Critical and Creative Thinking in a Cooperative Learning Context with Emerging Technologies in Maths A

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Abstract

The development of critical and creative thinking skills is a priority in contemporary curricula and is essential for the holistic education of students and their preparation for the challenges of the 21st century (OECD, 2019). In this context, active methodologies such as cooperative learning, combined with the integration of new technologies, are effective in promoting more dynamic, reflective and creative learning environments (Gillies, 2016). This communication presents an account of a pedagogical experience undertaken as part of a doctoral project aimed at understanding the impact of cooperative learning on the development of critical and creative thinking skills in Maths A students. The research, which was quantitative in nature and had a quasi-experimental design, involved 119 students from six STEAM (Science, Technology, Engineering, Arts and Mathematics) classes. The results presented in this communication refer specifically to two classes in the experimental group (n = 51). The activity was planned according to the collaborative method Pairs Think Aloud to Solve Problems (Silva et al., 2019) and consisted in solving, in heterogeneous collaborative groups of four, a geometric task that involved programming, in the Python language and on a graphing calculator, a path on the Cartesian plane based on vectors and angles. The graphing calculators were connected to the TI-Innovator Rover robot, which physically executed the paths on sheets of graph paper, allowing visual analysis of the accuracy of the proposed solutions. Data collection included direct observation, written productions, individual reflections and multimodal records (photographs and videos). Progress was observed in critical thinking (interpreting information, analyzing, explaining, evaluating, and synthesizing strategies) and creative thinking (fluency, flexibility, and originality in idea production) (Catarino., 2019). The cooperative method used promoted the verbalization of reasoning and individual and collective responsibility, while the integration of technology facilitated the contextualized application of mathematical content. It can be concluded that the combination of cooperative learning and new technologies can be an effective pedagogical strategy to promote critical and creative skills, in line with the Essential Learning for Mathematics A (DGE, 2018) and the Profile of Students Leaving Compulsory Education (Martins et al., 2017).

Keywords: *cooperative learning, critical and creative thinking, emerging technologies, Maths A*.

1. Introduction

In the current educational scenario characterized by complexity, technological acceleration and the unpredictability of social and professional challenges, the training of students with critical and creative thinking skills is a priority in contemporary educational systems. The ability to critically analyze information, formulate reasoned hypotheses, argue logically and propose original and appropriate solutions to solve complex problems is widely valued in international curriculum guidance documents, such as the OECD Learning Compass 2030 (OECD, 2019), and national ones, such as Essential Learning (DGE, 2018) and the Profile of Students Leaving Compulsory Education (Martins et al., 2017).

In this context, several studies have shown that the use of active methodologies, with special emphasis on cooperative learning, significantly favors the development of higher-order cognitive skills, by promoting the active participation of students in the construction of knowledge, the sharing of ideas, reasoned argumentation and critical reflection (Gillies, 2016; Johnson & Johnson, 2018). When articulated with the integration of emerging technologies in pedagogical environments, these methodologies enhance motivation, creativity and the contextualized application of school knowledge (Voogt et al., 2018; Lopes et al., 2020).

In the case of the subject of Mathematics A, a central component of the scientific training of students in the STEAM (Science, Technology, Engineering, Arts and Mathematics) areas in secondary education in Portugal, the requirement to simultaneously develop logical rigor and creativity represents

a constant challenge (Leikin, 2009; Mann, 2006). Recent research points to the hypothesis that cooperative environments, underpinned by open-ended and technologically mediated tasks, promote deeper conceptual understanding, greater affective engagement, and the stimulation of divergent thinking (Kaufman & Glăveanu, 2021; Silva et al., 2019).
This article aims to describe a pedagogical experience developed within the scope of a PhD project in Educational Sciences. The intervention was carried out in a classroom context with students from the 11th grade of the Mathematics A subject, using the cooperative learning method *Pairs Think Out Loud to Solve Problems*, solving geometric problems with the use of emerging technologies, namely programming in Python language, computers, graphing calculators and programmable robots.
The reasoned analysis of the experience aims to understand how the articulation between cooperative learning and emerging technologies can constitute an effective pedagogical strategy for the development of critical thinking skills, namely interpretation, analysis, explanation, evaluation and synthesis and creative thinking, fluency, flexibility and originality in the production of ideas, in the teaching of Mathematics A. This research thus aims to contribute to a reflection on innovative pedagogical practices in the teaching of Mathematics, aligned with a critical, creative and technologically integrated vision in the teaching and learning process.

2. Theoretical Framework

2.1 Critical and Creative Thinking in the Teaching of Mathematics

Critical thinking and creative thinking are skills widely recognized as essential in the twenty-first century, particularly in the field of mathematics education, where students are required not only to reproduce algorithmic procedures, but also to mobilize analytical reasoning, creativity, and the ability to solve complex problems (Facione, 2011; OECD, 2019; NCTM, 2000). Critical thinking, in this context, encompasses the rigorous interpretation of information, the logical analysis of situations, the reasoned explanation of procedures, the evaluation of hypotheses, and the synthesis of coherent solutions (Lopes et al., 2021). In turn, creative thinking translates into fluency in the creation of ideas, flexibility to consider different approaches, and originality in formulating innovative responses (Kaufman & Glăveanu, 2021).
In the teaching of Mathematics A, these skills play a central role, as students are often faced with tasks that require a deep conceptual understanding, generalization skills and reasoned decision-making (Sullivan et al., 2016). In this way, the development of critical and creative thinking should be intentionally promoted through pedagogical practices that challenge students to explore multiple solutions, to justify their reasoning and to critically reflect on the processes adopted (Bolear, 2016).
Research has shown that learning environments that foster inquiry, questioning, and experimentation — namely through open-ended problem-solving — provide favorable conditions for the mobilization of higher-order thinking (Lopes et al., 2021). In these contexts, the articulation between critical and creative thinking is particularly effective in promoting meaningful learning and building meaningful mathematical knowledge (Schoenfeld, 2016).
Additionally, the implementation of cooperative work strategies in mathematical contexts promotes the joint construction of knowledge, encouraging the verbalization of reasoning, the critical comparison of approaches and mutual evaluation among peers. These interactions not only facilitate the consolidation of mathematical concepts, but also promote metacognitive learning, encouraging the simultaneous development of critical and creative thinking in collaborative and contextualized contexts (Silva et al., 2019; Johnson & Johnson, 2018; Gillies, 2016).

2.2 Cooperative Learning

Cooperative learning has been widely recognized as an effective active methodology in promoting the development of students' cognitive, social, and emotional competencies (Johnson & Johnson, 2018; Gillies, 2016). This approach is characterized by an intentional organization of interaction between students, promoting positive interdependence, individual and group responsibility, stimulating interaction preferably face-to-face, the development of interpersonal and small group skills, and group assessment or reflection on group work (Gillies, 2016; Johnson & Johnson, 2018).
Due to its formal structure, cooperative learning favors the creation of inclusive learning environments in which active listening, argumentation, respect for diversity, and empathy are central dimensions (Lopes et al., 2020; Gillies, 2016). The literature has shown that these interactions facilitate the joint

construction of knowledge, self-regulation, and metacognition, contributing to more meaningful and lasting learning (Lopes & Silva, 2022).
In the teaching of Mathematics, cooperative learning has shown promising results in promoting conceptual understanding, problem solving and joint construction of knowledge (Boaler, 2015). The verbalization of reasoning, the justification of strategies and the critical evaluation of solutions proposed by peers are practices that enhance the simultaneous development of critical and creative thinking (Silva et al., 2019).
Among the various cooperative methods used in the educational context, *Pairs Think Out Loud to Solve Problems* stands out, particularly for the teaching of Mathematics. The implementation of the method requires that, in the first phase, students organized in heterogeneous groups of four elements, work in pairs, verbalizing their ideas, strategies and reasoning while solving a common task. This moment of dialogue promotes the clarification of concepts, the identification of doubts and the constructive confrontation of perspectives for the resolution of learning tasks. In a second phase, the two pairs, in each cooperative group, share the ideas previously discussed and critically analyze them, refining solutions, synthesizing ideas and making reasoned decisions (Silva et al., 2019; Catarino., 2019).
Research has been reinforcing that the methods promote not only the active involvement of students, but also the development of higher-order thinking skills, essential in the current educational context and aligned with the guidelines of curricula oriented towards the development of critical and creative thinking skills (Martins et al., 2017; OECD, 2019).

2.3 Emerging Technologies as Mediators of Learning

The integration of emerging technologies in the teaching and learning process has been affirmed as a transformative element of educational contexts, enabling more interactive, meaningful, and student-centered practices (Voogt et al., 2018; Czerkawski & Lyman, 2015). These digital resources favor the reconfiguration of conventional pedagogical models, traditionally based on the unidirectional transmission of content, towards more collaborative environments oriented towards solving real problems.
In the teaching of Mathematics, tools such as programmable graphing calculators, computers, programming languages, and robotic devices have shown high potential in strengthening mathematical reasoning and understanding abstract concepts (Aldon & Trgalova, 2020; Christine, 2017). Its use allows students to experiment with solutions, test hypotheses, observe the effects of their decisions, readjust strategies in real time, and critically reflect on the processes carried out, promoting more investigative and contextualized learning (Araya, 2022; Christine, 2017).
When integrated into cooperative learning dynamics, these digital tools enhance the shared construction of knowledge, mathematical communication and co-responsibility among the elements of the group. Technological mediation, in these contexts, acts as an enhancer of peer interaction, promoting students' cognitive and emotional involvement, creativity in problem-solving, and verbalization of reasoning (Voogt et al., 2018). Such conditions are conducive to the development of critical thinking evidenced in the analysis, evaluation and justification of strategies and creative thinking, manifested in the generation of original, flexible and effective solutions to the problems that students face.
The literature shows that the articulation between active methodologies and emerging technologies contributes to educational practices that are more aligned with the challenges of the twenty-first century, by integrating disciplinary knowledge, digital literacy and higher-order thinking (Mishra & Koehler, 2006; OECD, 2019; Christine, 2017). This pedagogical approach, by incorporating technology intentionally and critically, not only reinforces students' autonomy and logical reasoning, but also boosts the development of critical and creative skills that are indispensable in today's educational landscape.

3. Methodology

The present research is an integral part of a PhD project in Educational Sciences, in which a quantitative methodology with a quasi-experimental design was adopted, involving an experimental group and a control group. The total sample was composed of 119 students from the 11th grade of schooling, distributed in six classes of a Portuguese public school, in STEAM (Science, Technology, Engineering, Arts and Mathematics).

The pedagogical intervention was implemented throughout the second and third periods of the 2023/2024 school year, covering three classes as an experimental group. The educational action focused on the development of critical and creative thinking skills, through the implementation of cooperative learning, in which some of the cooperative activities were carried out using emerging technologies. The data analyzed in this communication refers to the implementation of an activity with technological integration, carried out in two 50-minute classes, and only the results obtained in two classes (n = 51) of the experimental group are presented.
At the beginning of the experiment, the students were organized into heterogeneous cooperative groups of four elements. The criteria of heterogeneity used in the constitution of the groups were gender and school performance, based on the average of two evaluation questionnaires applied during the first school term that focused on mathematical concepts and procedures. This strategy has ensured a balanced cognitive diversity that has favored productive and inclusive interactions.
The learning activity presented in this communication was structured based on the cooperative method *Peers Think Out Loud to Solve Problems* (Silva et al., 2019), which consists of a teaching strategy that promotes the structured verbalization of reasoning and the collaborative construction of solutions. The proposed task consisted of the elaboration of a program in Python language that would allow the execution of a geometric path in the Cartesian plane, using vectors and angles. Each cooperative group consisted of four students, initially organized in two pairs. In the first phase, in each cooperative group of four elements, each pair analyzed the task statement and explored possible resolution strategies. Afterwards, the peers shared their ideas with each other, discussing the proposals and consolidating a joint solution at the team level. The final code, after being written on the computer, was introduced into the TI-84 Plus CE-T Python Edition graphing calculators and connected to the TI-Innovator Rover robot, which physically performed the route on a sheet of scenery paper previously placed on the classroom floor. This practical visualization allowed us to validate the accuracy of the programmed solutions and establish connections between different mathematical representations: symbolic, algorithmic and geometric.
Data collection followed a multimodal approach, using direct observation grids, students' written productions (including codes, schemes and calculations), individual reflections after the activity and photographic and videographic records. The data analysis adopted a categorical content methodology, based on previously defined categories for critical thinking (interpretation, analysis, explanation, evaluation and synthesis) and for creative thinking (fluency, flexibility and originality in the production of ideas).

4. Results and Discussion

The proposed task was structured in five fundamental steps: (1) reading and interpretation of the statement, (2) identification of geometric constraints and formulation of hypotheses, (3) planning of the route and programming in Python language, (4) validation of the solution using the TI-Innovator Rover robot and (5) individual reflection on the process and the results obtained. Each of these stages is designed to intentionally mobilize skills associated with critical thinking, including interpretation, analysis, explanation, evaluation and synthesis, as well as creative thinking, which encompasses fluency, flexibility and originality in the production of solutions. The articulation between the structure of the task and the analytical objective of the research is reflected in the organization of the following subchapters (4.1 to 4.4), where the results are discussed in the light of the defined theoretical categories and the empirical evidence collected.

4.1 Critical Thinking Skills: Interpretation, Analysis, Explanation, Evaluation and Synthesis

The resolution of the task required the students to carefully read and carefully interpret the statement, recognizing the restrictions imposed (absence of crossings, prohibition of right angles, total coverage of the area, return to the initial position and fixed number of segments). This phase mobilized the ability to interpret the statement rigorously and to accurately identify the conditions and constraints of the problem, with a direct impact on the planning of the route.
During the work in pairs, the students performed geometric analyses, testing mentally and on paper several possibilities of vector composition (Fig. 1). Their notes demonstrate reasonable explanations of the choices made, namely in the selection of angles and the direction of the vectors to respect the criteria of the task.

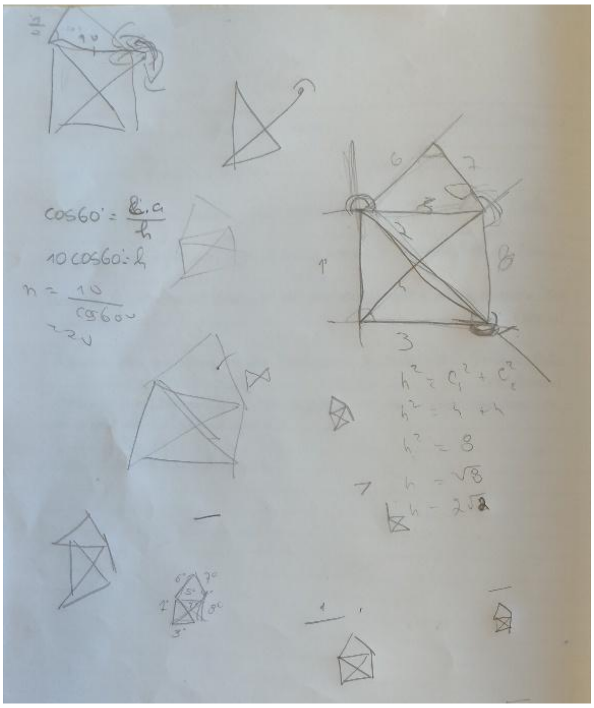


Fig. 1. Vector plane with students' justification notes, demonstrating geometric analysis and argumentation.

In the programming phase, on the computer, a critical evaluation of the implemented strategies was observed, because whenever the execution of the route in the robot revealed deviations or errors, the students proceeded to reformulate the code (Fig. 2), reevaluating the commands and adjusting parameters based on the reading of the results and the comparison with the initial plan.

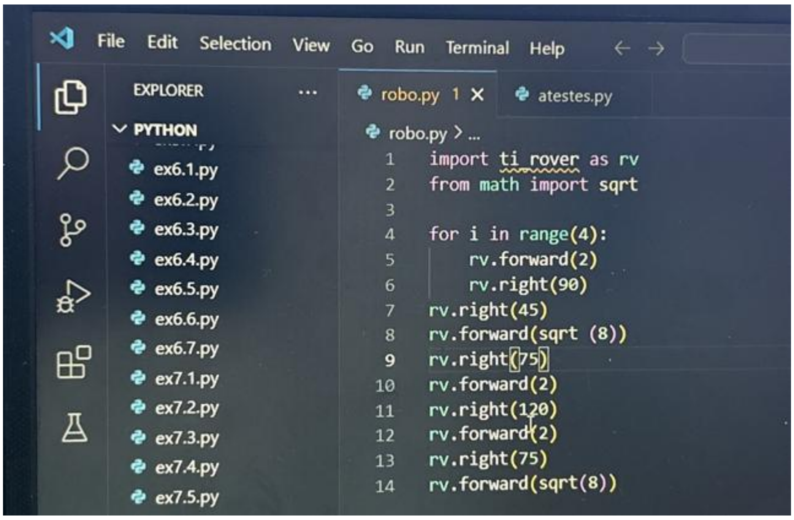
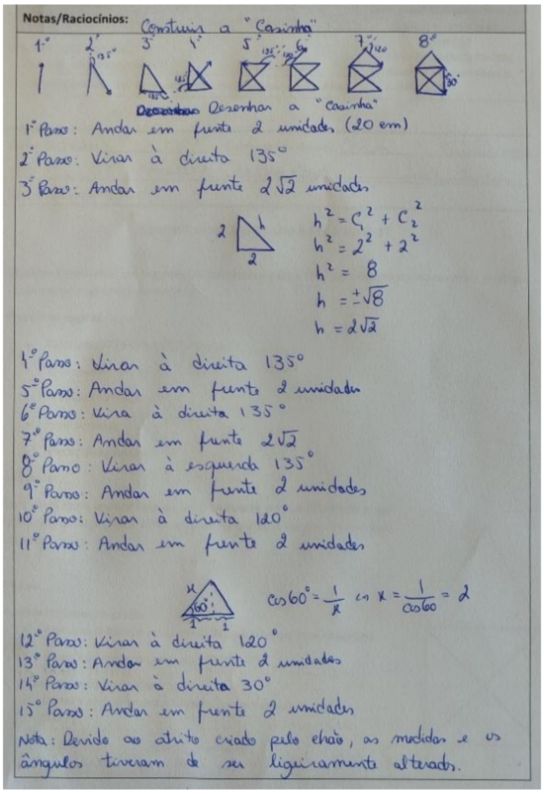


Fig. 2. Python code with rephrasing annotations made after incorrect execution.

Finally, the synthesis of ideas emerged in the extended group discussion, when the pairs confronted the different strategies and decided together which was the most accurate, clear and efficient solution to program and validate the geometric path (Fig. 3).
This moment of sharing and confrontation of ideas between peers made it possible to deepen mathematical argumentation and the collaborative construction of a more robust solution, the result of the collective synthesis of individual contributions.


Notas/Raciocínios: Construir a "Casinha"

Desenhar a "Casinha"

1º Passo: Andar em frente 2 unidades (20 cm)

2º Passo: Virar à direita 135°

3º Passo: Andar em frente $2\sqrt{2}$ unidades

$h^2 = c_1^2 + c_2^2$

$h^2 = 2^2 + 2^2$

$h^2 = 8$

$h = \pm\sqrt{8}$

$h = 2\sqrt{2}$

4º Passo: Virar à direita 135°

5º Passo: Andar em frente 2 unidades

6º Passo: Vira à direita 135°

7º Passo: Andar em frente $2\sqrt{2}$

8º Passo: Virar à esquerda 135°

9º Passo: Andar em frente 2 unidades

10º Passo: Virar à direita 120°

11º Passo: Andar em frente 2 unidades

$\cos 60° = \frac{1}{x} \Leftrightarrow x = \frac{1}{\cos 60} = 2$

12º Passo: Virar à direita 120°

13º Passo: Andar em frente 2 unidades

14º Passo: Virar à direita 30°

15º Passo: Andar em frente 2 unidades

Nota: Devido ao atrito criado pelo chão, as medidas e os ângulos tiveram de ser ligeiramente alterados.

Fig. 3. Collective record resulting from the intra-group discussion, evidencing the process of synthesis of strategies and the consolidation of the final solution.

Communication between the elements of the group, focused on the explanation of the justifications, allowed the critical validation of the initial proposals and encouraged the making of reasoned decisions.

4.2 Creative Thinking: Fluency, Flexibility and Originality

Creative thinking was evidenced in the diversity of strategies proposed for the route layout (Fig. 4). Fluency manifested itself in the multiplicity of ideas generated during the planning phase, with different groups exploring varied combinations of angles and vector directions.

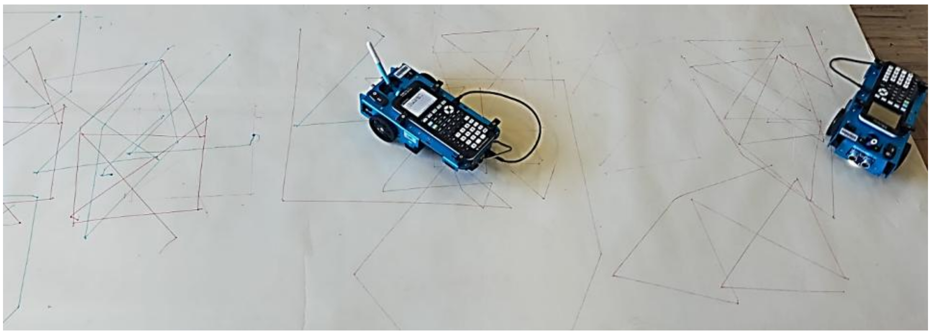


Fig. 4. Different proposals for geometric layouts elaborated by the cooperative groups.

Cognitive flexibility was revealed in the students' ability to adjust strategies whenever faced with errors or unforeseen events during the execution of the course (Fig. 5). The reformulation of the paths demonstrated openness to new approaches and adaptation to practical experience, promoting creative thinking applied to mathematical problem solving.

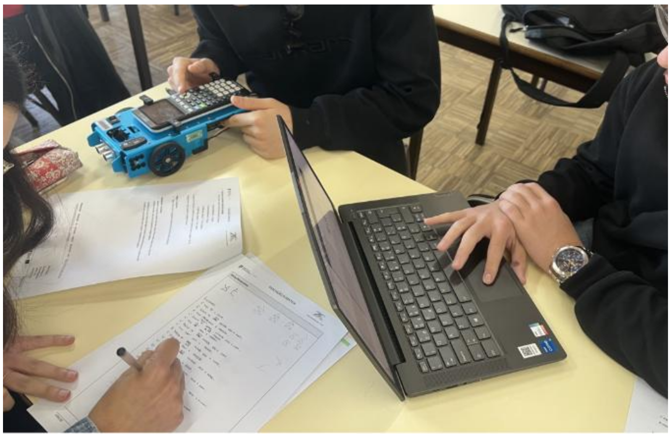


Fig. 5. *Cooperative group reformulating Python code after incorrect execution, illustrating cognitive flexibility in reformulating strategies.*

Originality stood out in the creation of unconventional paths (Fig. 6), respecting the criteria of the task but incorporating aesthetically differentiated or unexpected solutions, revealing divergent thinking.

Fig. 5. *Cooperative group reformulating Python code after incorrect execution, illustrating cognitive flexibility in reformulating strategies.*

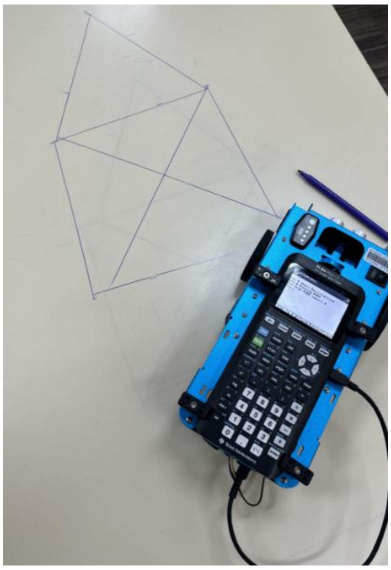


Fig. 6. *Route prepared by a cooperative group with a creative and efficient structure.*

The graphic productions prepared by each cooperative group revealed a creative mastery of the mathematical tools and concepts involved, while allowing students to visualize and adjust their reasoning in real time. The originality of the solutions was also observed in the way the groups attributed aesthetic or symbolic meaning to the routes, giving identity to the final product.

4.3 Impact of Technologies and Cooperative Work

The use of digital tools, namely the Python programming language, the TI-84 Plus CE-T graphing calculators and the TI-Innovator Rover robot, had a significant impact on the students' involvement in the learning process. The multimodal records show high levels of concentration, collaboration and enthusiasm on the part of the students during the completion of the task (Fig. 7). The visualization of the route through the movement made by the robot allowed the establishment of connections between different forms of representation: symbolic (vectors), algorithmic (code) and geometric (physical path), promoting more meaningful and integrated learning.

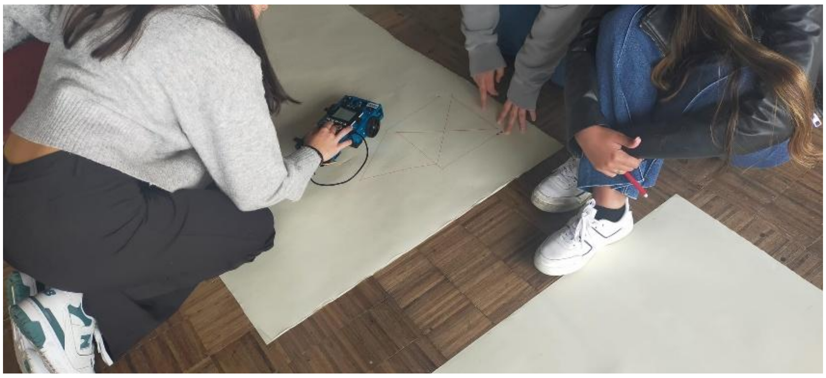


Fig. 7. Robot rides on backdrop paper, with active observation of students.

At the same time, the *Pairs Think Out Loud to Solve Problems* method contributed decisively to the structured verbalization of reasoning, the analysis of hypotheses in real time and the collaborative adjustment of strategies (Fig. 8).

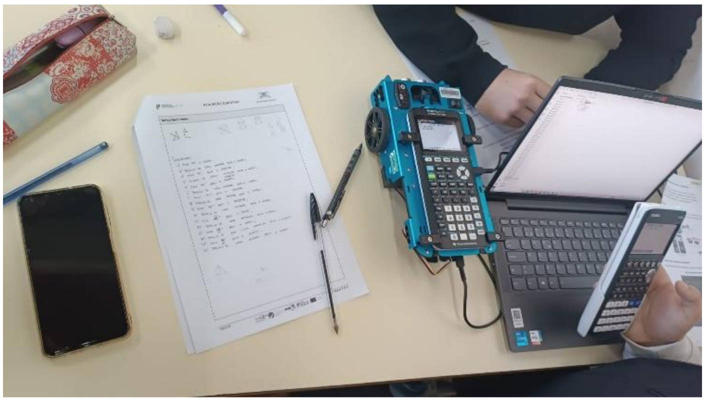


Fig. 8. Cooperative group discussing solutions and fine-tuning the code collaboratively, during the final validation process.

This cooperative method fostered a culture of active listening and shared accountability, in which error was seen as an opportunity for cognitive and social growth.

4.4 Valuing Cooperative Work in the Voice of Students

The individual reflections showed the students' appreciation for the dynamics of group work, highlighting mutual help, shared responsibility and mutual enrichment as central aspects of the cooperative experience they lived.
One of the students highlighted: *"The most positive aspect is the support regarding the difficulties, because when I have any doubts, my colleagues help and try to explain in the best possible way and, sometimes, they even do it in a more simplified language."*
Other testimonies reinforce this perception of collective benefit, mentioning *"The mutual help between group colleagues to complete the activity with the best possible results"* and *"the fact that I work in a group I think helps people a lot, both to work as a team and to discuss the different ways to solve the various challenges."*
These reports suggest that cooperative learning promoted not only cognitive skills, but also attitudes of active listening, empathy and mutual accountability. Cooperation was mentioned as essential for the success of the task and as an opportunity for interpersonal growth: *"The most positive aspects of our group are cooperation, respect for everyone's ideas and responsibility. We worked well together, listened to each other and each member fulfilled their part of the task."*
This recognition of the importance of cooperation by the students themselves reinforces the pedagogical relevance of cooperative learning, confirming its potential to foster transversal skills valued in current educational contexts.

5. Conclusions

The results obtained throughout this pedagogical experience corroborate the relevance of the theoretical framework outlined, in which the importance of the articulated development of critical and creative thinking skills in the discipline of Mathematics A is established (OECD, 2019; Facione, 2011; Kaufman & Glăveanu, 2021). The articulation between the use of the cooperative method *Peers think aloud to Solve Problems* and emerging technologies proved to be pedagogically and didactically effective, validating the assumptions pointed out by authors such as Johnson and Johnson (2018), Lopes and Silva (2022), Gillies (2016) and Voogt et al. (2018).
The cooperative method *Peers Think Out Loud to Solve Problems* promoted positive interdependence, deep cognitive engagement and the joint construction of mathematical knowledge in highly complex contexts. This approach is in line with previous research that highlights the role of cooperation in promoting argumentation, critical reflection, and creativity (Silva et al., 2019; Lopes et al., 2020).
At the same time, the integration of emerging technologies - Python programming, the use of computers, graphing calculators and educational robotics - allowed a practical application of curricular content and fostered logical reasoning, problem solving and digital literacy. The visualization of physical pathways reinforced metacognitive processes, allowing self-regulation and the analysis of one's own mistakes, fundamental aspects in critical learning processes (Voogt et al., 2018).
The categories of analysis applied to data collection - interpretation, analysis, explanation, evaluation and synthesis for critical thinking; fluency, flexibility and originality for creative thinking - proved to be adequate for the interpretation of the students' manifestations. The data obtained allow us to conclude that there was consistent progress in both dimensions, which was reflected in the quality of the mathematical strategies developed.
From a pedagogical point of view, this study confirms that cooperative learning environments, technologically mediated and oriented to open tasks, constitute an effective response to the challenges of teaching Mathematics in the 21st century.
In accordance with the Profile of Students Leaving Compulsory Education (Martins et al., 2017) and with Essential Learning (DGE, 2018), this pedagogical proposal allows the development of transversal skills such as autonomy, critical thinking, creativity and problem-solving skills.
Among the limitations inherent to the study of the investigation, the analysis focused solely on the experimental group stands out. Future research could compare the effects between groups and extend the study to other subject areas, as well as explore the effect of using different cooperative learning methods and technological tools. This approach may contribute to deepening the understanding of the impact of active methodologies on the development of essential skills for the integral training of students.

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