of the course and any graduate attributes the impact of these activities on students' employability can be more fully explored. For instance, longitudinal studies will provide more roust data to draw conclusions about the impact of CTA on learning. Modifications such as changing the weight of the assessment item could also encourage greater participation in CTAs.

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