

From integration to transformation: STEAM teaching methods and generative artificial intelligence to develop critical thinking, creativity and co-design in secondary schools

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Abstract: This study explores the transformative potential of integrating STEAM teaching and generative artificial intelligence (GAI) in promoting critical thinking, creativity and co-design skills among secondary school students. Using a quasi-experimental research design with a mixed-methods approach, both the cognitive and collaborative effects of the teaching intervention and the students' perceptions and the transformation of the teacher's role were analysed. The quantitative results show significant improvements in problem solving, academic self-efficacy and collaboration, with particularly positive outcomes among students with ADHD. Qualitative data confirm greater motivation, engagement and agency, as well as a redefinition of the teacher as a facilitator and cognitive mediator. The study also highlights ethical issues related to the use of AIG, including authorship, algorithmic transparency and assessment. The results suggest that, when adopted critically and pedagogically, AIG can contribute to building inclusive, reflective, and future-oriented learning ecologies.

Keywords: STEAM; generative artificial intelligence; secondary school; critical thinking; creativity



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1. Introduction

Generative artificial intelligence (GAI) represents one of the most significant innovations in contemporary education, offering new opportunities to rethink teaching and learning processes. In particular, its integration into STEAM (Science, Technology, Engineering, Arts and Mathematics) teaching allows us to move beyond an instrumental approach to technology and embrace a broader, more transformative vision. GAI, in fact, is not only a technical support, but also *an epistemic and creative partner*, capable of stimulating the production, negotiation and critical reflection on knowledge (Luckin, 2018; Holmes et al., 2022; Kern et al., 2023).

Generative technologies, ranging from linguistic models (such as ChatGPT) to graphic models (e.g. DALL·E) and 3D design tools, introduce learning dynamics centred on co-creation, personalisation of pathways and interdisciplinarity. From this perspective, STEAM teaching methods lend themselves to a profound reconfiguration: it is not simply a matter of integrating AI into existing teaching processes, but rather of generating *fruitful hybridisations* and ' ' (SIREM, 2024) that promote new critical and creative alphabets, adapted to the complexity of contemporary society.

The most recent scientific literature confirms the potential of AIG in fostering the development of critical thinking (Yang & Evans, 2023), the co-construction of shared meanings (Ng et al., 2023) and the creation of participatory and personalised learning environments (Zawacki-Richter et al., 2019). These benefits are particularly relevant in the context of secondary school, where students, at an advanced stage of cognitive maturation, are able to reflectively and independently address the ethical, epistemological and design implications of the use of artificial intelligence.

Another crucial aspect concerns the promotion of *algorithmic literacy* (Kiss & Carretero, 2023), understood as the ability to understand, deconstruct and critically evaluate the outputs generated by artificial intelligence models. These skills are now essential for training informed digital citizens who are able to interact responsibly with the intelligent systems that increasingly pervade everyday life.

At the same time, the role of the teacher is also undergoing a significant transformation, evolving from a transmitter of content to a facilitator and curator of intelligent environments and co-design processes. Collaboration between humans and artificial intelligence requires new professional skills and a renewed pedagogical awareness. The European Digital Competence Framework for Education (DigCompEdu, 2022) highlights the importance of teacher training that integrates technological innovation with the ethical, inclusive and reflective dimensions of educational practice.

However, this new scenario is not without its challenges: questions arise regarding assessment, the authorship of the products generated, the originality of the content and the possible dependence on intelligent tools. It is therefore necessary to accompany the adoption of AIG with a profound pedagogical reflection that guides its conscious and responsible use.

In light of these premises, this study aims to investigate how the integration of STEAM teaching and generative artificial intelligence can affect the development of critical thinking, creativity, co-design skills and the professional role of the teacher, contributing to the construction of new educational scenarios in upper secondary schools.

2. Aims of the Research

This study aims to explore in depth the educational potential of integrating STEAM teaching and generative artificial intelligence (GAI) in upper secondary schools, in line with the latest research in the field of education and technology (Holmes et al., 2022; Luckin, 2018; Kern et al., 2023). The aim is to contribute to the understanding of the pedagogical, cognitive and ethical implications that emerge from these 'fruitful hybridisations' (SIREM, 2024), analysing their impact on both students and teachers.

In particular, the research is divided into the following specific objectives:

- To assess the impact of AIG-mediated STEAM activities on the development of students' critical thinking, considered a key competence for 21st-century citizenship (OECD, 2019) and closely linked to the ability to analyse, problematise and reflect independently and consciously (Yang & Evans, 2023).
- Analyse the extent to which the use of AIG stimulates individual creativity and promotes co-design skills through collaborative, exploratory and interdisciplinary practices consistent with the STEAM perspective (Henriksen et al., 2019; Mishra,

2020). The focus is on how AI can act as a catalyst for creative and transformative processes, offering students opportunities for expression and innovation.

- Exploring students' perceptions, emotions and representations of AIG, understood not only as technology, but as a semiotic and dialogic agent in the learning process (Ng et al., 2023). This includes analysing the degree of trust, engagement and sense of agency developed during the use of generative AI.
- Investigate changes in the role of the teacher in hybrid learning environments, highlighting how GAI redefines the teaching function from transmissive to facilitative, oriented towards educational direction, interaction management and cognitive mediation (Zawacki-Richter et al., 2019; DigCompEdu, 2022).
- Identify the main pedagogical and ethical implications of introducing GIA into teaching practices, focusing on issues of authorship, assessment, intellectual property, algorithm transparency, and educational responsibility (Kiss & Carretero, 2023; UNESCO, 2021). These aspects are central to ensuring the conscious, fair, and reflective use of artificial intelligence in schools.

3. Sample selection

The educational intervention was conducted at a state scientific high school in the province of Caserta during the second term of the school year. The sample, consisting of 150 second-year students, was defined using a stratified randomisation procedure to ensure fair allocation to the two study groups: experimental group ($n = 75$) and control group ($n = 75$). This procedure, consistent with the methodological recommendations for experimental research in education (Creswell & Guetterman, 2021), ensured balance between the groups, reducing the risk of bias and increasing the internal validity of the study (Mertens, 2020).

Each group included 15 students with a certified diagnosis of Attention Deficit Disorder (ADHD), in accordance with Italian legislation on special educational needs (Law 170/2010) and the principles of equity and inclusion supported by the international framework on school inclusion (UNESCO, 2020). The balanced distribution of pupils with ADHD between the two groups made it possible to comparatively evaluate the effectiveness of the intervention even in the presence of neurocognitive variability, valuing heterogeneity as an educational resource (Florian & Spratt, 2013).

The inclusion criteria for participation in the study were as follows:

- Voluntary participation in the project, formalised by signing an informed consent form. For underage students, participation was authorised by at least one parent or legal guardian, in accordance with ethical protocols for research involving minors (ESRC, 2015).
- Regular enrolment at the state scientific high school in the province of Caserta involved in the experiment, with active and continuous attendance at the school throughout the period of the educational intervention.
- Enrolment in the second year of the course, motivated by the need to work with students who had already acquired a basic knowledge of scientific subjects and sufficient cognitive maturity to tackle complex design, reflection and critical evaluation activities (OECD, 2019).
- For students with Attention Deficit Disorder (ADHD): presence of a certified clinical diagnosis in accordance with Law 170/2010, issued by health authorities

accredited or authorised by the relevant Region. The certification had to be valid and recognised within the student's Personalised Education Plan (PDP).

- Participation in at least 50% of the planned activities, established as the minimum threshold for considering exposure to the stimulus (educational intervention) sufficiently representative and significant for the purposes of measuring its effects (Biesta, 2021). Attendance was recorded using a digital signature register countersigned by the teachers.

The following were excluded from the study:

- students repeating the second year, to avoid inconsistencies in the composition of the sample with regard to academic progression and cognitive-emotional development, in line with the literature on confounding factors in experimental designs (Muijs, 2011);
- students with an absence rate of more than 50% of the scheduled meetings, as insufficient exposure would compromise the relevance and analysability of the results.

The intervention took place over six months, with two weekly meetings, each lasting two hours, for a total of approximately 48 hours of activity for each participating student. The sessions were held in person and were co-led by an external expert in artificial intelligence applied to education and the science and physics teacher, with a view to interdisciplinary and cooperative co-design of teaching (Laurillard, 2012; Holmes et al., 2022).

This methodological approach enabled a rigorous and differentiated assessment of the effects of AIG-mediated STEAM activities, while ensuring equal treatment between groups, attention to special educational needs and reliability of the data collected according to the latest standards of evidence-based educational research (Biesta, 2021; Zawacki-Richter et al., 2019).

4. Assessment Tools

This study adopted a mixed methods research approach, integrating the collection and analysis of both quantitative and qualitative data (Creswell & Plano Clark, 2018; Johnson et al., 2007). This choice was dictated by the need to obtain an in-depth and multifactorial understanding of the impact of the integration of STEAM teaching and generative artificial intelligence. While quantitative tools made it possible to measure the extent of changes in key variables such as problem solving, self-efficacy and peer collaboration, qualitative methodologies allowed us to explore the perceptions, experiences and meanings attributed by participants, enriching our understanding of the phenomena with contextual and narrative depth.

Quantitative data collection was conducted through self-report and peer-assessment questionnaires, administered in the pre-test phase (before the intervention) and post-test phase (at the end of the intervention) for both groups (experimental and control). All instruments were adapted and validated for the Italian secondary school student population (e.g., for Italian adaptations, see: xxx, 202X; yyy, 202Y).

To assess problem-solving skills, an ad hoc subscale of the Motivated Strategies for Learning Questionnaire (MSLQ) (Pintrich et al., 1991) was used, focusing on items that investigate cognitive and metacognitive strategies for planning, monitoring and evaluating solutions to problems. Responses were collected on a 7-point Likert scale (from 1 'Not at all true for me' to 7 'Very true for me'). The Academic

Self-Efficacy Scale (ASES) (Bandura, 1997; Caprara et al., 2008) was used to measure students' perceived academic self-efficacy, with items exploring confidence in their ability to achieve learning goals and manage academic challenges, using a 6-point Likert scale (from 1 'Not at all confident' to 6 'Totally confident'). To investigate students' preferences and attitudes towards peer collaboration and cooperation, the Student's Tendency between Collaborative and Cooperative Learning Questionnaire (STCCLQ) (Sun et al., 2012) was administered, based on a 7-point Likert scale (from 1 'Strongly disagree' to 7 'Strongly agree'). Finally, for a more objective and behavioural assessment of peer collaboration, Peer Assessment Questionnaires (Ohland et al., 2012) were used, with a 5-point rating scale (from 1 'Not at all' to 5 'Very much'), which allowed each student to assess their peers on dimensions such as contribution to work, interaction and communication, group management, quality of work, and reliability and commitment.

Qualitative data collection, on the other hand, allowed us to capture the nuances and personal experiences of the participants, providing a narrative complementary to the numerical data. Semi-structured interviews were conducted with a selected sub-sample of pupils (including students with and without ADHD) from the experimental group and the control group, with the aim of analysing in depth the impact of STEAM and AI integration on their learning process. The guiding questions explored their perceptions of the use of AIG, their emotions during collaborative activities, and the impact of the intervention on their motivation and sense of agency. At the same time, semi-structured interviews were conducted with teachers from the classes involved (both from the experimental and control groups) to investigate their perceptions of the pupils' ability to work in groups and feel involved in the teaching activity in the presence of AI tools, while also exploring their experiences in using AIG, the challenges faced, perceived changes in their professional role and emerging training needs, in line with the objectives of the Council of Europe (Council of Europe, 2022).

The analysis of the qualitative data collected through semi-structured interviews was conducted using a thematic analysis approach (Braun & Clarke, 2006; Braun & Clarke, 2022). This method allowed us to identify, analyse and report patterns (themes) within the data, providing a rich and detailed account. To facilitate the process of coding, categorising and retrieving themes, NVivo qualitative analysis software (version 14) (QSR International, 2023) was used.

5.Methods

The educational intervention was designed and implemented to integrate generative artificial intelligence (GAI) into the curricular teaching activities of physics and mathematics, with the aim of stimulating higher cognitive processes (analysis, synthesis, evaluation) and developing transversal skills through interdisciplinary approaches typical of the STEAM framework. The choice to focus on these two disciplines was motivated by their centrality in scientific curricula, as well as their propensity to favour learning models based on problem solving, modelling and iterative design (Bybee, 2013; OECD, 2021).

The intervention took place over a period of six months, for a total of 48 hours divided into two weekly meetings of two hours each. The entire process was organised into two distinct educational paths, one for the experimental group and one for the

control group, in order to allow for a comparative evaluation of the effectiveness of the methodologies adopted.

The students in the control group followed a conventional teaching programme, consisting of lectures, theoretical explanations, individual exercises and written tests. The topics covered included:

- in physics: electrostatics, Ohm's laws, direct current circuits, laws of motion, vector representation of forces;
- in mathematics: linear algebra, solving systems, study of functions, probability.

The activities focused on the one-way transmission of knowledge, with the teacher acting as an expert who guides and assesses learning (Bruner, 1996). Students solved exercises based on example models, using paper-based tools and textbooks. This setting is in line with what the literature describes as the transmissive model, which is still prevalent in many schools (Laurillard, 2012; OECD, 2021).

The teaching programme for the experimental group was designed according to a modular and interdisciplinary approach. This approach promoted the active and reflective construction of knowledge by students through a continuous cycle of exploration, formalisation, representation and critical review, consistent with experiential learning models (Kolb, 2014) and the principles of educational design thinking (Mishra, 2020; Beetham & Sharpe, 2019). The activities were developed in four thematic modules. Each module focused on an authentic design challenge, designed to encourage interaction between disciplinary knowledge and transversal skills, in line with problem-based pedagogy and the logic of meaningful learning (Jonassen, 2011; Thomas, 2020).

In the first module, dedicated to electrical circuits and mathematical models, students designed a sustainable lighting system for a classroom. Using tools such as PhET Circuit Construction Kit and Wolfram|Alpha, they calculated physical parameters such as intensity, voltage and resistance in circuits of different configurations. At the same time, they used ChatGPT to verbally describe problems, identify solution strategies and compare analytical and simulation approaches, in line with the literature on the use of AI for personalisation and conceptual exploration (Holmes et al., 2022; Kern et al., 2023). The data collected was reprocessed using Excel and GeoGebra, generating tabular representations, graphs and linear functions. The module concluded with the production of a multimedia presentation, enriched with infographics created using DALL·E and Canva AI, promoting the integration of mathematical and visual languages (Kress, 2010).

The second module focused on kinematics and vector representation. Students were asked to analyse the movement of a drone in a simulated urban environment. Using Desmos, Tinkercad and AI visualisation tools, they described rectilinear and parabolic motion with the aid of kinematic equations. The fundamental physical parameters (acceleration, velocity, time) were represented in animated infographics created with Powtoon and Copilot Designer. The activity was complemented by scientific storytelling, in which physics concepts were narrated within realistic scenarios (e.g., rescue operations), accompanied by texts generated with ChatGPT and original images processed using Bing Image Creator. These practices reflect the effectiveness of the narrative and visual approach in conceptual learning (Bruner, 1990; Oatley, 2011).

In the third module, focused on statistics and applied probability, students developed educational board games for which they estimated the probability of events using both classical and frequentist approaches. The design of the games was accompanied by empirical data collection, the construction of histograms and distributions, and simulations supported by generative AI. In particular, ChatGPT was used to generate and document the rule algorithms. This module also included moments of critical reflection on cognitive biases and the most common systematic errors in the perception of randomness, promoting metacognition and critical thinking (Tversky & Kahneman, 1982; Wing, 2006; Yang & Evans, 2023)..

The fourth and final module addressed linear algebra and mathematical modelling. The challenge involved representing the flow of students within the school building, with the aim of optimising movement and improving safety. Students developed linear systems of equations to model paths and distributions, using GeoGebra for visualisation and ChatGPT to generate variations of the problem, analyse alternative solution strategies, and justify their choices. The final graphical representations were transformed into dynamic storyboards using AI graphics tools such as DALL·E and Adobe Firefly, while a concluding reflection compared the theoretical models with empirical data collected in the school setting. This type of activity reflects current research trends in model-based learning and interactive simulations (OECD, 2023; Zawacki-Richter et al., 2019).

Across all modules, collaborative methodologies such as peer tutoring and role rotation within groups (leader, reporter, resource manager, AI manager) were implemented as effective strategies for developing responsibility, autonomy and communication (Nicol, 2020). At the end of each project phase, students participated in self- and peer-assessment sessions, using shared rubrics and digital peer feedback tools, to develop solid and continuous metacognitive awareness (Hattie & Timperley, 2007; Nicol & Macfarlane-Dick, 2006). In addition, each student kept a digital logbook, which was useful for monitoring personal reflections, insights, doubts and their relationship with artificial intelligence as a co-creation tool.

Particular attention was paid to students with Attention Deficit Disorder (ADHD). To ensure an effective and inclusive learning experience, methodological adaptations were adopted, including the segmentation of activities into micro-tasks (Durand & Crim, 2018), the use of dynamic visualisations and immediate feedback, intuitive and responsive digital work environments, as well as scheduled cognitive breaks and customisation options for autonomous task management. These strategies are in line with international recommendations for supporting SEN (DuPaul et al., 2011; Sutherland et al., 2023).

Overall, the modular structure adopted has enabled the harmonious integration of subject content, AIG technologies and collaborative educational practices, promoting authentic, motivating and transformative learning. The approach has fostered the development of complex skills such as agency, computational thinking, creativity and cognitive responsibility, in line with the latest guidelines on digital education and active inclusion (Holmes et al., 2022; Kern et al., 2023; OECD, 2023).

6. Quantitative data analysis

Quantitative data analysis was conducted to evaluate the effectiveness of the educational intervention based on the integration of STEAM teaching and generative artificial intelligence (AIG), comparing the results obtained by the experimental group

with those of the control group, which followed a traditional teaching programme. The data collected were processed using inferential statistical tests (t-tests for independent samples and ANOVA for repeated measures), with a significance level set at $p < .05$, according to the procedures recommended for quasi-experimental studies in education (Creswell & Guetterman, 2021; Johnson & Christensen, 2020).

The scores obtained in the problem-solving subscale of the *Motivated Strategies for Learning Questionnaire* (MSLQ) (Pintrich et al., 1991) showed a marked increase in the experimental group, with a shift from $M = 4.01$ ($SD = 0.66$) in the pre-test to $M = 5.29$ ($SD = 0.54$) in the post-test, compared to a more modest increase in the control group ($M_{pre} = 4.03$, $SD = 0.61$; $M_{post} = 4.24$, $SD = 0.59$). The t-analysis revealed a statistically significant difference ($t(148) = 8.23$, $p < .001$, $\eta^2 = .31$), indicating that the use of AIG, particularly for simulating complex scenarios and automatically generating alternative solutions, enhanced students' ability to plan, monitor, and evaluate problem-solving strategies. These findings are consistent with recent evidence on the potential of generative technologies to promote *inquiry-based learning* and *scaffolded problem solving* (Luckin, 2018; Jeong et al., 2023).

Similarly, the results of the Academic Self-Efficacy Scale (ASES) (Bandura, 1997; Caprara et al., 2008) show a significant improvement in academic self-efficacy in the experimental group ($M_{pre} = 3.62$, $SD = 0.74$; $M_{post} = 4.88$, $SD = 0.63$), with a marginal increase in the control group ($M_{pre} = 3.58$, $SD = 0.70$; $M_{post} = 3.74$, $SD = 0.65$). The effect found ($t(148) = 9.12$, $p < .001$) suggests that AIG, acting as a *cognitive partner* in authentic project activities, strengthens students' perception of control and competence, as also highlighted by Wang et al. (2022).

With regard to collaboration and co-design, data from the *Student's Tendency between Collaborative and Cooperative Learning Questionnaire* (STCCLQ) (Sun et al., 2012) and the *Peer Assessment Questionnaire* (Ohland et al., 2012) show significant growth in the experimental group. In particular, the average STCCLQ score rose from $M = 4.18$ ($SD = 0.60$) to $M = 5.44$ ($SD = 0.52$), while in the control group it remained stable ($M_{pre} = 4.15$, $M_{post} = 4.22$). *Peer assessment* data confirm a significant improvement in the dimensions of shared responsibility, communication, quality of contributions, and peer interaction ($p < .001$ for all dimensions), highlighting the effectiveness of AIG as a facilitator of collaborative dynamics (Zawacki-Richter et al., 2019; Holmes et al., 2022).

Creativity, although not measured using an ad hoc scale, was assessed by triangulating observational data, selected items from the MSLQ, and analytical rubrics on the final digital products (infographics, prototypes, multimedia narratives). The work produced by the experimental group obtained higher average scores ($M = 4.6/5$) than that of the control group ($M = 3.2/5$), demonstrating greater expressive variety, conceptual complexity, and originality. The integration of tools such as DALL·E, Canva AI, and ChatGPT encouraged creative exploration of problems and the co-construction of original solutions (Jin et al., 2023).

Focus: Comparison between students with ADHD

Particular attention was paid to the 30 students diagnosed with ADHD included in the study (15 in each group) to assess the effectiveness of the intervention in terms of equity and inclusion. The results show significant differences between the two subgroups.

In the experimental group, students with ADHD showed a significant increase in the *problem-solving* scale (MSLQ): $M_{pre} = 3.81$ ($SD = 0.61$), $M_{post} = 5.15$ ($SD = 0.58$),

while in the control group the increase was much more modest ($M_{pre} = 3.85$, $SD = 0.59$; $M_{post} = 4.05$, $SD = 0.57$). In terms of self-efficacy (ASES), the ADHD students in the experimental group also showed a marked improvement ($M_{pre} = 3.42$, $SD = 0.65$; $M_{post} = 4.69$, $SD = 0.61$), compared to a minimal increase in the control group ($M_{pre} = 3.41$, $SD = 0.62$; $M_{post} = 3.58$, $SD = 0.66$).

In terms of collaboration, *peer assessment* data indicate an improvement in group dynamics even among ADHD students in the experimental group, particularly in the dimensions of 'reliability', 'task management' and 'creative contribution', with significantly higher scores than their peers in the control group ($p < .01$). The methodological adaptations adopted (micro-tasking, visual feedback, cognitive breaks) contributed to improving active participation, concentration and perceived self-efficacy, in line with the recommendations of DuPaul et al. (2011) and Sutherland et al. (2023).

Overall, the quantitative data confirm that the integration of AIG into STEAM teaching contexts not only produced generalised positive effects on cognitive and socio-relational performance, but also significantly supported the inclusion and school well-being of students with ADHD. These findings reinforce the hypothesis that adaptive and visually rich digital environments can act as catalysts for active participation, reducing barriers related to neurocognitive variability (Florian & Spratt, 2013; OECD, 2023).

7. Qualitative data analysis

The thematic analysis conducted on the semi-structured interviews with students and teachers from the two groups involved in the experiment identified a series of emerging conceptual clusters that reflect significant differences in perceptions and experiences related to the learning process, the use of generative artificial intelligence (GAI), the collaborative dimension and the role of the teacher. In particular, the macro-categories identified concern: engagement and motivation, perception of the role of technology, activation of critical thinking, collaborative experience, perceived inclusion, and redefinition of teaching professionalism.

Students in the experimental group repeatedly expressed a sense of curiosity, enthusiasm and greater mastery of the content covered. One student said: *'For the first time, I felt like I was creating something of my own in mathematics. Not just numbers, but ideas, images, projects.'* Others highlighted the stimulating effect of AI on the reflection process: *'Artificial intelligence gave us ideas, confused us, but in doing so forced us to think about it, to review our assumptions.'* The support provided by AIG technologies was perceived as "not replacing the teacher, but complementing them," and many emphasised how interaction with AI strengthened their decision-making autonomy and sense of agency, contributing to a more constructivist view of learning (Ng et al., 2023).

In contrast, students in the control group described their learning experience as more "orderly" but less engaging. One student said, *'I understood what I had to do, but I didn't feel I had an active role. It was more like listening and repeating.'* There were also expressions of dissatisfaction related to the lack of visual tools or collaborative activities: *'When we did exercises on the board, it was always the same pattern. I would have liked to try different things, to see the results of what we were doing.'*

The differences were even more pronounced in the subgroup of students with ADHD. Participants in the experimental group described the experience as "engaging," "more tolerant of my pace," and "finally tailored to those who are easily distracted." One boy said: *'When it started to get difficult, we changed activities. There were images,*

videos, moments when even if you didn't understand everything, you stayed within the group." This confirms the usefulness of flexible, interactive and visual teaching strategies in supporting motivation and concentration in individuals with attention disorders (DuPaul et al., 2011; Sutherland et al., 2023).

In contrast, students with ADHD in the control group expressed discomfort and frustration: *"I always felt behind. All it took was a moment's distraction and I lost track of the lesson."* Some highlighted the difficulty of sustaining long, monotonous activities, complaining about the lack of alternative stimuli or structured breaks: *"There was nothing to help you get back on track if you lost focus."* These difficulties had a negative impact on both performance and perceived self-efficacy.

From the teachers' point of view, the interviews highlighted a profoundly different experience between the two groups. Teachers involved in the experimental group spoke of a "progressive transformation of their role" from transmitters to orchestrators of knowledge. One of them said: *"I was sceptical at first. AI seemed distracting to me. Then I realised that it was a powerful tool, as long as I guided it and guided the students in its use."* Another emphasised: *"I found myself learning alongside them. It was stimulating for me too."* There was a strong awareness of the need for new professional skills and the complexity of pedagogical mediation in hybrid digital environments (Zawacki-Richter et al., 2019; DigCompEdu, 2022).

In contrast, teachers in the control group reported greater organisational stability, but also a certain lack of motivation. *"It worked with the more motivated students, but many fell behind. It was difficult to understand who was really following."* In particular, they expressed concerns about inclusion: *"Children with ADHD were often inattentive. There was not enough time to follow them one by one."* The feeling of relational distance and the absence of dynamic pedagogical devices were perceived as structural limitations of the traditional setting.

Overall, the qualitative analysis showed that the integration of STEAM and AIG teaching methods fostered a more motivating, dialogical and inclusive learning environment, capable of enhancing the diversity of cognitive profiles and strengthening the students' sense of participation. The testimonies collected confirm that the approach adopted stimulated not only critical and h us thinking and creativity, but also metacognitive awareness, collaborative work and the shared construction of knowledge, in line with the objectives outlined in recent literature (Holmes et al., 2022; OECD, 2023; Yang & Evans, 2023).

8. Discussion

The results of this study clearly confirm the effectiveness of integrating STEAM teaching and generative artificial intelligence (AIG) in promoting complex cognitive and social skills in secondary school students. In particular, the significant increase in dimensions related to problem solving, academic self-efficacy and collaboration suggests that GAI, when integrated in a pedagogically conscious manner, can play a catalytic role in triggering metacognitive, reflective and participatory processes (Luckin, 2018; Jeong, Lin & Simpkins, 2023).

The metacognitive dimension of learning, greatly enhanced by the use of AI, seems to emerge as one of the main levers through which generative technologies support knowledge construction. The results confirm what has already been highlighted by Holmes et al. (2022) and Zawacki-Richter et al. (2019), according to whom AIG can act as an epistemic partner capable of stimulating critical reflection, negoti-

ation of meanings and self-regulation of cognitive processes. Furthermore, the role of co-creator attributed to AI by students – as emerged from qualitative interviews – is linked to recent work by Selwyn and Nemorin (2023), which explores the dialogic function of technology in the participatory construction of knowledge.

One particularly relevant aspect concerns educational inclusion. Thanks to the adoption of visual, interactive and flexible teaching methods, students with ADHD have shown a clear improvement in engagement and learning, in line with the findings of recent studies on Universal Design for Learning (UDL) and inclusive technologies (Rose et al., 2021; Sutherland et al., 2023). The effectiveness of the AI-centric approach in promoting equity of access and well-being at school is also confirmed by the work of Wang et al. (2022), who emphasise how customisable digital environments increase the sense of agency of neurodivergent students.

Comparison with the control group revealed the persistence of structural limitations in traditional teaching contexts, characterised by transmissivity, poor interactivity and a reduced capacity to support critical and creative processes. The role of the teacher, within AIG-mediated contexts, is transformed into one of orchestration and planning, requiring new professional skills, including algorithmic literacy, the management of intelligent environments and ethical awareness (Redecker & Punie, 2017; DigCompEdu, 2022; Popenici & Kerr, 2023). In this sense, education in the critical use and of technology cannot be separated from the continuous training of teachers, as also suggested by the OECD (2023) and UNESCO (2021) guidelines.

However, there are some critical issues that deserve careful consideration. The evidence gathered highlights the risk of excessive dependence on generative tools, a reduced capacity for independent verification of outputs and a tendency towards uncritical automation of responses, in line with the findings of Pasquinelli & Jatón (2022). Ethical issues are also central: the use of AIG raises questions about the transparency of algorithms, the authorship of school productions, fairness in access to tools, and the reliability of generated content (Kiss & Carretero, 2023; Floridi, 2020; UNESCO, 2021).

It is therefore essential that every technological innovation be accompanied by profound pedagogical and ethical reflection. Only through critical, responsible, and contextualised use of AIG will it be possible to promote truly equitable and transformative educational environments. In this regard, the construction of new formative and narrative assessment models (Bearman et al., 2022) and the development of shared ethical and regulatory frameworks (Cios & Zapala, 2023) represent urgent challenges for the educational community.

Finally, the results suggest the need to further explore the impact of AIG on the affective and relational dimension of learning, an area that is still partially unexplored but potentially crucial for the sustainability of educational innovation (Roschelle et al., 2020). The adoption of a hybrid educational paradigm – in which AI does not replace humans but supports them as a cognitive and social amplifier – appears to be a promising prospect for 21st-century education.

9. Conclusion

This study confirms the transformative potential of integrating STEAM teaching and generative artificial intelligence (AIG) in secondary schools, highlighting benefits on both a cognitive and socio-emotional level. The methodological approach adopted, based on co-design, personalisation, collaboration and interdisciplinarity,

has generated a dynamic and inclusive educational environment, fostering the development of key skills such as critical thinking, creativity, self-efficacy and peer cooperation (Holmes et al., 2022; OECD, 2023; Wang et al., 2022).

The results obtained, supported by a triangulation of quantitative and qualitative data, indicate that the use of AIG can be a powerful lever in building more flexible, responsive and student-centred 'learning ecologies' (Luckin, 2018; Jeong et al., 2023). When guided by solid pedagogical frameworks, technology can be used as a tool to broaden participation rather than replace it. In particular, AIG has had a significant impact on the educational well-being of neurodivergent students, such as those with ADHD, who have benefited from its modularity, dynamic visualisation and the possibility of interacting with content in a personalised way (Rose et al., 2021; Sutherland et al., 2023).

The success of the intervention suggests that educational innovation does not lie solely in the adoption of emerging technologies, but in the school's ability to redefine its spaces, times and roles. Central to this is the rethinking of the role of the teacher, who is transformed from a simple transmitter to a mediator and orchestrator of intelligent environments, capable of promoting agency, digital citizenship and reflective thinking (Redecker & Punie, 2017; DigCompEdu, 2022; Popenici & Kerr, 2023).

However, the full exploitation of AIG in schools requires an adequate cultural and organisational infrastructure. It is necessary to implement policies for equitable access to digital resources, ensure continuous and critical training for teachers, and build a shared ethical and regulatory framework for the use of smart technologies (UNESCO, 2021; Floridi, 2020). Only in this way will it be possible to avoid the risk of a pedagogical divide and ensure that innovation is truly inclusive and sustainable.

For the future, it is recommended that research be extended to heterogeneous school contexts, including schools with different resources, methodological orientations and socio-cultural profiles. Furthermore, it will be essential to investigate the potential of AIG in authentic assessment, the promotion of creativity and digital inclusion, as well as its role in formative feedback and self-reflection processes (Bearman et al., 2022; Selwyn & Nemorin, 2023).

Finally, a crucial challenge will be to promote AI education that is not limited to the functional use of tools, but that fosters the development of 'critical algorithmic literacy', capable of interpreting, questioning and governing intelligent systems in the complexity of the contemporary world (Kiss & Carretero, 2023; Ng et al., 2023). Only through an alliance between research, educational practice and policy will it be possible to build a public school system capable of addressing the challenges of 21st-century education in an ethical and transformative way.

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