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Development of scientific thought in an advanced research internship: building up a performance assessment system

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ABSTRACT: The scientific research experiences of engineering students allow them to develop practical thinking skills necessary for their professional work, especially scientific and critical thinking. This case study evaluated the performance in the thinking skills competencies of engineering students who interned in an advanced research project. Two instruments were designed: a survey for students and an observation rubric for evaluators. Data were collected on-line at the end of the academic term and reviewed using descriptive statistics. The results showed more students' interest in the technical work of the scientific experience and less in the thinking skills that might be needed to do this task. This finding may be influenced by the previous Covid-19 lockdown that prevented laboratory practices for a long time. The two instruments demonstrated their usefulness qualitatively and descriptively, assessing the development of the mentioned competencies in the students who completed the internship.

Keywords: Critical thinking, competency-based education, educational innovation, higher education, scientific thinking

INTRODUCTION

The globalised world of the 21st Century is a time of great complexity that demands rigorous training in thinking skills for students, especially those in higher education [1], due to new digital learning systems that incorporate competency requirements, new learning methods, artificial intelligence, and computational technologies for both higher and lower-order levels of thinking. Learning in the 21st Century requires contextual lessons derived from emerging technology, creative environments, flexibility, paradoxes, complexity and uncertainty [2]

A classic definition of critical thinking is the purposeful self-regulated judgment that results in interpretation, analysis, and explanation of evidential, conceptual, methodological, criteria-based and contextual considerations supporting that judgment [3]. It can be interpreted as a set of interrelated cognitive processes and also as a way of thinking that improves the quality of one's thinking. There is no globally agreed definition of this ability, resulting in the difficulty of proposing a model and the instruments that allow it to be explained and measured unambiguously [4].

Scientific thinking is the mental process that guides the search and improvement of knowledge. It is the ability to observe, record, describe, question and explain a phenomenon. More generally, it is thinking about the entities and processes of science, while also being a process of inductive, deductive, experimental and causal reasoning based on the analysis of natural phenomena using the scientific method. Scientific thinking requires argumentative skills that go from simple to complex; therefore, it requires critical thinking [5].

In current university education, there is a trend towards integrating approaches in programmes that assess and maintain a consistent quality among different countries, similarly formulating their competencies, as stated, for example, in the Bologna Agreement [6]. As a result of the wide diversity of students who undertake an engineering programme, institutions are responsible for preparing them according to their needs. Simultaneously, they must meet the demands of the industry to have competent engineers, so that they can find meaningful jobs anywhere in the world. The response to these requirements has been to conform engineering education to a competency-based learning approach.

Competency-based education (CBE) is a pedagogical approach focusing on mastering specific knowledge and skills that students must demonstrate measurably. In CBE, students demonstrate their progress in their learning by validating their competencies in a particular programme topic. Competency results from a learning experience that integrates knowledge, skills and attitudes to build a bridge between the university and industry, hence the widespread interest in competency development worldwide [7].

Research internships involve individual students in faculty research laboratories and provide the opportunity for one-on-one mentoring. It is essential to comprehend the costs and benefits of research experiences to enhance educational results, diversify the workforce, develop human capital and help students [8]. They participate in laboratory activities during their research internships, learning skills, including supporting arguments with evidence. The objective is to provide new knowledge focusing on innovation and discovery or to ascertain whether recent preliminary results can be repeated. These initiatives aim to improve experimental design, experimental questions or the collected data through iteration, encouraging students to reflect on the problems they are resolving and their efforts to solve them. They are structured and supervised by a mentor, with students taking on increased responsibility for the project [9].

Some studies include other skills related to the internship research programme for undergraduate students, like tolerance for obstacles, working independently and learning ethical conduct. Some research considers networking possibilities as a skill that is necessary to make the scientific experience more inclusive because these programmes prefer the best students. Mentors usually agree that undergraduate research experiences provide significant educational benefits [10].

Critical thinking and scientific thinking have been considered mental processes that open a series of learning possibilities necessary for everyone's performance in the contemporary world. Evaluating critical and scientific thinking has not always been clearly explained. There are several ways to seek to establish mechanisms to understand their development and results based on learning in vocational training [11].

Through research efforts the role of professors and researchers has been examined as trainers of university students, the latter being responsible for the intentionality behind training in these types of thinking throughout the curriculum. In addition, research efforts have focused on how critical and scientific thinking processes are triggered using graphic organisers and didactic techniques, such as problem-based learning, project-oriented learning and case studies [12].

All the above allows to understand that evaluating this type of thinking contributes not only to understanding the capacity students develop for their exercise. An additional benefit of assessing pertains to the scope of the performance levels expected in the labour market [13]. Understanding more about the conjunction of critical and scientific thinking with the formative intention driving instructional design and learning evaluation is necessary.

METHOD

This study employed the case study methodology to understand and describe the development of the thinking skills of a group of students. According to Zainal, a case study is appropriate for small-scale research with a limited time frame, space and resources, where the subjects must be observed in their environment [14]. The authors view that this type of research is suitable for situations, where it is desired to study the essential characteristics of groups with few units, as in this work. Its exploratory objective was to evaluate the performance in critical and scientific thinking skills of engineering students who interned in one of the advanced research projects at a private Mexican university.

This university is undergoing a significant change in the competency-based educational model, incorporating some innovations. For instance, students attending the 7th semester can choose to enrol in an international exchange programme, a thematic concentration or a scientific or business internship as if these experiences were normal subjects. In the research area, the internship experience is designed to develop scientific and critical thinking skills at the highest performance level throughout the curriculum.

Of 21 students asked to choose an internship field, 10 enrolled in the research internship attached to the Surface Engineering Research and Development Laboratory, where graduate students usually work. Of the total, 70% majored in nanotechnology engineering and 30% in mechanical engineering. Approximately, 50% were women and 50% were men. They were aged 21 (70%) and 22 (30%). Seventy percent received some scholarship, half regularly participated in extracurricular activities and only 20% had a full-time job.

The evaluation was performed with two instruments: 1) a critical and scientific thinking questionnaire for students; and 2) an observation rubric to be used by faculty. The questionnaire was divided into three sections: a first group of 13 statements about how a person with critical thinking acts, then another group of 14 statements about what a person with scientific thinking does. In both cases, responses were selected from a 5-level Likert scale: 1 - not necessary; 2 - somewhat necessary; 3 - not sure; 4 - necessary; and 5 - very necessary. The third section had five open questions to explore the students' perceived acquisition of the scientific process. The authors designed this instrument, which was reviewed and adjusted by five educational specialists in evaluation and psychology, who verified its consistency.

The observation rubric was designed using the university definitions of the different levels of achievement to be observed in students' development of thinking skills. It consisted of two parts: the first to assess the ability of scientific thinking, divided into seven sub-competencies (numbered 1-1 to 1-7) that integrate the dimensions of this thinking, each evaluated with four levels of performance: 1) incipient; 2; basic; 3) solid; and 4) outstanding. The second part assessed critical thinking ability, also broken down into 7 sub-competencies (2-1 to 2-7).

The survey data was collected directly from the students at the end of the semester through an on-line questionnaire. Prior legal notice of informed consent was provided. The students participated voluntarily and individually by pressing a legal authorisation button to start the instrument. All students agreed to participate. The authors filled out the observation rubric at the end of the evaluation period. The data was reviewed using descriptive statistics, supported by Excel and SPSS, version 27.

RESULTS

The results of the survey are presented in Figure 1. Here it can be seen the mean value of each student's perception of their development of critical and scientific thinking. In most cases, students perceived developing critical thinking (bold upper line) more than scientific thinking (lower dotted line). Three students considered the behaviours that allowed them to have these thinking skills as *very necessary*; another student did not share that perception about these abilities, especially critical thinking.

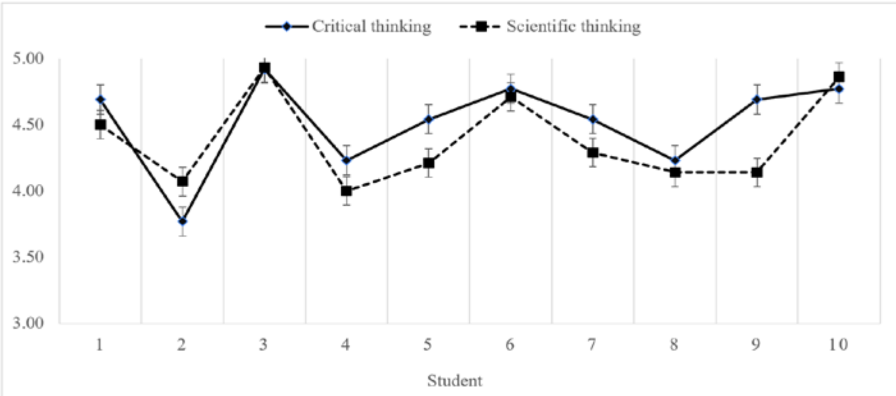

Figure 1: Survey results assessing critical and scientific thinking (individual students).

Individual responses can be compared with the group's general performance to report the variations. This makes possible to identify students above the group average and quantify their *gain* in their thinking skills compared to the rest of their classmates. It is only necessary to calculate the percentage of variation on the mean value of the group. Regarding critical thinking, this average value was 4.52 (with a standard deviation of 0.35), with five students with variations from 3.7% to 9% higher, two students practically in the average value and three that are between 6% and 16% higher below. Regarding scientific thinking, the mean was 4.39 (with a standard deviation of 0.34), with four of the five previous students with variations between 2.5% and 10.7% above the mean; the students with the previous average value here were between 2% and 4% below the group average, and the three students with the previous low variation were also below between 5% and 12% here.

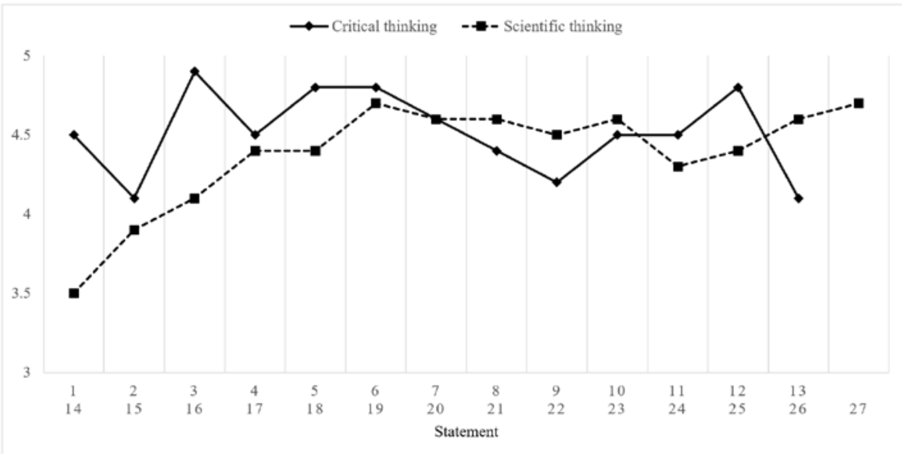

Figure 2: Survey results of critical and scientific thinking per students' statements: critical thinking, statements 1 to 13; scientific thinking, statements 14 to 27.

Figure 2 presents the critical and scientific thinking results of students' statements. Here one can identify which statements were the weakest and which were ingrained in more students' minds. In the case of critical thinking, statements 2, 9, and 13 (Establish objectives from the beginning; Avoid incurring contradictions; and Exercise autonomous thinking) are the ones the students agreed with the least. In contrast, statements 3 and 12 (Identifying reliable sources; and Supporting conclusions with objective evidence) are the ones with which they mostly agreed. In the case of scientific thinking, most of its values remained below those of critical thinking. The low values of statements 14, 15 and 16 (Being a curious person; Being a good observer of reality; and Identifying a situation to solve and ask questions) are especially noteworthy. Statements 19 to 23, which deal with experimental work and obtaining results, were consistently rated higher. The need to communicate the results of an investigation (statement 27) had the highest score.

A chi-square test and Cramer's V coefficient were run on the groups of critical and scientific thinking statements, finding five correlated thought traits shown in Table 1. It was seen as convenient to carry out some statistics that could establish if there is any association between the elements of critical and scientific thinking [15]. In addition, Cramer's V was calculated to determine the degree of the association relationship. Five factors show a correlation between the methodological sequence of the scientific procedure and its relationship with the dimensions of critical thinking that were clear to the students.

Table 1: Correlations of sub-competencies.

Critical thinking	Scientific thinking	Chi-square	Cramer's V
2. Establish objectives	24. Solve the problem	0.007	0.837
3. Identify reliable sources	20. Documentary research	0.007	1.000
4. Provide relevant data	25. Solution evaluation	0.027	0.742
9. Evidence-based position	27. Communicate the results	0.033	0.826
12. Conclusions supported by evidence	23. Comprehensive analysis of results	0.053	0.612

Regarding the open questions, the first one collected the opinion of what the students liked the most in their research internships, and the next three were metacognitive reflections on the scientific process and the acquisition of thinking skills. The answers to the first question were grouped into three categories: 70% of the students indicated that they most liked the practical experience in a laboratory, the value of *hands-on* and learning experimental techniques. Second were mentions of the freedom to propose or conduct an investigation according to the students' interests; they felt supported by the professor who advised them without dictating what to do next. Third were various aspects of collaborative work, finding answers to unknowns that transcend, and, in only two cases, developing thinking or research skills.

To the question, *How do you know that your scientific process went well?*, two students mentioned that their results were compatible with similar investigations in the literature, another two referred to the care of the methodology to obtain consistent results, and one more mentioned that the results confirmed the research objectives. For the other students, the process was not straightforward. To the question, *What strengths of the scientific process have you managed to develop?*, the students primarily recognised the acquisition of practical and technical skills. Two students mentioned the identification of problems and proposing a solution, and another mentioned the development of scientific thinking and the ability to defend their proposals. Aspects of responsibility, organisation, leadership, commitment or collaboration were also mentioned. The questions about whether they acquired scientific and critical thinking and how they proved it received affirmative answers in all cases; that is, all the students considered that they did. The verification arguments included own certainties, the identification of a problem, the methodological design to solve it, the empirical verification of ideas and theories, the openness to the debate and being critical concerning their results, among others.

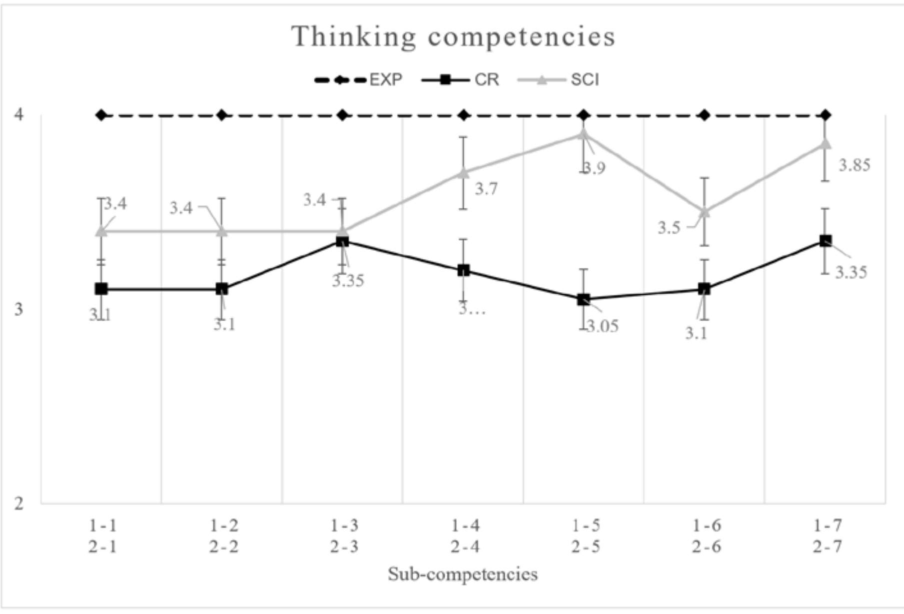

Figure 3: Results of the observation of competencies: expected values (EXP) and obtained values for critical thinking (CR) and scientific thinking (SCI) in each sub-competency.

The results of the faculty observation rubric are presented in Figure 3. The values reported are the average of the evaluation. Contrary to the students' results, the teachers believed that the best-developed competency was scientific thinking and, to a lesser extent, critical thinking. Sub-competency 1-5, which refers to collecting results correctly and relevantly, was the highest, along with 1-7 regarding the approach to a correct and comprehensive solution; this coincided with the students' perception. But the interpretation dimension (1-6) of these results was reduced, indicating that this part was problematic and cost them more work. The faculty rated asking questions about reality (1-1) and working hypotheses the lowest. In critical thinking, four sub-competencies had the lowest evaluation (3-1) and referred to making judgments, evaluating information, informed decision-making and independent thinking. In other words, the skills that constitute the dimensions of critical thinking were moderately attained.

DISCUSSION

In absolute terms, participation in a research internship is an experience that helps develop most of the dimensions of students' critical and scientific thinking, especially those that involve experimental work, and these allow them to achieve research objectives. Disciplinary engineering learning through hands-on work allows for acquiring new knowledge, while providing specialised field experience that benefits the student's future job placement. This agrees with what has been reported in other investigations [16][17].

Figure 1 and variation results allow to infer that, in general, students are more sensitive to the dimensions that comprise critical thinking than scientific thinking, something later confirmed in the results shown in Figure 2. Here it can be seen that the initial steps to developing scientific thinking invoked little interest, while those that imply the approach and development of the experimental stage attracted the most attention. This may be because, throughout their studies, students have had more opportunities to familiarise themselves with the *should be* of this competency (Identify reliable information; Use different methods to analyse; Consider different perspectives; and Support conclusions) than one implied in scientific thinking, which is more directly linked to the experimental work of the internship and not so much to a particular way of thinking. This result agrees with the work of Hendrich et al, who found that students defined scientific thinking as what happens in a laboratory and not as something valuable for posing and solving problems [18].

It must also be considered that the research internship is the first practical experience in a laboratory these students have had because they spent the previous two years in confinement due to the Covid-19 pandemic. Understandably, they feel less secure with their execution. This adverse effect of confinement on acquiring practical skills due to lack of opportunities is consistent with what other authors have commented [19].

The chi-square test provides an additional context for analysing the relationship between categorical variables, which in this case are the critical and scientific thinking components of the questionnaire. In this case, it can be observed that, according to the answers, in the students' minds there is a relationship between some of the actions that a person with critical and scientific thinking is expected to do, such as solving a problem if the objective has been previously established or providing a conclusion if a comprehensive analysis of the data has been made. Cramer's V confirms the strong association between the thinking components contained in Table 1.

Regarding the open questions, the students' perception was more focused on the practice of scientific investigation and less on the thinking skills that might be needed to do this task. This result coincides partly with that reported by Faber et al regarding the interest aroused by the topics of making discoveries and dissemination [20]. Although some students recognised the possibility of building new knowledge, which does not happen in their regular classrooms, the thinking skills required to achieve this (analysis, synthesis, critical thinking, creativity) were unclear.

The results in Figure 3 allow to deduce that teachers consider that there is a better development of scientific thinking, which attained evaluations between 10% and 18% higher than those of critical thinking. In scientific thinking, the practical skills to implement experimental methods and collect their results dominated, while those of the analytical type (problem statement and its variables and interpretation of results) seemed less clear or conclusive. In other words, higher-order thinking skills [21][22], such as analysis, decision-making, evaluation and using knowledge to generate new knowledge, were less favoured than practical work. This would also explain why critical thinking received lower evaluations.

The two instruments used in this evaluation showed their usefulness to qualitatively and descriptively assess the development of critical and scientific thinking skills in engineering students in an advanced research internship. However, their performance could be improved in experimental problem-solving if some of the statements mentioned by Kleemola et al [12] were included to align them more with the scientific approach.

CONCLUSIONS

The results of this study support the inference that students who enrol in an advanced research internship and work closely with a full-time researcher have a high chance of developing most of the dimensions that comprise scientific and critical thinking competencies practically and experientially, which helps disciplinary learning to be acquired more naturally.

One study limitation was the choice of research methodology, which focused on a particular case to understand a singular reality of a few students, which, at the moment, does not allow generalising its results. However, it does have some validity in explaining the relationship between advanced scientific work and the development of contextual thinking skills, which is progress.

Future research on this topic requires quantitative validation of the results with more students. It is necessary to study the relationship that links specialised scientific work and the development of mental abilities that contribute to the student's disciplinary learning.

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