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Developing the skills for complex thinking research: a case study using social robotics to produce scientific papers

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The development of university students' skills to successfully produce scientific documents has been a recurring topic of study in academia. This paper analyzes the implementation of a training experience using a digital environment mediated by video content materials starring humanoid robots. The research aimed to scale complex thinking and its sub-competencies as a hinge to strengthen basic academic research skills. Students from Colombia, Ecuador, and Mexico committed to preparing a scientific document as part of their professional training participated. A pretest to know their initial level of perception, a posttest to evaluate if there was a change, and a scientific document the students delivered at the end of the training experience comprised the methodology to demonstrate the improvement of their skills. The results indicated students' perceived improvement in the sub-competencies of systemic, creative, scientific, and innovative thinking; however, their perceptions did not align with that of the tutor who reviewed the delivered scientific product. The conclusion was that although the training experience helped strengthen the students' skills, variables that are determinants for a student to develop the knowledge necessary to prepare scientific documents and their derived products remain to be analyzed.

KEYWORDS

higher education, research skills, educational innovation, complex thinking, scientific thinking, critical thinking, innovative thinking, social robotics

1 Introduction

One academic activity performed by university students during their professional training is to document the knowledge acquired during their studies and the formative practices for the exercise of their disciplines (Calisto, 2021), i.e., academic writing in higher education is indispensable for students to construct and externalize their learning and develop innovative solutions for the challenges of their professional fields (Navarro, 2018).

However, writing an academic text is not easy because it must meet requirements such as knowing the structure of a scientific document and the social-historical context of the subject phenomenon, having writing skills, determining the purpose of the writing, and organizing previous and emerging knowledge to yield innovative contributions to a field of study (Álvarez-Álvarez and Del Boillos-Pereira, 2015; Castelló and Mateos, 2015). Therefore, one can infer that having the basic literacy for reading and writing texts is insufficient to generate the academic writing required during university education (Maddens et al., 2021).

Academic writing translates into the development of products such as reports, observations, syntheses, and, in some cases, papers for scientific congresses or articles for journals; however, some research highlights areas for student improvement to adequately develop these products, especially the final degree projects and theses (Álvarez and Difabio, 2019). Some of the difficulties in achieving this relate to the effectiveness of teacher tutoring (Molina Jaén et al., 2020), the poor supervision of research work (de Kleijn et al., 2015), the personal affinities manifested in the teacher-student learning interactions (Sotos Serrano, 2019), the self-assessments of the writing skills to compose answers to questions or problems (Böttcher et al., 2019), and the ability to self-regulate the writing process (Romero and Álvarez, 2020).

In higher education, strengthening research skills is highly relevant, so students must have high aptitudes to solve academic problems and generate new knowledge by producing texts (Alsaleh, 2019; Uebel et al., 2020). However, scaling and improving these skills is not easy because the students must internalize a critical, scientific, and systematic attitude that triggers them to acquire knowledge about the methodological and theoretical bases of research (Ain et al., 2018) and design learning ecosystems that motivate them to learn to investigate (Hegde and Karunasagar, 2021).

In this sense, strengthening basic research skills has entailed various digital strategies, such as the design of online tutorials (Iwasaki et al., 2019), the development of argumentation strategies in virtual environments (Luna et al., 2020), the use of immersive resources and active strategies (Chura Quispe et al., 2022), gamification (Lam et al., 2018) and the flipped classroom (Yoon and Na-Young, 2022). However, few disruptive technologies, such as implementing humanoid or social robots, have been reported. This proposal is rare and novel because it offers a little-explored option of accompaniment and motivation, partly because it requires considerable resources unavailable to some educational institutions (Khaksar et al., 2019).

However, this does not prevent developing reference frameworks that guide using social robots as agents of accompaniment, tutoring, and motivation, which allows teachers to improve and scale students' research skills, including basic tasks, such as selecting and managing bibliography efficiently (George-Reyes, 2019) and knowing the structure of a scientific document, to more complex ones like formulating a research question, stating objectives and hypotheses, designing a methodology, and appropriately analyzing the results to write a discussion and conclusion, all of which are challenging aspects of the research process (Agricola et al., 2018).

Therefore, this research presents the result of implementing a training experience for university students from three countries who developed complex thinking skills to prepare scientific documents using a web page with videos of social robots deployed as content socializers. Knowledge transfer can be unidirectional in universities due to traditional expository strategies, such as teacher monologs, which offer little interaction. Therefore, it is necessary to implement innovative learning strategies to achieve the desired learning outcomes. In particular, developing research skills requires continuous interactions between the teacher and the students because their dialog leads to the construction of methodological resources essential to accessing knowledge (Lateh, 2017; Sever et al., 2019).

Research skills must be cultivated during university education because they represent the knowledge and experience necessary to disseminate scientific knowledge through text writing with theoretical, logical, and methodological articulation (Ramírez-Montoya, 2016) and apply critical inquiry strategies to access, analyze, organize, and socialize information, and encourage academic reading and writing practices (Castillo-Martínez and Ramírez-Montoya, 2020).

Developing these skills allows students to possess the theoretical and methodological foundation to identify resolvable problems using the conceptual and empirical bases of their disciplines (George-Reyes and Glasserman, 2021) and to explain phenomena of academic life through conclusions based on theory and empirical evidence (Paz Delgado and Estrada, 2022).

Similarly, students must refine skills such as observation, reading, argumentation, problematization, and socialization of an investigation's results (Castillo-Martínez and Ramírez-Montoya, 2020). So, it can be said that research skills strengthen the habit of permanent inquiry, develop critical and scientific thinking, and promote accomplishing an essential skill: writing academic texts (Mas-Torelló, 2015). The study of this ability has generated various classifications (Castañeda et al., 2018; Domingo-Coscollola et al., 2019; Griffioen, 2019); however, most converge in agreeing that skills for academic research entail the development of complex thinking (Baena-Rojas et al., 2022).

Complex thinking as a hinge notion explains various understandings of disciplinary scientific research with different academic purposes (Cruz-Sandoval et al., 2022; Ponce and López-Orozco, 2022; Sanabria, 2022; Vázquez-Parra et al., 2022; Ramírez Montoya et al., 2022a). It can be conceived as a hinge in developing knowledge, skills, competencies, and skills necessary to solve research problems in complex environments, both in the classroom and outside it (Ramírez-Montoya et al., 2022b), such as the complicated and digitalized environments of Education 4.0 and in developing academic literacy to produce texts and perform analyses (Suárez-Brito et al., 2022).

Complex thinking includes the sub-competencies of critical thinking, which involves analyzing, synthesizing, and evaluating information; systemic thinking, which facilitates analyzing and understanding complex phenomena; innovative thinking, which involves creative capacity and the generation of disruptive proposals to develop new knowledge; and scientific thinking, which allows resolving problems based on objective evidence (Ramírez-Montoya et al., 2022c; Sanabria, 2022). Thus, complex thinking in higher education involves the knowledge inherent to scientific research; it is essential to improve student learning results (Willison, 2018). Figure 1 illustrates the sub-competencies of complex thinking.

Interweaving research skills and complex thinking in the interactive dynamics of social robotics presents an opportunity to design a frame of reference that is the conceptual backbone for teaching strategies that enable students to create different types of scientific production. This imbrication involves systematic, critical, scientific, and innovative thinking, using disruptive and innovative technologies like social robotics in a preponderant role; the methodology creates interactive learning spaces that trigger creativity and motivation to obtain sufficient knowledge to undertake academic research activities (Cardoso and Cerecedo, 2019).

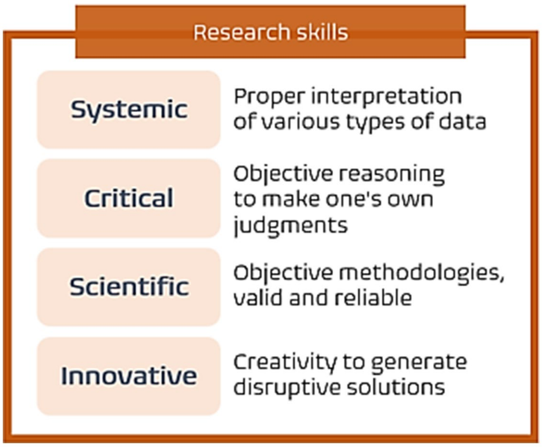

FIGURE 1
Sub-competencies of complex thinking.

1.1 Social robotics and its application in education

Robots first appeared in educational contexts as a tool to develop elementary programming skills, as models to explain the development of programming codes, or to reveal how technology works. However, in the knowledge society, humanoid robots have become accompaniers in the training of students of all educational levels (Belpaeme et al., 2018) due to the perception that they increase student motivation, commitment, and concentration (Keane et al., 2017; Pandey and Gelin, 2017).

Social robotics as a learning deployment strategy in formal and non-formal education has expanded and become a topic of interest among academic researchers (Woo et al., 2021). Thus, the tasks associated with robots have gone beyond the premise of being solely related to programming and performing repetitive or dangerous work (such as working assembly lines in factories) (Bishop et al., 2019) to explore their potential contributions to education in different ways (Chiou et al., 2020; Ceha et al., 2021). Thus, social robots in training processes represent a real possibility to solve persistent classroom challenges (Blackburn et al., 2021).

Notably, social robots are semi-autonomous entities that interact and communicate with humans, observing social behaviors and rules defined for a role in human-machine interactions (Alemi et al., 2017). In this regard, two types of profiles have developed in the context of learning: (1) that of the passive robot as a tool to motivate and interest the students and (2) the robot as an active participant in learning situations through social interactions, such as communication and content dissemination.

In the second case, the robot can be a learning partner, supporting students by explaining and directing training activities (Ekström and Pareto, 2022). Robots of this type are distinguishable by their technical and social dimensions. The former relates to their physical form, particularly their humanoid morphology and their degree of autonomy. The second relates to their level of interaction and social integration in the teaching context, i.e., the extent to which it can operate independently without immediate human intervention. Figure 2 shows the technological-social model of social robotics, and the roles robots can assume in education (Guggemos et al., 2020).

In this regard, research in the field of education converges in pointing out that the presence of a robot in teaching has a positive effect on learning outcomes (Alemi et al., 2020; Ponce and Ramirez, 2022), motivating students to participate in academic activities (Calvo et al., 2020). However, little research has been conducted in higher education (Donnermann et al., 2020; Erden, 2020; Donnermann et al., 2022).

We need to mention some relevant aspect about using social robotics:

- First, interaction with robots capable of social and emotional behaviors can significantly increase student interest and motivation. Unlike traditional teaching methods, robots can provide a more immersive and participatory learning experience, which can be particularly effective in capturing students' attention and sustaining it over time. This increased engagement can lead to a deeper understanding of scientific concepts.
- Second, social robotics allows for experiential and experimentation-based learning. Students not only learn about theory, but also can apply what they have learned in practice by designing, programming, and interacting with robots. This hands-on approach helps develop problem-solving and critical thinking skills, which are essential for scientific thinking.
- Third, robots as teaching tools can be adapted to the individual needs of students.
- Fourth, working with robots fosters teamwork and communication skills. Robotics projects often require students to work in groups to solve complex problems. This not only improves their ability to work as a team, but also teaches them how to effectively communicate their ideas and solutions to others (Lopez-Caudana et al., 2022).

1.2 Research objective

The objective of this study is to explore and analyze the impact of using NAO robots as pedagogical tools on the development of skills to write scientific documents among university students in Colombia, Ecuador and Mexico. It seeks to identify how interaction with these robots can foster critical research skills, including critical thinking, problem solving, experimental design and data analysis, and determine the differences in the effectiveness of this methodology in the three educational contexts. The research question that accompanies this study is: How does the use of NAO robots in the university context contribute to the development of skills to write scientific documents in students from Colombia, Ecuador and Mexico, and what are the differences in the effectiveness of this pedagogical strategy in the three countries?

2 Method and instruments

2.1 Method

This study employed the case study methodology, which is acceptable among social science researchers (Lai and Roccu, 2019). It

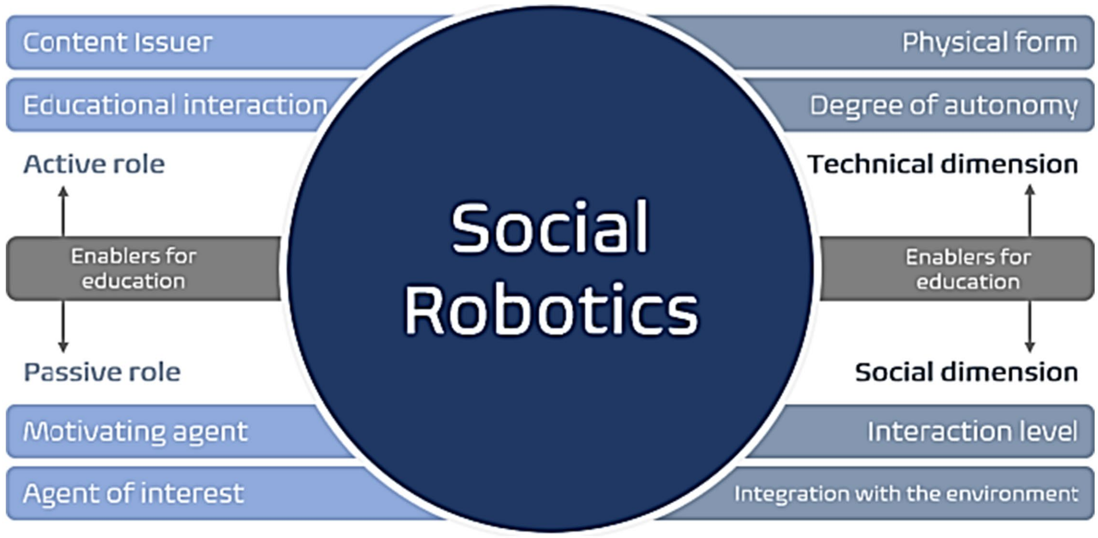

FIGURE 2
Technological-social model of a robot in education.

TABLE 1 Reliability coefficients of the instrument's dimensions.

Instrument dimension	Cronbach's Alfa	McDonald's Omega
Systematic thinking	0.8440	0.8036
Critical thinking	0.8178	0.8104
Scientific thinking	0.8069	0.8300
Innovative thinking	0.8277	0.8004

entails collecting and analyzing data related to a specific group or groups that share common goals (Nooll and Guerra, 2021). In quantitative studies, conducting this type of research requires interpreting numerical data to understand and describe a social phenomenon (Qiang et al., 2022); on the other hand, the research is sequential (Creswell and Creswell, 2017).

The hypotheses that emerged from the case study are as follows:

> *H1:* There are significant differences in the quality of students' scientific paper production, depending on the scaling (improvement) of their complex thinking competency before and after participating in a formative digital training experience mediated by social robotics.
>
> *H2:* There are no significant differences in the quality of students' scientific paper production, depending on the scaling (improvement) of their complex thinking competency before and after participating in a formative digital training experience mediated by social robotics.

2.2 Participants

Participants in this study were students from three universities: the Universidad Bolivariana of Ecuador (*n* = 15; 5 men, 10 women); the Universidad Sergio Arboleda of Colombia (*n* = 14; 6 men, 8 women); and the Universidad Politecnica Metropolitana de Hidalgo in Mexico (*n* = 22; 10 men, 12 women). In total, 51 people participated (21 men and 30 women), all of them were graduate students about to graduate, none of them had experience in the production of scientific texts. It should be noted that during the training experience they were asked to write in Spanish.

All had in common the commitment to write a document with the characteristics of a scientific article to obtain their professional degrees. In addition to the students, a tutor with experience producing academic texts such as articles and speaking at conferences participated (Google Scholar h index = 13).

2.3 Instrument

The instrument used to perform a pretest and posttest was an adaptation of the *ecomplexity* questionnaire (Vázquez-Parra et al., 2022), which measures the participants' perceived development of complex thinking competency. This research adapted the questionnaire to measure systemic, critical, scientific, and innovative thinking sub-competencies when writing scientific papers. From this instrument, a rubric was also designed so that the tutor of the training experience could evaluate the quality of the final product delivered by the students. Before applying the questionnaire, the authors analyzed reliability using an alternate sample of 92 students. Table 1 shows the calculated Cronbach's alpha and McDonald's omega coefficients, which are appropriate to confirm that the measurement error does not risk the instrument's reliability (McNeish, 2018).

3 Implementation of the training experience

A purpose-built methodology facilitated the development of the case study called i4C (identification, ideation, invention, information for complexity), which represents the imbrication of design thinking, an accepted method for developing didactic strategies (Kremel and Wetter Edman, 2019) and complex thinking, which promotes a deeper and more holistic understanding of reality (Ramírez-Montoya et al., 2022b), aiming to strengthen the learning of a specific topic or skill systematically (Vázquez-Parra et al., 2022). The experience occurred in four learning modules placed on an open-access website, where students found various study materials, including videos in which social robots offered explanations of various topics (see Figure 3).

The authors created the open-access website (https://sites.google.com/tec.mx/research4c/). Before starting module 1, the authors applied a *pretest* to know the participants' initial level of research skills. At the end of the experience, a *posttest* measured participants' perceived improvement. Finally, the tutor applied a rubric to objectively evaluate the quality of the documents students delivered at the end of their course participation. To carry out the implementation of the activities for writing the scientific document, the i4c pedagogical method (identify, ideate, invent and report) was used (George-Reyes et al., 2023), in Figure 4 shows the learning path, and Table 2 describes the activities in each module.

4 Results

4.1 Pretest and posttest comparison

A comparison of pretest and posttest results by country was performed. Figure 5 shows that in the pretest, the highest concentration of outliers occurred among students from Ecuador, particularly items 9, 10, and 11 in the questionnaire that describe the development of scientific thinking (Q9: I can distinguish the structure required to write the chapters of a research project; Q10:I can identify the structure of a scientific paper; and Q11: I can select the research method necessary to produce a scientific paper). These outliers indicated the need to adjust the training experience to level the participants' knowledge in these subjects.

Among students from Colombia and Mexico, the atypical data found were insignificant because only item 18 had a significant dispersion (Q18: I review my research to comply with ethical guidelines before sending it to a recipient, Mexico), which means that emphasis should fall on teaching all participants the principles and moral standards that should guide the scientific research process to ensure that the scientific documents they produce respect the rights and well-being of all parties involved.

FIGURE 3
Video presentation of a topic by a social robot.

Once the training experience finished, the *posttest* results shown in Figure 5 indicated a lower concentration of outliers in students from Ecuador, reflecting improved knowledge acquisition on the part of some students regarding how to organize information for research (Q5: I can organize information to solve research problems efficiently and effectively.) It can be inferred that among Colombian students, there was a disparate learning (Q1. I can identify the criteria needed to determine a research problem; Q6: I can solve research problems by interpreting different types of data; Q16: I can identify false arguments in a text or speech; Q19: I critically evaluate the solutions derived from a research problem); i.e., some participants perceived that after the experience they have more understanding than others regarding scientific research. The above invites subsequent studies to understand the reasons for this situation (Figure 6).

Regarding the difference in the means of the students of the three countries in the pretest and the posttest, Figure 7 shows that in the posttest, participants achieved higher scores in perceived complex thinking competency to develop scientific documents, particularly Mexico, where a more significant increase in critical thinking was perceived: the Mexican students had a pretest mean of 2.80 and 3.50 posttest (a difference of 0.7). Notably, Colombia students had no change in perceived systemic thinking competency (mean = 3.32 pretest and posttest), although there were positive differences in the other sub-competencies of complex thinking.

Regarding the analysis of variances, Table 3 shows that the variance (of standard deviation or dispersion) for the *posttest* was lower than the *pretest*, which indicates that after the students participated in the training experience, their perceptions were closer to the average, i.e., the students' knowledge was more homogeneous than before, which could indicate improving the development of a research product by better applying systemic, scientific, creative and innovative thinking.

On the other hand, the results confirm a low concentration of outliers in the posttest. In general, the concentration of responses fell to a minimum mean of 3.22 and a maximum of 3.69, representing an improvement in the perception of complex thinking competency. Figure 8 shows no equivalence between the pretest (mean = 3.0013; sd = 0.8122) and the posttest (mean = 3.4293, sd = 0.0132).

4.2 Comparison of complex thinking sub-competencies

The first analysis to know the differences between the sub-competencies of complex thinking consisted of performing a *student's t*-test on the two samples. The results indicated that the value of the overall mean (complex thinking) in the *posttest* ($M = 3.4293$) was higher than the *pretest* ($M = 3.0013$), indicating an improvement in research skills; also the Pearson correlation (0.5005) indicated a positive linear correlation. Tukey's method ($T = 0.24$) determined if there were significant statistical differences between the *pretest and posttest,* finding differences in all sub-dimensions of complex thinking. Table 4

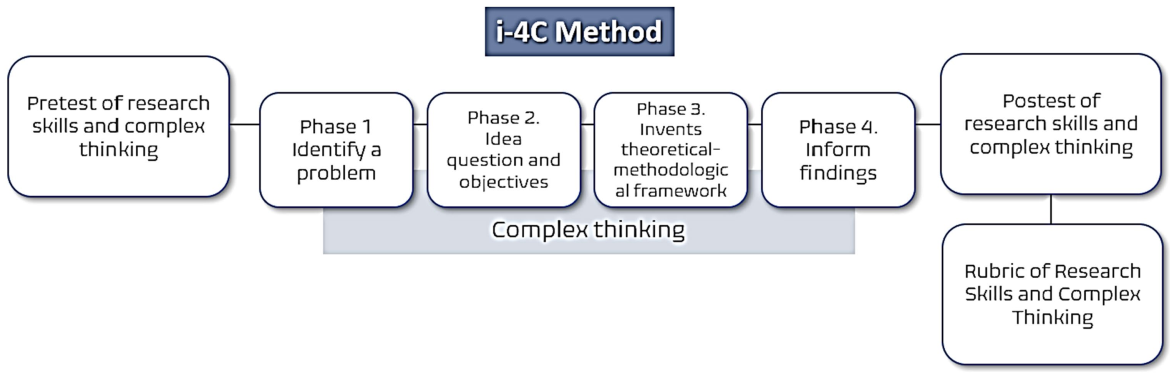

FIGURE 4
Learning path and assessment.

TABLE 2 Activities developed during that training experience.

Modules	*i*4C Method	Thinking	Activity	Deliverable document	Time
1	Identification	Systematic	Analyze and select a research problem by identifying and analyzing various problems present in the educational context.	Introduction Diagnostic	60 m.
2	Ideation	Critical	Refine the research problem. Elaborate the research questions and objectives through case study analysis.	Research problem Research objectives Research questions	120 m.
3	Invention	Scientific	Elaborate a systematic literature review map to know the theoretical and empirical approaches to the research problem.	Systematic literature mapping Framework Methodology	120 min.
4	Information	Innovative	Report the results creatively using various statistical tools.	Results Discussion Conclusion References	120 m.

shows a positive change in how students perceived their research competencies before and after participating in the training experience.

Subsequently, a fixed-effects ANOVA was performed to check for significant statistical differences in student participation in the training experience between the *pretest* and the *posttest*. Table 5 shows the attainment of a critical value (Fc) of 4.0517 and an F coefficient of 82.2308, which infers that there are differences because the value of $F > \text{Fc}$. This also indicates that one can *reject* hypothesis H2: There are no significant differences in the quality of students' scientific paper production, depending on the scaling (improvement) of their complex thinking competency before and after participating in a formative digital training experience mediated by social robotics.

4.3 Comparison between pretest, posttest, and rubric

The second research objective was to compare the students' perceived sub-competencies in complex thinking to elaborate a scientific document vs. the perception of the tutor who guided the experiment. This involved comparing the pretest and posttest scores against the rubric used by the tutor to assess the works presented by the students. The standard deviation test ($p < 0.0001$) was performed to begin. Table 6 shows significant differences in the standard deviations, and that the deviation between the pretest and the posttest diminished, so one can deduce that there was an improvement in the formation of students' research skills. However, the deviation changes when the tutor evaluates the scientific product, suggesting that the students' evidenced skills do not coincide with their perceptions.

On the other hand, the graph of main effects (Figure 9) shows that although there is a positive difference in the perception of skills improvement to elaborate a scientific document, the tutor's perception contrasts with the students'. This indicates that the skills acquired during the training experience were enablers to develop the requested scientific product, but there are still areas of opportunity to improve.

Figure 10 shows that the dispersion in the means between the pretest and the posttest diminished. When the tutor evaluated the scientific product, the dispersions were not pronounced, suggesting that from the tutor's perspective, the students improved significantly in their skills to prepare scientific documents by developing complex thinking. However, it is necessary to identify areas of opportunity to improve the quality of the products delivered.

Finally, Figure 11 presents the correlation graph of the *pretest*, *posttest,* and *rubric* analysis. The strongest correlation was between the posttest and the rubric (0.573), indicating that the perceptions of the

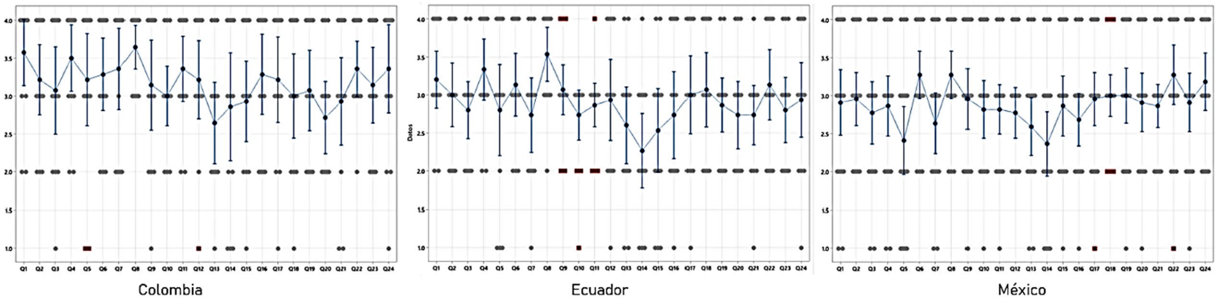

FIGURE 5
Comparison of values obtained in the pretest.

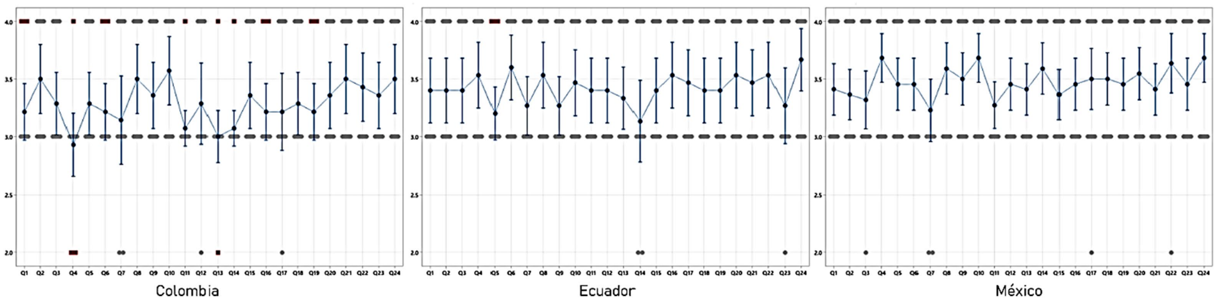

FIGURE 6
Comparison of values obtained in the posttest.

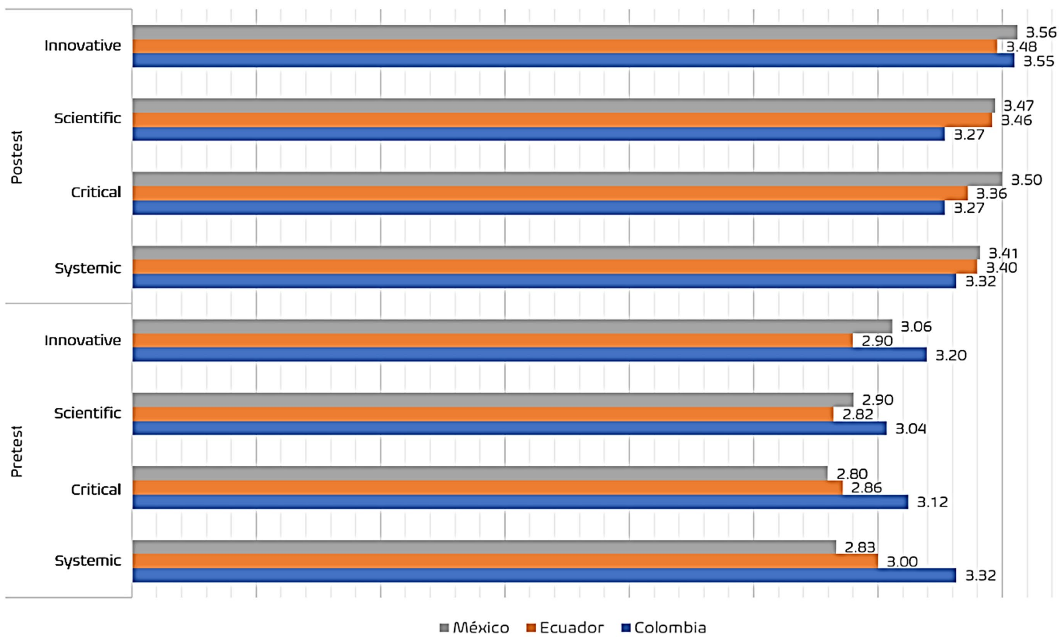

FIGURE 7
Comparison of means in Colombia, Ecuador, and Mexico.

students and the tutor regarding the abilities of the former to develop scientific documents applying complex thinking were close. The weakest correlation was between the pretest and the rubric (0.397), highlighting the significant difference between the students' perceptions of their skills before the training experience and the tutor's perception of the final product.

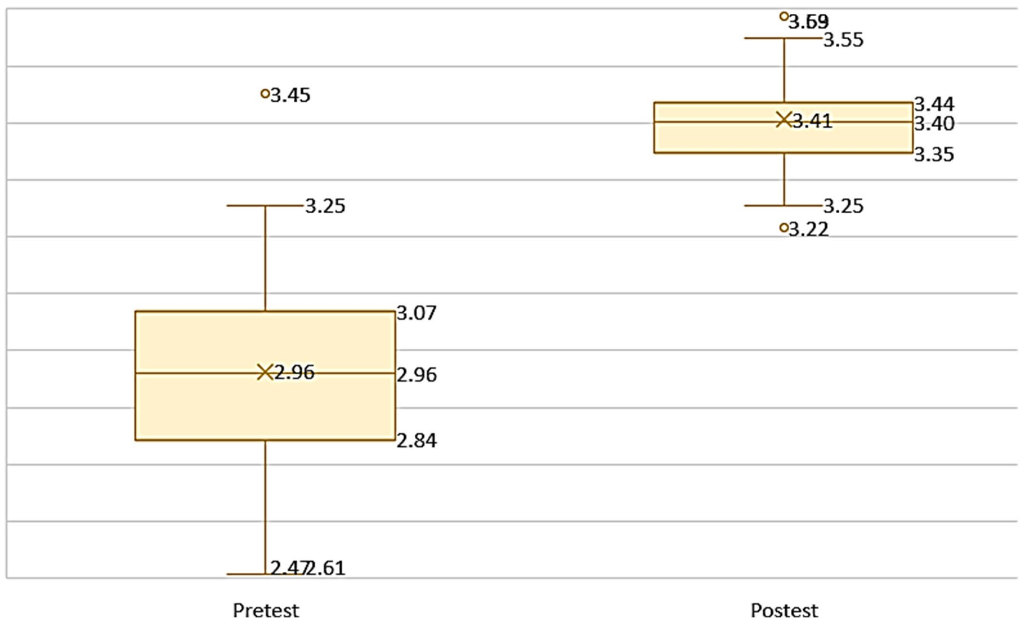

FIGURE 8
Boxplots showing differences in the pretest and posttest means.

TABLE 3 Variances analysis.

Sample	*N*	SD	Variance	CI 95% for σ^2	Estimated ratio	CI 95% using Bonett	CI 95% using Levene
Pretest	24	0.217	0.047	(0.161, 0.317)	2.14134	(1.305, 3.438)	(1.335, 3.837)
Posttest	24	0.101	0.001	(0.077, 0.146)			

TABLE 4 Analysis of the *t*-test by dimension (sub-competency).

Dimension	*t*-test	Pretest mean	Posttest mean	Difference in means	Tukey method (0.24)
Systematic thinking	0.00089	3.04103	3.4119	0.37082	Significant difference
Critical thinking	0.00306	2.92401	3.4225	0.49848	Significant difference
Scientific thinking	0.00023	2.97872	3.4202	0.44149	Significant difference
Innovative thinking	0.00602	3.10904	3.4628	0.35372	Significant difference

TABLE 5 One-factor ANOVA analysis.

Variance source	Sum of squares	Degrees of freedom	Quadratic mean	*F*	*p*-value	Fc
Between the groups	2.3530	1.0000	2.3530	82.2308	0.00000	4.0517
Inside the groups	1.3163	46.0000	0.0286		0	7
Total	3.6692	47.0000				

5 Discussion

Through a case study, the researchers could show it was possible to improve the students' perception of their skills to produce scientific documents. The researchers established different analysis parameters using validated and reliable instruments, and the results were favorable. Qiang et al. (2022) showed that collecting data for corresponding analysis can measure or verify the performance or validity of a hypothesis. In this proposal, the analyses of several quantitative factors provided evidence that social robotics can enable the generation of scientific papers on students' perception.

The comparison between the pretest and post-test indicated improvement in students' perceptions of their ability to perform scientific writing in the three countries. Figure 5 compares the differences between the different countries but allows us to observe the general improvement in perception. Kremel and Wetter Edman (2019) discuss how design thinking is an appropriate tool for the implemented didactic strategy. Using complex thinking and its

TABLE 6 Standard deviation analysis.

	Mean	SD	Minimum	Maximum	Differs from
Pretest	2.9632	0.21675	2.4710	3.4510	Posttest and rubric
Posttest	3.4060	0.10122	3.2157	3.6275	Pretest
Rubric	3.4581	0.06398	3.3526	3.5680	Pretest

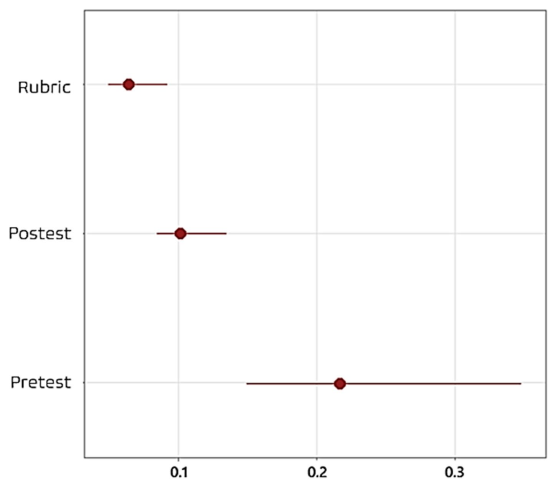

FIGURE 9
Graph of main effects between pretest, posttest, and rubric.

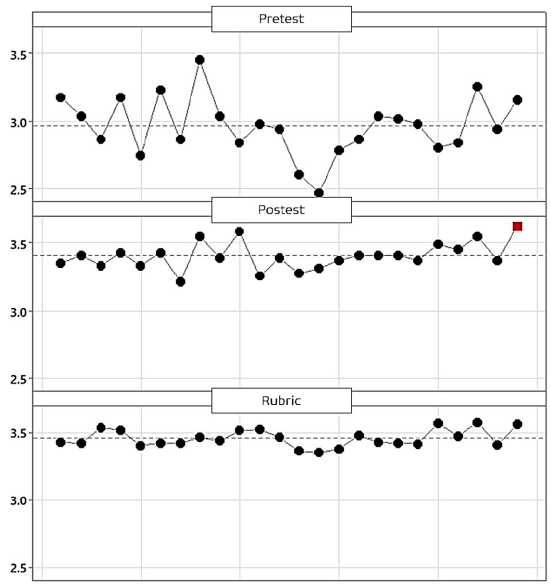

FIGURE 10
Graph of main effects between pretest, posttest, and rubric.

sub-competencies enhances the ability to write scientific documents, with social robotics mediating the process.

The students' perceptions of the formative modules of complex thinking varied by nationality. Figure 7 presents noteworthy changes in the national perceptions pretest and posttest, showing different means in each sub-competency of complex thinking, as discussed in Baena-Rojas et al. (2022). Each type of thinking (systemic, scientific, innovative, and critical) helped to improve the students' perception of their improvement in preparing scientific documents. The perceptions are of different magnitudes but support the central hypothesis: By scaling complex thinking upward, students can improve the production quality of scientific documents.

Some differences were found among the students in the countries analyzed, and although there was an improvement in the overall results as shown in Figure 7, in the case of Colombia the improvements were less noticeable than in the other two countries. According to Castillo-Martínez and Ramírez-Montoya (2020), it is pertinent to find a scale to measure the perception that university students have about the mastery of research competencies to develop academic literacy and it is intended that this scale can be transferred to other university contexts in addition to the environment in which it was applied for validation. In this study conducted we can observe that the measurements are relevant by presenting adequate instruments, even though the environments could be different.

Developing a better research product is possible by applying the sub-competencies of complex thinking. When analyzing the variances of the pretest and the posttest (Tables 3, 4), one observes a more homogeneous knowledge among the students, even showing no equivalences between both tests (Figure 8), i.e., the differences in means are significant. This type of analysis is characteristic of variables and their analyses, as is the ANOVA. This experience shows significant differences in the quality of producing a scientific document when using social robotics as an enabling technology within the framework of complex thinking.

6 Conclusion

Students can generate better scientific documents when applying complex thinking and embracing motivating and disruptive technologies during the educational process. This work analyzed different scenarios involving students from different countries, finding positive results in their perceptions of their systematic, creative, innovative, and scientific thinking skills.

A training experience with pre- and post-analyses measured students' perceptions of the proposed objective. The research employed validated analysis tools and an instrument adapted to this scenario; it took as a hinge the conceptual framework of complex thinking competency while using social robotics as an enabling technology to accompany the educational practice. Both the competency development and the technological tool contributed to achieving the primary hypothesis that the participants' perceptions of their skills in preparing scientific documents would improve.

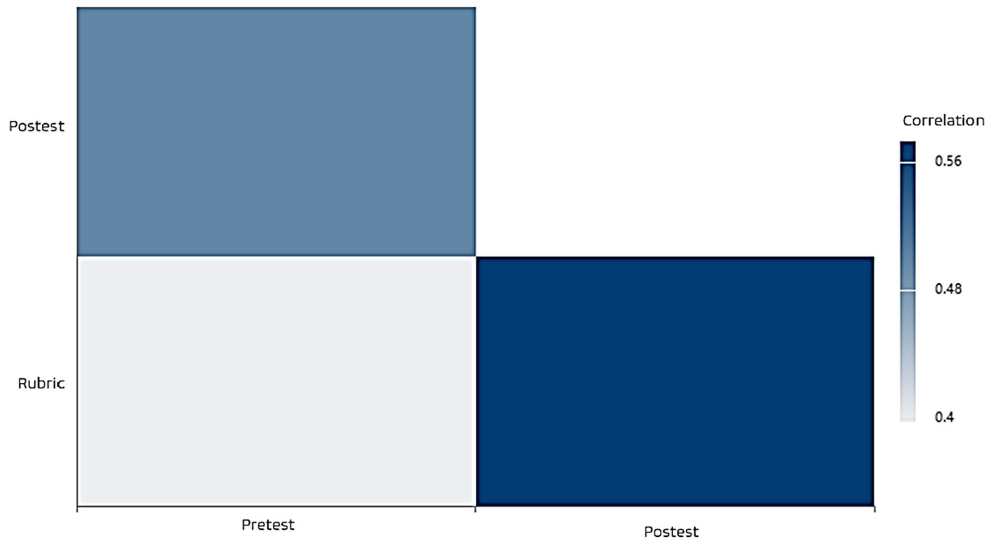

FIGURE 11
Correlation graph between pretest, posttest, and rubric.

A contrasting result was the students' perception and the tutor's opinion of the quality of the scientific document deliverable. The pretest was compared with the rubric of the expert evaluators, yielding significant differences, which gives rise to a more detailed analysis to understand why this difference in results; however, it is remarkable that the students felt more confident in their ability to generate scientific writing.

Also, social robotics introduces students to emerging technology and computer science from an early age, preparing them for future careers in STEM (science, technology, engineering and math) related fields. This hands-on, future-oriented approach to education is critical to developing a skilled workforce that can navigate tomorrow's changing technological landscape.

In short, robots as educational tools offer a multifaceted approach to learning that can overcome the limitations of more traditional teaching methods. By providing more interactive, hands-on, and personalized learning experiences, social robotics has the potential to transform education and foster the development of scientific thinking more effectively.

Although artificial intelligence through social robotics is a technology characteristic of Education 4.0, it is necessary to carry out longer studies to verify that it is a tool that yields lifelong learning. While it is true that it is motivating and engages students, it must be administered gradually and effectively to achieve better results. A relevant point to consider is to have a better knowledge of the academic contexts of the participants to obtain better or at least somewhat more reliable results. It would be necessary to carry out more accompanying studies for the students in terms of their academic environment, as well as the temporality of the application of the technological tools, in this case, humanoid robotics.

The limitations of this study focus on the fact that, although social robots have a high potential to improve educational processes, it is still necessary to conduct studies that delve into their relationship with the development of complex thinking. Regarding the novelty effect, it is valid to note that robots can lose their effectiveness over time due to familiarity, which poses challenges for their long-term implementation.

On the other hand, it is equally necessary to complement this research with empirical studies that explore HRI (Human-Robot Interaction) in order to generate a clear understanding of how these can contribute significantly to specific educational needs, in the same way, in Future implementations must overcome the use of videos where recordings with robots appear, since although they provide a clear visual representation of how social robots work and apply complex thinking in different situations, it is not achieved between students and robots a degree of interaction that helps them better understand abstract concepts.

Finally, it is noteworthy that, from the teachers' point of view, students achieved better results in writing scientific documents thanks to complex thinking and its components. Using an enabling technology like humanoid robotics in a relevant, transcending framework, such as complex thinking and its sub-competencies, confers a valuable and exciting methodology to improve students' skills in science, innovation, and knowledge acquisition.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

EL-C: Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing – review & editing. CG-R: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. RA-M: Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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