frontiers | Frontiers in Education

TYPE Brief Research Report
PUBLISHED 25 July 2022
DOI 10.3389/feduc.2022.955285

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Digital Education, a section of the journal Frontiers in Education

RECEIVED 28 May 2022
ACCEPTED 05 July 2022
PUBLISHED 25 July 2022

CITATION
Gratani F and Giannandrea L (2022) Towards 2030. Enhancing 21st century skills through educational robotics. *Front. Educ.* 7:955285.
doi: 10.3389/feduc.2022.955285

Towards 2030. Enhancing 21st century skills through educational robotics

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Recent technological advances require new learning and teaching methods and a reform of traditional school curricula to promote STEM and 21st-century skills. Educational robotics is considered a powerful tool, not only to learn programing, but also to enhance soft and transversal skills, such as problem-solving, metacognition, divergent thinking, creativity, and collaboration. This contribution presents a one-year research project aimed at integrating maker education and educational robotics into the primary and lower secondary school curriculum. The project is developed through a multidisciplinary and longitudinal approach and adopts the Design-Based Implementation Research methodology. It involved 50 fourth and fifth grade Italian students until the following school year. As an integrating background theme, we chose the 17 Goals outlined by the UN in the 2030 Agenda. Each selected goal was addressed by solving challenges in groups. Educational robotics became a tool for learning many concepts, such as renewable energies, human body systems or states of matter, but especially for working on creativity and ability to design, build, collaborate, and revise. We investigated students' attitude toward STEM and 21st-century skills and their perceived school self-efficacy administrating two questionnaires pre and post the two parts of the project. This paper discusses findings on students' attitude toward 21st-century skills. In the post analyzes of both Part 1 and 2, this field showed the highest scores compared to STEM fields. The pre-post data show an improvement in organizational, interpersonal, and leadership skills from Part 1, but also a gradual increase in personal and management skills.

KEYWORDS

21st century skills, educational robotics, 2030 agenda, maker education, school curriculum

Introduction

Employability and professional skills have evolved significantly since the beginning of the 21st century, emphasizing creativity, design, and engineering processes (Gratani and Giannandrea, 2021). Recent technological advances require new learning and teaching methods and a reform of traditional school curricula to promote STEM (Science, Technology, Engineering, Mathematics) and 21st century skills.

The World Economic Forum (2015) investigated the skills that meet the needs of a 21st century marketplace, conducting a meta-analysis of research about 21st century skills in primary and secondary education. It defined a set of 16 crucial skills divided into three broad categories: foundational literacies, competencies, and character qualities:

1. Foundational literacies refer to how students apply core skills to everyday tasks. They include the traditional literacy and numeracy skills, but also scientific literacy, ICT literacy, financial, cultural, and civic literacy;
2. Competencies refer to how students approach complex challenges and include critical thinking, creativity, communication, and collaboration;
3. Character qualities refer to how students approach their changing environment. Students need qualities as persistence and adaptability, curiosity and initiative, leadership and social and cultural awareness.

A broad strand of research focuses on the potential of Educational Robotics (ER) to improve students' scientific conceptual understanding and technological literacy (e.g., Nugent et al., 2010; Eguchi and Uribe, 2017; Santos et al., 2019). Specifically, Khanlari (2019) argues that ER provides an alternative teaching method to traditional lecture-style classes to improve understanding of mathematical and science concepts by facilitating the processes of investigation, planning, recording, analysis, and interpretation. This often results in a positive attitude toward STEM subjects and an incentive to pursue education and careers in these fields.

ER is considered a powerful tool, not only for teaching and learning programing, but also for enhancing soft and transversal skills, such as problem-solving (Turner and Hill, 2007; Castledine and Chalmers, 2011; Gratani et al., 2021), metacognition (La Paglia et al., 2018), divergent thinking (Leroy et al., 2021), creativity (Yang et al., 2020; Badeleh, 2021), and collaboration (Gueorguiev et al., 2018).

Interest in the effects of ER on the cognitive and metacognitive processes underlying learning has increased exponentially in recent years. La Paglia et al. (2018), argue that robotics-based educational systems promote the use of specific cognitive and attentional skills, strengthening mental processes and affecting executive functions. Furthermore, logical thinking is often related to creative thinking. Indeed, Komis et al. (2017) distinguish between ER activities focused on rigorous and procedural resolution and more interdisciplinary activities oriented toward a collaborative and creative approach that require co-creative problem-solving strategies (Romero and Dupont, 2016). Finally, a stimulating environment based on an active and cooperative approach particularly stresses socio-relational and collaborative skills and emotional-motivational components (e.g., Menekse et al., 2017; Screpanti et al., 2021).

This contribution presents a one-year research project aimed at integrating maker education and ER into the primary and lower secondary school curriculum, through authentic challenges linked to curricular content, aimed at promoting students' skills, and included in the assessment process.

Methods

The project was developed through a multidisciplinary and longitudinal approach and by referring to the four steps of Design-Based Implementation Research (Fishman et al., 2013): (1) a focus on persistent problems of practice from multiple stakeholders' perspectives; (2) a commitment to iterative, collaborative design; (3) a concern with developing theory and knowledge related to both classroom learning and implementation through systematic inquiry; (4) a concern with developing capacity for sustaining change in systems.

It lasted about a year and consisted of two main parts: Part 1 from February to June 2021 and Part 2 from November 2021 to March 2022. Each part was preceded by a phase of co-designing with the teachers and familiarization with the tools by the students. Indeed, together with the teachers, we started from context-related resources and problems and the specific class curricula to design the activities and define possible integration of proposals. We identified three guiding criteria: linking activities to curricular content; working for/on skills; including activities in student assessment. Most of the project took place during the covid-19 emergency period. However, we tried to maintain the collaborative and laboratory approach while respecting the security measures.

The Maker approach fosters a new way of teaching and future-focused, project-based, and learner-centered learning, where technology and handcraft combine to make students' ideas, interests, and passions tangible (Martinez and Stager, 2013; Gratani and Giannandrea, 2021). In line with this approach, we designed challenges based on devising, planning, building, and solving, to be carried out in pairs or small groups. Specifically, we followed these guiding principles:

1. Activating students at home through the flipped classroom strategy (Bergmann and Sams, 2012);
2. Giving each session the same structure: anticipation (Ausubel, 1968), brainstorming and presentation of the challenge, planning and implementation, debriefing;
3. Proposing tasks that are authentic (of interest to the pupils), challenging (in the zone of proximal development) and open (more possible solutions to ensure creativity and personalization) (Rossi et al., 2021).

Population

The project involved 50 fourth and fifth grade students distributed among three classes and schools of the "S. De Magistris" Comprehensive Institute in Caldarola (MC), Italy. Specifically, 30% of the students attended a fourth class, 42% a fifth class, and 28% a multi-grade class with fourth and fifth graders. The activities took place between two school years, which for some students (58%) coincided with the transition to lower secondary school. The pupils involved attended the classes of the teachers who voluntarily joined the project: in Part 1, three primary teachers (one per class) taught mainly scientific subjects; in Part 2, the two remaining primary teachers and two secondary teachers taught science and technology, respectively. The context and the sample were necessarily limited due to the Covid-19 health emergency. Before starting the project, we administered an entry questionnaire to collect demographic information about the students (gender, country of birth, age, grade), useful to examine the composition of the sample (see **Table 1**). Students are evenly distributed in terms of gender and grade. The entry questionnaire also detected, through closed-ended questions, their level of experience with LEGO kit and application, 3D printer and the use of technological tools at school. Most of the pupils stated that they had never programed an object built with a LEGO kit (60%) or used a 3D printer (88%). Moreover, we found out that the use of traditional technological tools (computers, search engines like Google, programs to create text or images) still prevails at school.

Activities overview

To plan the activities, we started from the class curricula and chose some of the 17 Sustainable Development Goals outlined by the United Nations (2015) in the 2030 Agenda as the integrating background theme. In agreement with the teachers involved, we selected 6 goals based on its pertinence to the curricula, and we scheduled weekly two-hour meetings for each class. The selected goals were addressed by solving challenges in small groups and almost all of them included a challenge to be solved through ER. As anticipated, each challenge included a series of regular phases: anticipation/activation at home; plenary presentation of the challenge to be solved; division into groups (generally changed for each goal) and assignment of a specific theme; group planning on logbooks; construction, testing, revision of the solution; final return with discussion; and individual self-assessment.

Specifically, in Part 1 we addressed Goal 7 *Affordable and clean energy* to take up and explore renewable energy; Goal 11 *Sustainable cities and communities* to get pupils reflecting about the concepts of safety, sustainability, and accessibility starting from their towns; and Goal 15 *Life on land* to address the conservation of mountain ecosystems, including the protection of biodiversity and the provision of sustainable tourism, again with reference to their local area. To carry out the activities, the pupils used the following tools: recycled or everyday materials, electricity kits, Lego WeDo 2.0 kits and application with icon programing; TinkerCAD software; Thinglink web application; Ultimaker3 3D printer; Qr code generator website. ER was used to creatively depict, through model building, the experimentation and functioning of various types of renewable energy (solar, wind, hydropower), solutions to safety, accessibility, and inclusion problems found in towns, and strategies to safeguard the surrounding area and its biodiversity. A more detailed description of Goal 7 activities can be found in Gratani and Giannandrea (2021).

Then, in Part 2 we addressed Goal 3 *Good health and well-being* to take up concepts relating to matter, substances, and the human body and raise awareness of healthy or harmful behaviors/effects; Goal 13 *Climate action* to explore issues related to climate change and possible strategies to prevent/reduce its impact and safeguard our climate; and Goal 14 *Life below water* to explore issues related to marine and coastal ecosystems and promote their relevance and protection. To solve these challenges, the fifth-grade pupils continued with the Lego WeDo 2.0 kits, this time programed with block programing on Scratch (adding the specific extension), while the first-year secondary school students worked with Lego Spike Prime kits and the related application with block programing. In addition, students used the Makey Makey kits, also by extension on Scratch, and the Cospaces software for creating virtual environments. ER was used to design and build models on the characteristics and functioning of the human body apparatus by primary students and on changes in the

TABLE 1 Summary of data concerning the sample from the entry questionnaire.

	Index	Value (%)
Gender	F	54
	M	46
Country of birth	Italy	94
	India	2
	Peru	2
	Cuba	2
Age	9 y.o.	36
	10 y.o.	58
	11 y.o.	6
Grade	Fourth	42
	Fifth	58

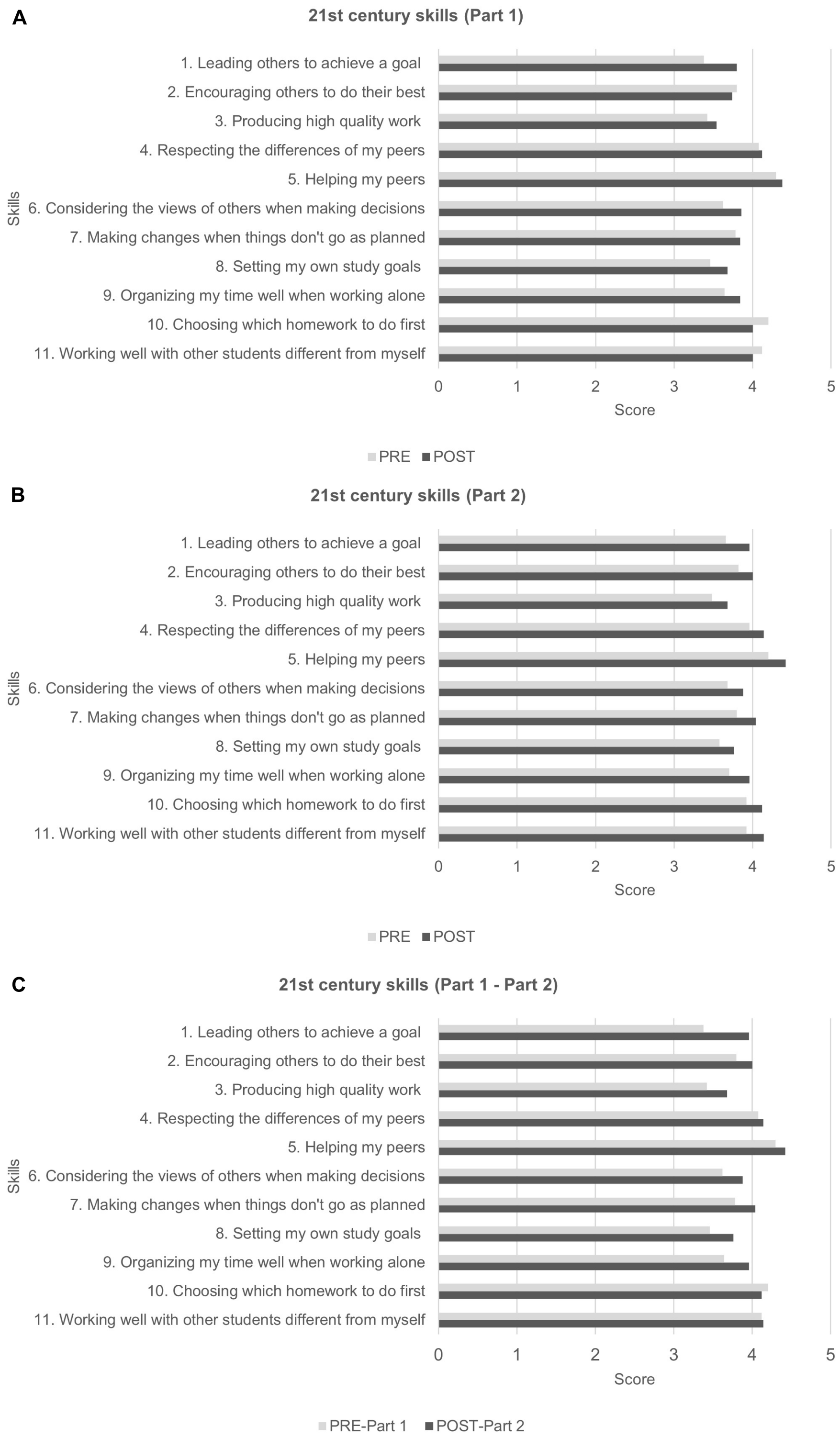

FIGURE 1
Students' attitude toward 21st century skills. **(A)** Histogram showing data from pre-post Part 1. **(B)** Histogram showing data from pre-post Part 2. **(C)** Histogram showing data from pre-Part 1 - post-Part 2.

state of matter and substances (simple and complex) by secondary students. Moreover, all students build projects to prevent/reduce the impact of climate change in relation to water, air, and soil.

Data collection tools

Our investigation focuses on detecting changes in students' attitude toward STEM and 21st century skills and their perceived school self-efficacy. To assess the attitude, we chose the S-STEM Survey developed by the Friday Institute for Educational Innovation (2012) and then translated, modified, and validated by Screpanti (2020). To detect self-efficacy, we chose the Perceived School Self-Efficacy Scale originally developed by Bandura (1993) and then translated and validated by Pastorelli and Picconi (2001). The two questionnaires were administered at the beginning and at the end of the project's two parts. At the end of Part 1, we also conducted a focus group with the primary teachers involved to find out their opinion on the sustainability of the proposal, its main limitations and positive effects, changes in their approach and daily teaching, and possible improvements.

The S-STEM survey is divided into five sections that measure changes in students' attitude toward STEM subjects and 21st-century learning skills. Specifically, the 21st century skills section consists of 11 questions with a 5-point Likert-type response scale: form "strongly disagree" to "strongly agree". The questions interrogated the students' perceived confidence regarding:

1. Leading others to achieve a goal;
2. Encouraging others to do their best;
3. Producing high quality work;
4. Respecting the differences of their peers;
5. Helping their peers;
6. Considering the point of view of others when making a decision;
7. Making changes when things do not go as planned;
8. Setting their own study goals;
9. Organizing their time well when working alone;
10. Being able to choose which homework to do first;
11. Working well with other students who have different knowledge, skills and experience.

The quantitative analysis was supported by observation, documentation, and the pupils' logbooks. Each logbook included an introductory section on the challenge, a planning section, and a reflection section with self-assessment. Finally, we designed a rubric with the teachers to facilitate the assessment of activities and their integration into the curriculum.

Results

This paper presents and discusses findings on students' attitude toward 21st century skills. In both the Part 1 and Part 2 post analyzes, attitude toward 21st century skills showed the highest scores compared to the other areas investigated, with an average score of 3.89/5 (post-Part 1) and 4.01/5 (post-Part 2).

Figure 1A reports data from pre-post analysis of Part 1. Specifically, in the post-administration, the highest scoring areas are (4) and (5), more related to the interpersonal sphere (respect and mutual help), while those with the lowest scores are (3) and (8), more related to the personal sphere (results and personal goals). However, the main areas of improvement are: (1) [+12,4%], (6) [+6,2%], (8) [+6%], and (9) [+5.5%]. Therefore, this first analysis suggests an initial impact mainly on students' organizational and social skills.

The pre-post analysis of Part 2 confirms this preliminary result. Specifically, **Figure 1B** shows a general improvement in all areas, with a better balance of increase between them. In the post-administration, the topics with the highest scores are (5), (4), and (11) while those with the largest range of increase are: (1) [+8,20%], (9) [+7%], (7) [+6,3%], (11) [+5,6%]. With the lowest scores we still find (3) and (8), which, however, show a good increase: (3) [+5,70%] and (8) [+5%]. Compared to pre-post of Part 1, we can therefore confirm an improvement in interpersonal and organizational skills, but also a better ability to cope with the unexpected and to change plans (7).

Finally, further data come from the comparison between pre-Part 1 and post-Part 2 (see **Figure 1C**). In this case, we find a low variance in (4), (5), (11), as they were already high in pre-Part 1, while we notice a further increase in (1) [17,2%], (9) [8,8%], with the addition of areas (8) [8,7%] and (3) [7,6%]. Compared to pre-post Part 1 and Part 2, we therefore notice a relevant progress in the skills more related to the personal sphere. Moreover, we still find a good improvement in (6) [7,2%] and (7) [6,9%].

Discussion

In this pilot project ER became a tool for learning many concepts, such as renewable energies, human body systems or states of matter, but above all it allowed students to work on their creativity and ability to design, build, collaborate, and revise. Pupils thus worked as designers, architects, and engineers, building several fundamental skills for the citizens and professionals of the future.

The direct connection with real problems and the possibility of hypothesizing, anticipating possible scenarios, testing, and reformulating provide a strong stimulus for problem-solving and problem-posing skills (Garavaglia et al., 2018). As Castledine and Chalmers (2011) show in their study, ER activities help students to reflect on problem-solving decisions and, with careful teacher assistance, students can relate these strategies to real-world contexts and experience authentic problem-solving.

The proposed activities strongly promoted the three categories described by the World Economic Forum (2015). Specifically, the eleven fields investigated cover almost all the categories of competencies and character qualities.

The regularity of the phases was aimed at gradually getting pupils to adopt a conscious, collaborative, and reflective working posture, improving their organizational and error management skills, as well as interpersonal, expository, and civic skills. Indeed, ER can significantly contribute to creating a stimulating learning environment for both students and teachers, with a clear incentive for relational and collaborative skills (Guastella and D'Amico, 2020).

The greatest progress emerged in the leadership skill, one of the key requirements for the 21st century marketplace. This skill, along with the others, was supported by group work with specific challenges and topics, assigned roles, work planning and meta-reflection on the outcomes. An added value of these environments is the immediate feedback on their work resulting from the robot-environment interaction that students have to deal with, to redesign and reflect on what they have done (Daniela and Strods, 2019; Gratani et al., 2021).

We identify as main limitations the restricted number of students and classes involved, their variation (change of school year, school, class composition), and the constraints due to the pandemic situation. Furthermore, it is important to consider that some particularly high values in the pre-Part 1 may be justified by a still immature self-assessment skill at the beginning of the project. Indeed, the classes were not used to carrying out self-assessment practices and we believe that there was also a growth in this skill, especially in terms of self-analysis and awareness.

Data availability statement

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

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

FG developed the research project and the overall manuscript. LG supervised the development of the research project and the drafting of the manuscript and contributed to sections "Introduction" and "Discussion". Both authors contributed to the article and approved the submitted version.

Acknowledgments

The authors would like to express their gratitude to the Headmistress and the teachers of "Simone De Magistris" Comprehensive Institute (Caldarola, MC), who made the fulfilment of the project possible.

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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