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Research Article

Research competencies in university students: Intertwining complex thinking and Education 4.0

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ABSTRACT

Research competencies are skills that university students must develop to create and socialize scientific products during their academic live. In this research, an experience was implemented to improve the students' competency levels through its imbrication with complex thinking and the use of Education 4.0 applications, such as remote team workflow development apps, web-based virtual reality, and social robotics. The study was sequential-quantitative and descriptive. A questionnaire was applied before and after the experience to know the perception of 105 Mexican university students, later a rubric was implemented for the teacher's assessment. The results indicate that the students perceived an improvement in their research skills, however, the evaluation showed a difference between the student's perception and the teacher's regarding improvement in said skills. The experience can be scaled to other scenarios, where disruptive teaching strategies can support research skills development.

Keywords: higher education, Education 4.0, research, educational innovation, complex thinking

INTRODUCTION

The influence of Education 4.0 (E4.0) on society is unquestionable. Today applications such as virtual reality, augmented reality, data analytics, blockchain, and social robotics, among others, are essential to participating in the digital ecologies of teaching and learning (Miranda et al., 2021). This type of education requires not only digital literacy and the development of critical thinking but also putting into practice skills related to complex thinking (CT) that allow solving real-world industrial problems in the academic world using E4.0 technologies (Noguez et al., 2021). In the university, one student activity is creating and disseminating knowledge through developing scientific products (Ain et al., 2019). Developing research skills is essential in preparing graduates to successfully face the demands of scientific and technological progress (Zlatkin-Troitschanskaia, 2021). It is also necessary for them to have a critical, scientific, and systematic attitudes that triggers knowledge acquisition from methodological and theoretical bases of research, to adequately manage information, and to provoke curiosity toward evolution of the disciplines (Lambrechts & Van Petegem, 2016).

In this sense, the approach to research competencies as an object of study has been recurrent (Emelyanova et al., 2017; Ha & Press, 2019; Hegde & Karunasagar, 2021). Likewise, instruments have emerged to measure them, such as (Böttcher & Thiel, 2018; Böttcher et al., 2019; Catalano, 2017 Cobos et al., 2016).

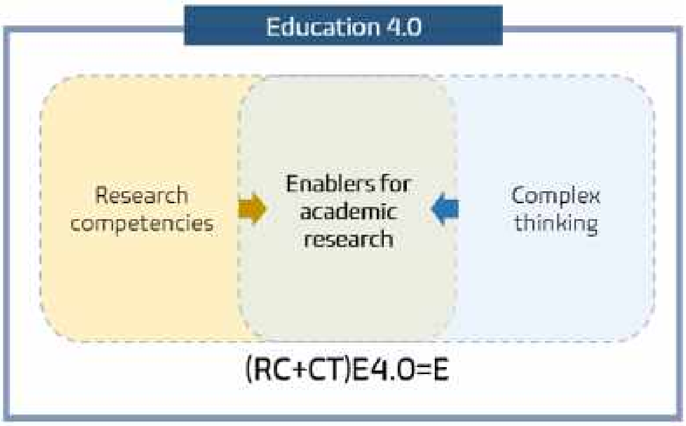

Figure 1. Enablers for academic research (Source: Authors)

There is a consensus that these assessment tools are very useful for students' performance during their university education (Calisto, 2021).

In higher education, having these competencies is critical because as students develop research skills, they will have better alternatives to solve problems that arise in their academic studies and the opportunity to apply their skills in creating new knowledge (Alsaleh, 2020; Maddens et al., 2021; Uebel et al., 2020). However, the process is complex because it requires students to strengthen skills among which communication, collaboration, and information systematization stand out, so they can formulate a research question or prepare a research proposal, which are challenging aspects of the research process (Agricola et al., 2018).

Therefore, it is necessary to create dynamics that interweave research competency (RC) with CT within the framework of E4.0. This creates enablers (Es) (Miranda et al., 2021) that allow students to generate products derived from research that helps them demonstrate the application of a scientific methodology to solve existing problems in their disciplines using multidisciplinary approaches mediated by disruptive technological environments (George-Reyes, 2023). In E4.0 environments, integrating changes in traditional training and teaching methodologies becomes imperative to equip students to develop problem-solving strategies (Gutiérrez-Martínez et al., 2021), helped by state-of-the-art technological resources (González-Pérez et al., 2022).

In this work, the relationship (RC+CT)E4.0=E shown in **Figure 1**, is explored through the design and evaluation of a pedagogical strategy to improve research skills based on the use of digital technologies 4.0, such as web-based virtual reality and teaching assisted by humanoid robots, within the guiding framework of systemic, scientific, critical and innovative thinking.

Research & Complex Thinking Competencies

Research skills are more significant in training university students because they allow putting into practice a set of abilities and skills to produce scientific knowledge in a theoretical, logical, and methodological way (Ramírez-Montoya, 2016). They also develop critical inquiry skills to access, reconstruct, and share information and promote the development of academic reading and writing (Castillo-Martínez & Ramírez-Montoya, 2021). However, it should be clarified that developing this skill is not synonymous with making the student an academic researcher; it also prepares them as future professionals with the theoretical and methodological bases to solve complex problems in the different areas of their disciplines (George-Reyes & Glasserman-Morales, 2021).

There are various contributions to understanding what research skills represent for students. Castillo-Martínez and Ramírez-Montoya (2021) mention that they are essential to developing scientific knowledge and refining skills such as observation, reading, argumentation, problematization, and socialization of research results. George-Reyes and Salado (2019) wrote that these competencies include functional strategies to select and manage a bibliography efficiently and skills to identify problems that can be resolved in academic disciplines and propose innovative solutions that allow knowledge to emerge. Thus, research should be promoted as a learning strategy (Campos & Ramírez, 2018). In this way, research skills can be understood as

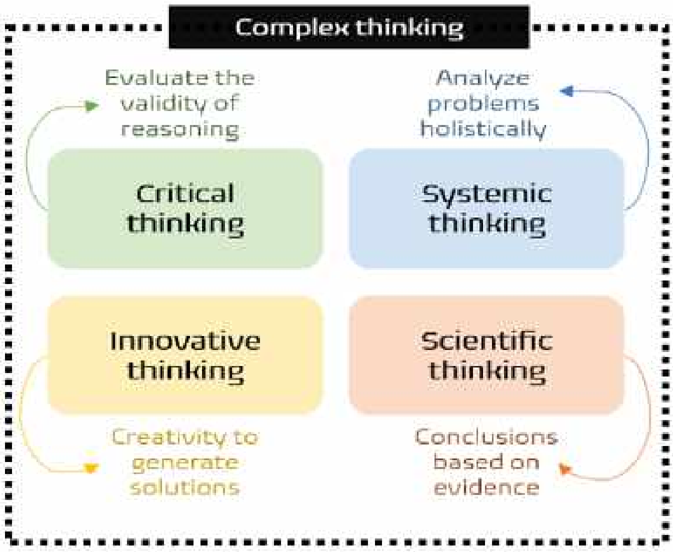

Figure 2. Complex thinking components (Source: Authors)

the ability to use scientific knowledge to identify problems and explain phenomena of academic life to draw theoretical and empirical conclusions (Paz & Estrada, 2022) that support social development, innovation, and industrial competitiveness. For this reason, the university must cultivate these competencies to successfully meet the demands of emerging educational and labor ecosystems and incorporate the technological advances of the knowledge society (Garay et al., 2021), including digital skills, as these have a positive impact on the scientific production of teachers and students (Rodríguez-García et al., 2019). This way, research skills strengthen the habit of permanent inquiry and constructing critical thinking (Mas, 2016). However, achieving a finite conceptualization of the term is complex.

Also, this regard, Potolea (2013) mentions that RC can be viewed from three approaches. The first is oriented toward analyzing the object of study and the appropriate use of scientific language. The second is constructive, critical, and ethical reflection, while the third is directed toward problem-solving and transferring real situations to academic research. The study of this competency has resulted in classifications that define them variously (Castañeda et al., 2018; Domingo et al., 2020; Griffioen, 2019; Gudmundsdottir & Hatlevik, 2018; Hamdan & Deraney, 2018). However, most of them coincide that there are at least four types of thinking that comprise them: systemic, critical, scientific, and innovative thinking (Ramírez-Montoya et al., 2021), which intervene and guide students to obtain sufficient knowledge to undertake projects that solve socially relevant problems (Cardoso & Cerecedo, 2019).

In **Figure 2** you can see the sub-competences that make up CT: the systemic one that allows us to appreciate reality in an interconnected way considering its complexity, avoiding reductionism; the critical is related to knowing how to evaluate the validity of reasoning to make logical judgments about a situation or problem; the scientist, which is based on the visualization and resolution of problems with objective, validated and standardized methods that address reality through inquiry and evidence-based research; and the innovative includes the promotion of creative capacity and the generation of disruptive proposals to develop new knowledge, and scientific thinking, which allows solving problems based on objective evidence (Patiño et al., 2022; Vázquez-Parra et al. al., 2022).

It can be stated that complex reasoning is a higher-order competence, as well as transversal to the disciplines (Ramírez-Montoya et al., 2022) and to the activities related to research, such as including sets of strategies that work to retrieve bibliography efficiently, develop skills in problem identification and suggest creative solutions that are theoretically validated (George-Reyes & Glasserman-Morales, 2021). On the other hand, a close link has been established between the formation of research skills and using digital applications of E4.0 (Briseño, 2021). In this regard, various authors have pointed out that this emerging education allows the teaching and learning process to be improved through: the use of digital technology (Fernandes et al., 2022), the implementation of online and distance learning (Miller et al., 2021), the personalization of learning (Kulkarni et al., 2020), the use of virtual and augmented reality (Prasad et al., 2021) and the incorporation of

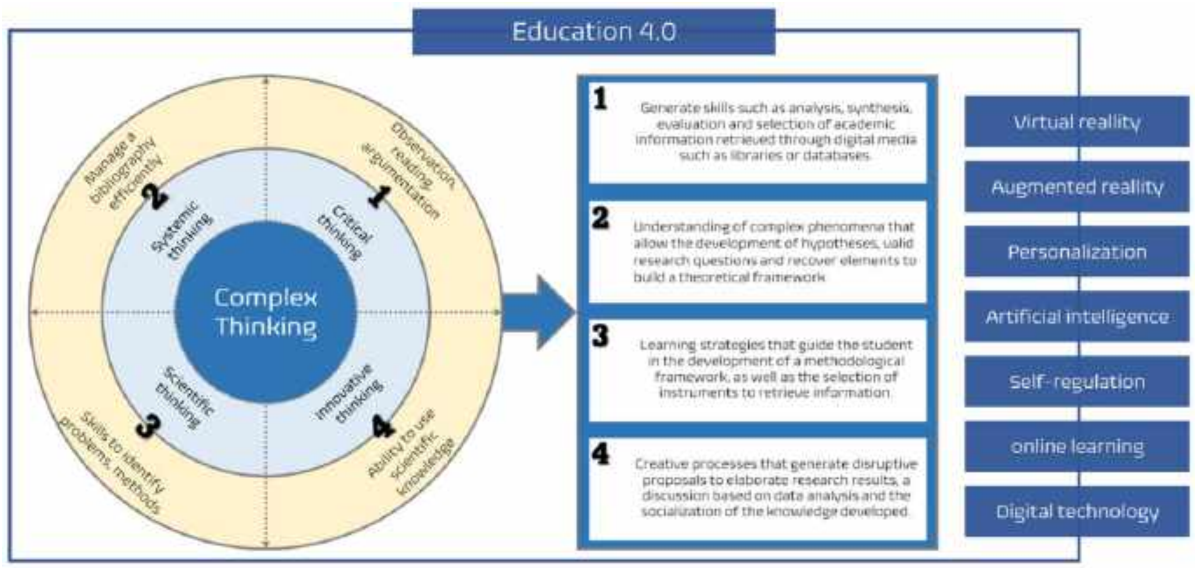

Figure 3. Imbrication Education 4.0–Complex thinking–Research skills (Source: Authors)

artificial intelligence (Masaong & Mas, 2019; Ciolacu & Svasta) and the self-regulation of learning in personal environments (Chaves Barboza et al., 2016).

Therefore, E4.0 is an approach that seeks to take advantage of digital technologies and the trends of the fourth industrial revolution to improve training processes and lifelong learning, and which has become an important resource for access learning and knowledge (Lateh, 2017; Sever et al., 2019). Therefore, interweaving research competencies and CT within the dynamics of E4.0 allows the opportunity to design teaching strategies that forge Es for students to create and disseminate represented knowledge through various types of scientific production (Ramírez-Montoya et al., 2022).

This imbrication implies ordering and systematizing methodological actions that promote knowledge management through systematic, critical, scientific, and innovative processes (Baena-Rojas et al., 2023). Disruptive technologies play a predominant role because they allow a better approach to sources of information, tools to manage scientific products, and designs of interactive and realistic learning spaces. In the latter, students' creativity is triggered in representative environments of E4.0, such as virtual and simulated reality, and immersion in ecologies, where database management and artificial intelligence are present (Suárez-Brito et al., 2022). **Figure 3** shows an approach to the interweaving of CT with some basic research skills.

This article aims to describe the assessment of university students' research skills by evaluating a scientific research product emerging from their participation in a formative experience employing CT and E4.0 applications. These included interactive web pages, augmented reality, and humanoid robots. The following research question was posed: What is the difference between the perception and the level of scaling of the investigative skills of the university students who have participated in learning experiences based on CT and using 4.0 applications?

METHOD

The research was sequential, descriptive, and based on quantitative methods (Creswell & Creswell, 2017). One hundred five university students who studied "research methodology" participated in August-December 2022 at a polytechnic university in the central region of Mexico. The distribution by gender was 73 women and 32 men. The average age was 22. The criterion for selecting the students was intentional and based on their availability to participate in the research. As a phase prior to their participation in the study, they read the privacy and personal data protection notice, likewise, they signed a letter of informed consent, which was approved by the Ethics Committee of the Interdisciplinary Research Group *Complex Thinking* from the Tecnologico de Monterrey.

Table 1. Reliability coefficients of instrument dimensions

Instrument dimensions	Cronbach's alpha	McDonald's omega
Systemic thinking	0.8440	0.8036
Critical thinking	0.8178	0.8104
Scientific thinking	0.8069	0.8300
Innovative thinking	0.8277	0.8004

The main objective of this study was to know the perception of improvement in the investigative skills of the students through the application of a pre- and a post-test and to compare it with the evaluation carried out by the teacher through a rubric. The following hypotheses were proposed:

1. **Hi.** There are significant differences between the perception of students about the scaling of investigative skills based on their perception before and after participating in a formative experience mediated by E4.0 technologies and the evaluation applied by the teacher through a rubric.
2. **Ho.** There are no significant differences between the perception of students about the scaling of investigative skills based on their perception before and after participating in a formative experience mediated by E4.0 technologies and the evaluation applied by the teacher through a rubric.

Instruments

An adaptation of the *e-complexity questionnaire* (Vázquez-Parra et al., 2022) was used to perform a pre-test and post-test. The questionnaire can be found at the link https://forms.gle/sk9oWRvY1piQeTHc9. It aimed to measure the participants' perception of their mastery of CT competency for research. Based on this instrument, a rubric was developed to measure the improvement of the students' research skills from the teacher's perspective. Before applying the questionnaire, a reliability analysis was conducted using an alternate sample of 72 students from the same university. **Table 1** shows the resulting Cronbach's alpha and McDonald's omega coefficients; both are appropriate to confirm that the measurement error does not represent reliability risks since they are above 0.8 (McNeish, 2018).

Intervention Strategy

The experience was developed in four learning modules. Before starting with module 1, a pre-test was applied to know the initial level of research skills of the students; later, the design and implementation of the learning experience were carried out by executing an activity called *production of scientific texts bootcamp*. The purpose was to strengthen learning for the development of a scientific document that contributed to the construction of a stay memory, which has the following structure:

1. definition of the problem,
2. background,
3. theoretical framework,
4. methodology,
5. results,
6. conclusions, and
7. references.

Table 2 shows that the boot camp was structured in four modules in which activities were defined so that the students could develop the document chapters. In these stages, CT was considered an articulating element to develop the skills necessary for the preparation of each chapter.

A post-test was implemented at the end of the Bootcamp to determine if students' research skills improved. A week later, the participants delivered the scientific product, which was evaluated by the teacher with the rubric derived from the *e-complexity questionnaire*, which can be accessed at the following link: https://forms.gle/ccbk5yUR93iAnZBn8

Table 2. Activities of scientific production bootcamp

Modules	Sessions	Thinking	Environment	Purpose	Activity
1	1 & 2	Systemic	Application to develop team workflows remotely through an infinite virtual whiteboard	Analyze & select a research problem by analyzing various problems in educational context	In Miro software, a design thinking strategy is applied to identify problems in educational field & analyze them & build a research problem.
2	3	Innovative	Web-based virtual reality	Refine research problem & elaborate research question & objective	Virtual campus platform is used to collaborate on design of a research question & objective.
3	4 & 5	Critical	Synchronous session in a videoconference	Explain to students how to develop a systematic literature mapping & elaborate background & theoretical framework of document	Synchronous sessions are held in which student is explained how to prepare an MSL & how it contributes to constructing background & theoretical framework.
4	6	Scientific	Asynchronous session in a videoconference	Explain to students topic of selection of methodology	Two videos are reviewed, where an assistant teacher & a humanoid robot explain topic of methodology selection.
	7		Synchronous session in a videoconference		Explanation of selection of methodology & results chapter is complemented with support of a humanoid robot.
	8		Synchronous session in a videoconference	Explain to students how to write conclusions & make references	Teacher ends experience by addressing final topics & instructions after experience.

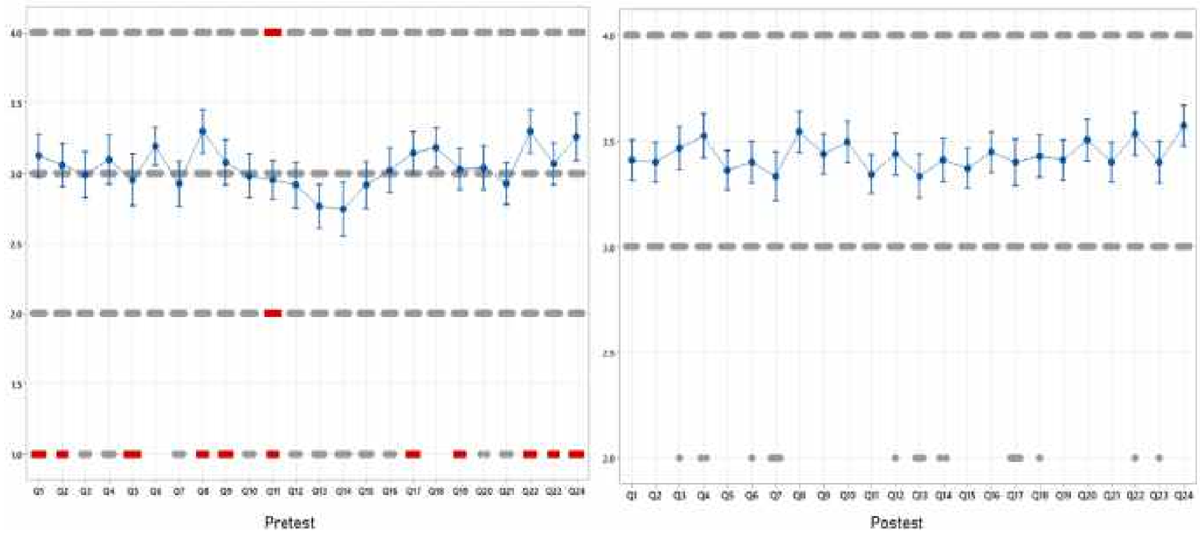

Figure 4. Comparison between pre- & post-test (Source: Authors)

RESULTS

Pre- & Post-Test

The first analysis was a comparison between the results of the pre- and post-test. **Figure 4** shows that a greater concentration of atypical values related to the option *totally disagree* occurred in the pre-test, particularly with items 1, 2, 5, 8, 9, 11, 17, 19, 22, 23, and 24, that is, the students perceived that their research skills were at an incipient level. It should be noted that item 11 (I can distinguish the structure required to write the chapters of a research project) is the one that had the most dispersion in the answers.

Post-test results indicated a lower concentration of atypical values, although there was a perception of poor development of competencies for research in some cases. These were not representative of the total

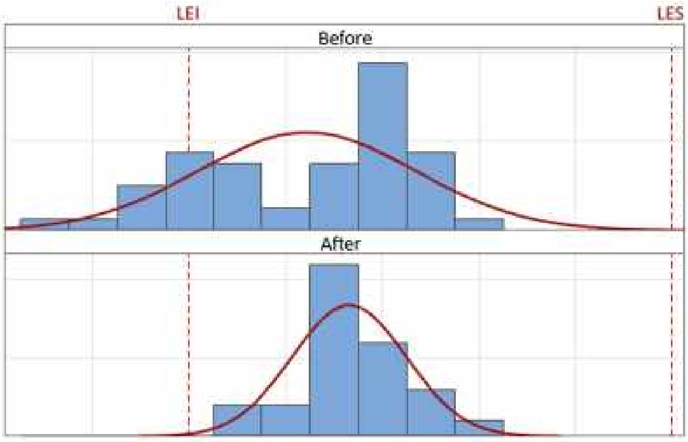

Figure 5. Values between options *agree* & *totally agree* before & after intervention (Source: Authors)

Table 3. Checking normality of distribution

Dimensions	Mean	Standard deviation	Asymmetry	Kurtosis
Systemic thinking	3.2306	0.6785	-0.2394	-0.8686
Critical thinking	3.1946	0.6781	-0.1276	-1.0946
Scientific thinking	3.2405	0.6542	-0.1414	-1.0662
Innovative thinking	3.3333	0.6785	-0.3491	-1.0296

Table 4. Analysis of t-test by dimension

Dimensions	t-test	Pre-test mean	Post-test mean	Mean difference	Tukey method (0.17)
Systemic thinking	0.0000	3.0476	3.4136	0.3660	Significant difference
Critical thinking	0.0001	2.9605	3.4286	0.4680	Significant difference
Scientific thinking	0.0002	3.0540	3.4270	0.3730	Significant difference
Innovative thinking	0.0044	3.1810	3.4857	0.3048	Significant difference

Table 5. Variance analysis

Sample	n	Standard deviation	Variance	IQ 95% for σ^2	Estimated ratio	IQ 95% relation using F	p-value
Pre-test	105	0.157	0.025	(0.019, 0.033)	5.25910	(3.573, 7.740)	0.000
Post-test	105	0.068	0.005	(0.004, 0.006)			

sample. On the other hand, **Figure 5** verifies that there was more grouping of the student's perceptions in the post-test in the response options in *agreement* and *totally agree*.

The next step was to check if the sample distribution met the normality parameters for which the asymmetry and kurtosis indicators were analyzed concerning the results of the *e-complexity questionnaire*. No extreme values were found for asymmetry (greater than |2.00|) nor kurtosis (between 8.00 and 20.00) (Bandalos & Finney, 2001), so it can be inferred that the sample adheres to a normal distribution (**Table 3**). For this reason, parametric contrast tests were applied in the quantitative study.

The following analysis consisted of performing a student's t-test for two samples. **Table 3** shows that the results indicated that the value of the general average in the post-test (M=3.4354) was higher than the pre-test (M=3.0514), indicating the perception of an improvement in research skills. Also, the correlation Pearson's test (0.6649) showed a positive linear correlation. Tukey method (T=0.17) was used to determine if there were significant differences between the pre- and post-test. As a result, differences in all the instrument dimensions were obtained. This suggests a change in how students perceived their research competencies before and after participating in the training experience. This situation is shown in **Table 4**.

Table 5 shows the variance analysis, indicating that the variance for the post-test is lower than the pre-test. Thus, after the students participated in the academic research boot camp, their perception of their research skills was closer to the average. That is, it was possible to make the students' knowledge more homogeneous, which could better support the development of a research product.

Table 6. Standard deviation analysis

	Mean	Standard deviation	IQ	Minimum	Maximum	Differs from
Pre-test	3.0514	0.1567	2.99, 3.12	2.7429	3.3619	Post-test
Post-test	3.4354	0.0683	3.41, 3.46	3.3333	3.5714	Pre-test
Rubric	3.3308	0.1183	3.28, 3.38	3.1100	3.6100	-

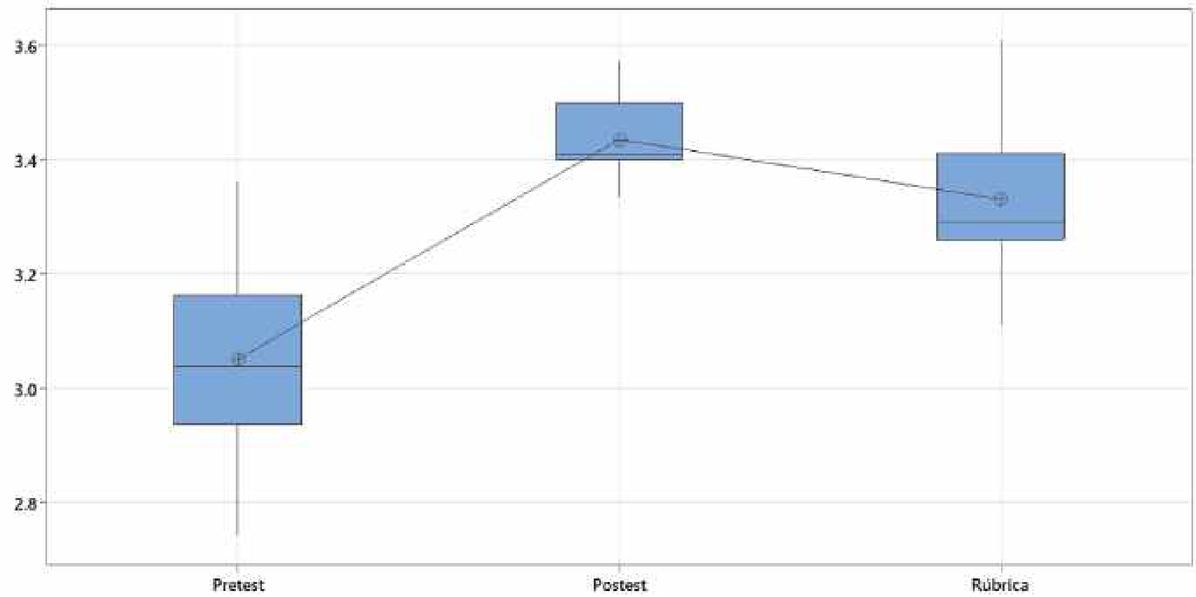

Figure 6. Graph of main effects between pre-test, post-test, & rubric (Source: Authors)

Comparison Between Pre-Test, Post-Test, & Rubric

The next study aimed to compare the students' perceptions against the teachers'. Initially, the standard deviation test ($p<0.0001$) was performed. **Table 6** shows differences in the deviations, and the variation between the pre-test and the post-test was reduced, so it can be deduced that there was an improvement in developing students' research skills. On the other hand, there was a positive change in the mean ($p=0.032$). However, the deviation increased again when the teacher evaluated the scientific product with the rubric, which suggests that the students' research skills did not improve to the levels they perceived.

When reviewing the main effects graph (**Figure 6**), it can be verified that although there was a positive difference among the students in the perception of their skills, the teacher perceived less, although positive, improvement. This indicates that the skills acquired during the students' participation in the boot camp served as Es to develop the scientific product requested as a training activity, but with less precision than they perceived.

On the other hand, in **Figure 7**, in the pre-test, the lowest averages were found in items Q13 (M=2.76) and Q14 (M=2.74), which corresponds to the *scientific thinking* dimension, while the highest mean was in item Q8 (M=3.30). In the graph corresponding to the post-test, it can be confirmed that the dispersion in the averages was reduced, the highest being the one belonging to item Q24 (M=2.57) and the lowest being Q7 and Q13 (M=3.33). However, when evaluating the scientific product delivered by the students, dispersions were again generated in the items, with the highest value being Q3 (M=3.61) and the lowest value being Q8 (M=3.11). The preceding suggests that from the teacher's perspective, the students improved significantly in identifying how the research problem variables correlate. However, they need to learn new methods to work on research projects.

Finally, the pre-test, post-test, and rubric scatter graphs were analyzed. **Figure 8** shows the slightest difference between the averages was found in item 8 (Q8=I can identify the necessary elements to formulate a question related to a research project). In contrast, in item 14 (Q14=Gender and I evaluate hypotheses to investigate problems related to research projects), the largest difference between the means was located. On the other hand, an analysis was carried out to know the effect between the participants before and after the

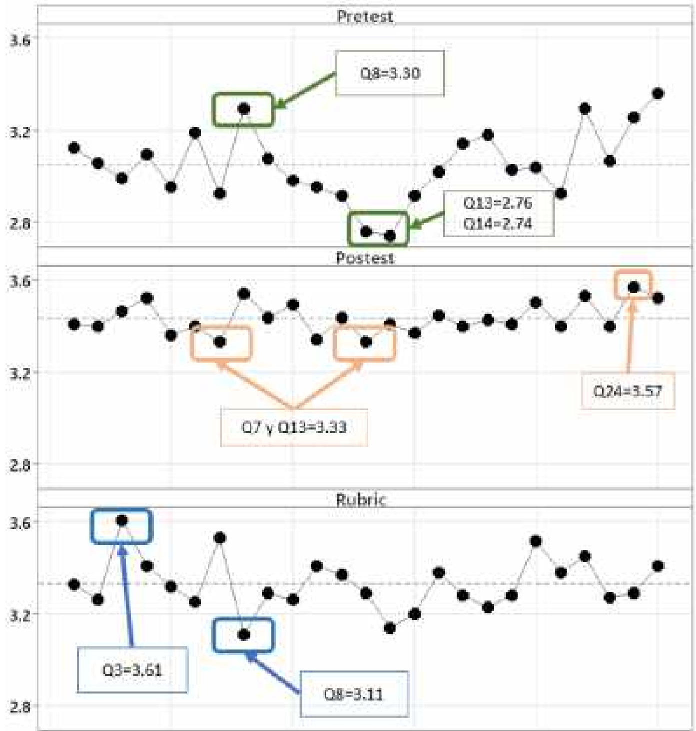

Figure 7. Plot of main effects between pre-test, post-test, & rubric (Source: Authors)

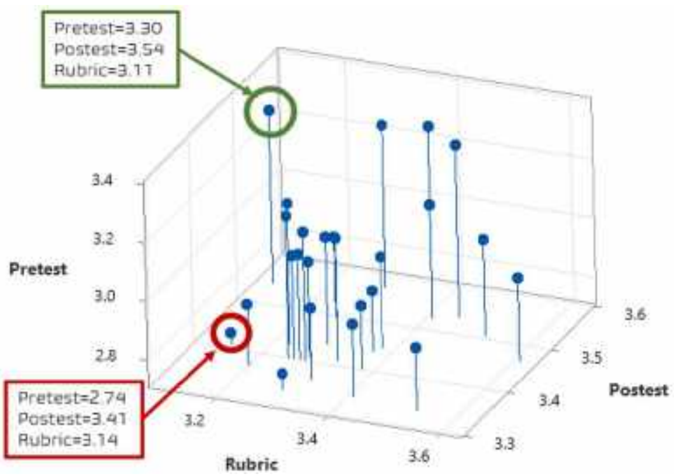

Figure 8. Scatter plot between pre-test, post-test, & rubric (Source: Authors)

intervention using Cohen's d coefficient, obtaining a value of 3.17766, which indicates a small effect, that is, the differences cannot be identified immediately. by the teacher, the above confirms the relevance of using a rubric.

DISCUSSION

The learning experience mediated by E4.0 technologies promises to be a method to strengthen the investigative skills of students. From the students' points of view, there was a significant improvement in their research skills, as shown in **Table 3**, **Table 4**, and **Table 5**.

This fact follows existing recommendations on the use of technological resources in the scientific inquiry process (González-Pérez et al., 2022). It allows us to infer that there are significant contributions in forming research skills when learning strategies using social robotics and virtual reality are implemented.

However, this appreciation is relative. In the evaluation carried out by the teacher, there was a variation regarding the perception of skills cultivated during the formative experience, as observed in **Figure 6**. The learning experience demonstrates its effectiveness in strengthening investigative skills since, despite the rigor of the rubric, progress in competencies continues to be present in the teacher's evaluation, as suggested by the results in **Figure 5**. The study suggests that the learning experience mediated by E4.0 technologies stimulate the development of investigative competencies. However, it is necessary to pay attention to other possible alternatives to work on developing skills for research projects (George & Glasserman, 2021).

Although the findings suggest that there are differences between the perception of the students and the evaluation carried out by the teacher, to verify it, it was decided to carry out the scatter diagram between the pre-test, the post-test and the rubric. As shown in **Figure 7**, the biggest difference is found in the ability to identify the elements necessary to formulate a question related to a research project. Still, as shown in **Figure 5** and **Figure 6**, it is possible to visualize an improvement in students' research skills.

In conclusion, the present study yields two findings. First, the results confirm that the use of E4.0 tools allows students to improve their abilities to identify and build research problems, build literature reviews and theoretical frameworks, as well as choose the appropriate methodology to participate in projects. research. However, there is a second finding that sheds light on the hypothesis that motivates this study, which proposes that there are significant differences between the perception of students about the scaling of investigative skills based on their perception before and after participating in an experience. training mediated by E4.0 technologies and the evaluation applied by the teacher through a rubric. This, although verified in a limited way, is in line with the results of other current studies (Toquero, 2021; Volynets et al., 2021; Wagner & du Toit, 2020).

These results indicate that research skills intertwined with CT skills and the use of disruptive technologies not only have a positive impact on the process of generating research projects, but also influence the scaling of students' perception of their skills at the time of research.

CONCLUSIONS

Improving research skills is one of the pillars of E4.0, where it is postulated to increase high capacities in university students. The study presented was based on the question: What is the level of scaling of investigative skills of university students who have participated in learning experiences based on CT and the use of 4.0 applications? The findings showed improved students' research skills development after completing the training activity.

The implications for educational practice are integrating challenging strategies to encourage the search for solutions to real problems (Salmento et al., 2021; Syzdykbayeva et al., 2015). Upgrading reasoning for complexity implies promoting critical, scientific, systemic, and innovative thinking in scenarios closer to reality (Castillo-Martínez & Ramírez-Montoya, 2021). Along these lines, it helps to implement applications of E4.0 in formative trajectories (González-Pérez et al., 2022). Some may be like the ones presented in this study (remote work, web-based virtual reality, and social robotics)

Among the implications for educational research, the focus on educational innovation stands out as an object of study, where integrating new resources and strategies can support the improvement of high-level skills, such as RC and reasoning for complexity.

The study's limitation is that it was restricted to one course with a moderate sample size (105 students). However, implementing E4.0 resources to promote high-level skills allows for seeking diversified applications that increase the impact and possibilities to continue generating knowledge of educational innovation. Global necessities and problems require citizen commitment to search for solutions for the common good. Hence this experience is an invitation to continue increasing the potential of E4.0 and improving students' high-level skills.

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Declaration of interest: The authors declare no competing interest.

Data availability: Data generated or analyzed during this study are available from the authors on request.

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