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Using Educational Robotics as Tools for Metacognition: an Empirical Study in Elementary STEM Education

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Abstract: Despite that educational robotics (ER) are considered a novel learning tool that can support students in developing higher-order thinking skills, their role in promoting students' metacognitive thinking remains unclear. This work aimed at investigating the potential added value of ER in promoting students' metacognitive thinking in the context of elementary STEM education. One-group (n=21) pretest–posttest research design was used to examine the hypothesis that ER can serve the learning process as metacognitive tools. Data collection included demographic data, questionnaires investigating students' metacognitive thinking and in-situ metacognitive processes evident via visualizations and performance (or calibration) judgments. Results showed a statistically significant improvement in students' abilities to regulate their own cognition performing actions of metacognitive regulation such as planning, monitoring, and debugging strategies. Besides, while the analysis showed that students' ability to visualize a problem scenario was not differentiated, students' accuracy on performance judgments (prediction and postdiction judgments) was significantly improved.

Keywords: educational robotics; metacognition; problem-solving; STEM education

1 Introduction

Educational robotics (ER) are constructible and programmable high-tech devices which can be employed in education as an innovative educational tool, within a social constructivism and constructionism spirit, to support teaching and learning through hands-on activities in an inviting learning environment. During the last decade, a number of researchers and instructors have been frequently and fruitfully used ER as learning tools, in several contexts and disciplines, for the teaching of particular content knowledge in a field (e.g., mathematics and science [1]) or for supporting learning associated mainly with transversal skills such as problem-solving [2], metacognition (MC) [3], computational thinking [4], creativity [5], and collaboration [6].

However, despite the high attention emerged around this topic and the promising results from empirical studies, the evidence is not clear. Mainly, regarding the use of

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ER as tools to support MC the evidence is still ambivalent and fuzzy. Several studies that investigate the potential impact of ER activities on students' metacognitive thinking do not use validated measurement instruments [3]. Moreover, most of the previous works have used qualitative approaches to evaluate the outcome of ER activities in MC [7]. A holistic perspective on the issue of promoting MC via ER is still missing from the literature. All in all, research in the field of ER and their potential impact on students' metacognitive thinking is still in its infancy.

The present study aimed at examining the potential added value of ER activities in students' metacognitive thinking in the context of elementary STEM education. A one-group pre-test post-test research design was used to examine the hypothesis that ER can serve the learning process as metacognitive tools, supporting and promoting students' MC. Three research questions framed this investigation:

- RQ1: Are there gains in students' metacognitive abilities?
- RQ2: Which elements of MC improved?
- RQ3: Are there gains in students' abilities in mathematical problem-solving?

In the rest of the manuscript, we present the theoretical framework of this work, previous related studies, the methodology, and the results. We conclude with the discussion section and the interpretation of the findings.

2 Theoretical Framework

2.1 The role of metacognition in the learning process

Over the past years, there has been a growing interest among researchers in the study of MC [8]. MC is defined as "thinking about thinking" [9] and refers to meta-level knowledge and mental actions used to steer cognitive processes [10]. While several conceptualizations about MC exist, researchers widely agree that MC can be divided into a knowledge component and a skill component. The knowledge component is the "knowledge of cognition," and the skill component is "regulation of cognition." Knowledge of cognition is an individual's awareness of cognition and includes three subcomponents: declarative (knowing about things), procedural (understanding about strategies and other procedures), and conditional (knowledge of why and when to use a specific strategy) knowledge. Regulation of cognition indicates an individual's actions or mental activities to control their own cognition and includes three types of control: planning, monitoring, and evaluating [11]. Planning refers to goal setting, activating previous knowledge, and determining time. Monitoring comprises the self-testing skills to control learning and can be used to identify problems and to modify learning behavior when needed [12]. Evaluation relates to assessing the outcome and procedures of one's learning.

Over the past years, MC was recognized as one of the most relevant predictors of accomplishing complex learning tasks [13]. Researchers have shown that students with superior metacognitive abilities are better problem solvers [14], they know when and how they learn best, apply strategies to overcome obstacles [9] and regulate their own cognition. Furthermore, many studies have already been conducted to show that through metacognitive training, students' ability to solve mathematics problems im-

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proves [15]. The present study examines the hypothesis that ER can serve the learning process as metacognitive tools, supporting and promoting students' MC.

2.2 Educational Robotics and constructionism

The theoretical approach behind ER draws mainly on the theoretical perspective of Papert's [16] constructionism. As a pedagogical philosophy, constructionism states that students can learn when they are actively engaged in building some type of external artifact that they can reflect upon and share with others. The construction of the artifact itself drives students to acquire their own knowledge. One of the first constructivist tools was the Logo programming language developed by Papert as an implementation for Piaget's constructivist theories. ER can be considered as an extension of Logo and turtle graphics involving the programming of physical objects. Students interact with robots as a physical object (although the programming is happening digitally) and employ their knowledge and skills to solve real-world problems by challenging their existing knowledge, generating and experimenting their solutions [17]. From this perspective, ER is a constructivist tool which provides students the freedom to investigate their own interests while studying content and simultaneously applying metacognitive and problem-solving skills [1, 3].

3 Background work

3.1 Metacognitive Skills in Educational Robotics Activities

Empirical research records positive outcomes from the implementation of several ER projects providing evidence on the potential of ER to enhance students' metacognitive skills. While some studies have revealed that ER activities contain a variety of metacognitive experiences, only three studies appear to have reported a significant positive impact on learning [3, 7 and 8]. On the other hand, other studies failed to present positive results on the matter [18].

In an attempt to investigate the process of building and programming a robot as a metacognitive one, La Paglia et al. [3] found that ER activities can indeed allow students to monitor and regulate their learning. Keren & Fridin studied how ER can support the teaching of geometric thinking and help to promote students' metacognitive skills in kindergarten [19]. The authors found that students' performances on metacognitive assignments were improved while they worked on ER activities. More recently, Atmatzidou, Demetriadis, and Nika [8] conducted a quasi-experimental study with primary and secondary school students to investigate the development of students' metacognitive and problem-solving skills in ER activities performing different levels of guidance (strong and minimal). According to their findings, strong guidance had a positive impact on students' metacognitive and problem-solving skills.

In the authors' own previous work [7], a micro-level examination of elementary school students' discourse was conducted to identify the elements of collaborative knowledge construction and the role of the technology in an ER learning environ-

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ment. The results made evident that MC, along with questioning and answering, were prevalent elements of collaborative knowledge construction discourse around ER.

4 Methodology

This work employed a one-group pretest–posttest research design to examine the effectiveness of ER activities in improving students' MC.

4.1 Participants and Procedures

The sample of this study was 21 primary school students (N=21, 4th graders) in a public elementary school in Cyprus (13 girls, 8 boys) who participated in ER activities during a period of two-months. Two children were students with special educational needs and motor impairments (1 boy and 1 girl), and only one student had previous experience with programming and ER. Before the study, all the ethical approvals from the Ministry of Education and consent forms from the students' legal guardians were obtained regarding the data collection.

The participants were divided into five groups of 4-5 students of different genders and abilities (as perceived by their teacher). Particularly four groups of four students and one group of five students were formed. Students participated in eight sessions (80 minutes each) of ER activities (one session per week) in a typical classroom setting over a two-month period (as in Fig.1), during April and May of 2018.

Fig. 1. Classroom setting from an introductory lesson

Designing the technology-enhanced learning experience was a task undertaken by a teacher and an educational technologist. As presented in Table 1, the first two sessions were introductory lessons with preparation activities to help students get familiar with the EV3 environment. During this phase, essential programming details associated with this environment were described to them by presenting examples (directional commands, sensors, loop, and wait for). The next six sessions were STEM problem-solving activities; students should program a robot using a tablet or a computer to solve different problems according to the instructions and conditions of the activity (see Table 1).

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Table 1. The eight sessions of the course (80 minutes each)

Sessions	Tasks
Session #1 Introductory	a) Introduction to the learning objects of the curriculum. b) Opening the software, writing and saving a program, connecting the tablet or the computer to the brick with Bluetooth, running a program. c) Controlling the EV3 Motors (start programming motors); start, to finish, backup to start; start, to finish, turn around, back to start.
Session #2 Introductory	Using EV3 Sensors (start programming sensors); ultrasonic sensor, touch sensor, color sensor, and gyro sensor.
Session #3	Program your robot to move forward exactly 1.20m using (a) rotations, (b) degrees and (c) seconds.
Session #4	a) Program your robot to turn exactly 90 degrees using a gyro sensor. b) Program your robot to move on a square using a gyro sensor.
Session #5	a) Use the ultrasonic sensor to stop before hitting a wall. b) Program your robot to move forward by pressing the touch sensor until the ultrasonic sensor is 10cm from the wall. c) Program a robot that can move into the classroom without hitting any objects.
Session #6	a) Program your robot to say “green” when seeing a green object and “red” when seeing a “red” object. b) Program your robot to move forward when seeing a green tape and stop when seeing a red tape.
Session #7	Program your robot to move a block from one square to the other using the medium motor (cargo deliver attachment).
Session #8	Design a maze using objects from the classroom and program your robot to solve the maze without touching any objects.

We followed a low coercion approach for students’ metacognitive training. Typically, in every session, the students were given a worksheet with tasks of increasing difficulty. The worksheets were structured to support students on technical aspects but not to lead or guide them in solving the problems. The teacher acted as a facilitator, supporting student’s thinking in the form of hints, prompts and feedback without providing any answers. He often prompted students with questions such as: Why are you doing it? What are you doing? He prompted students to externalize representations of metacognitive thinking and problem-solving procedures verbally.

The groups followed a typical problem-solving cycle, without any formal prompting from the teacher and without any previous training to do so. A typical problem-solving cycle of an ER activity as undertaken by the students included three major steps: (i) understanding the problem – teammates read and defined the problem, (ii) plan a strategy – teammates proposed ideas and planned together, (iii) executing of a plan – students used the robot to execute; their strategy was reconsidered based on the robot’s performance (i.e., teammates evaluated the outcome).

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4.2 Data collection and instrumentation

Data was collected via a profile questionnaire on demographic data and two assessments measuring individual metacognitive awareness, as presented below.

Profile questionnaire. Before the learning activities, students answered an individual profile questionnaire. This questionnaire recorded demographic data (such as gender and age) and learners' experience with programming and ER.

Metacognitive Awareness Inventory [MAI]. We used the MAI instrument [20] as pre- and post-assessment, to assess the development of children's metacognitive thinking. The MAI questionnaire was given to all participants before and after the learning experience. Due to low reading levels, the questionnaire was read aloud by the teacher i.e., the teacher read each statement to the whole class, students answered, and when he was sure that all the students completed an answer then he proceeded to the next question.

MAI questionnaire is a 52 items self-report instrument consisted of multiple items which can assess metacognitive awareness in two factors -- knowledge of cognition and regulation of cognition. The participants answered these items by indicating their degree of agreement with each statement, on a 5-point Likert scale, ranked from 1: strongly disagree to 5: strongly agree. The first factor, "knowledge of cognition" consists of 17 items and can be classified into three subscales: declarative knowledge (knowledge about self and strategies), procedural knowledge (knowledge about how to use a strategy) and conditional knowledge (knowledge about when and why to use a strategy). The second factor, "regulation of cognition" (35 items) consists of five subscales: planning (goal setting), information management (organizing), comprehension monitoring (assessment of one's learning and strategy), debugging strategies (strategies used to correct failures) and evaluation (evaluation of performance after a learning experience). The reliability and validity of the MAI have been recorded in several previous studies (e.g., [21, 22]). For example, Baker & Cerro [21] found that MAI had a strong internal consistency for the "knowledge of cognition" (Cronbach's alpha = .88) and "regulation of cognition" (Cronbach's alpha = .91) scales.

Visualization and Accuracy Instrument [VisA]. VisA instrument was given to all participants before and after the learning experience to further investigate the development of students' metacognitive thinking. VisA combines students' prediction judgments, postdiction judgments, and visualizations to assess online MC and particularly the combination of metacognitive monitoring and regulation which are interrelatedly used during problem-solving [15]. Students responded in four mathematical problems. In each problem students were asked to divide their solutions into four steps: (a) read and rate their confidence in solving the problem correctly (prediction judgment), (b) draw a sketch to visualize the problem (visualization), (c) solve the problem, and (d) rate their confidence for having found the correct answer (postdiction judgment).

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Mary plants rosebushes along a path to her home. The path is 27m long. She plants a rosebush every 3m on both sides of the path. She also plants rosebushes at the beginning of the path (on both sides). How many rosebushes does Mary need?

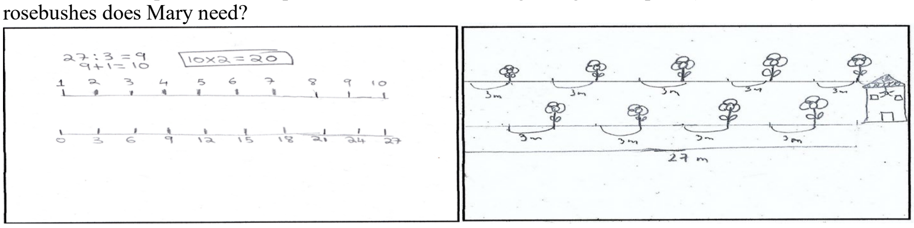

Fig. 2. Example of students' artifacts from post-VisA administration; schematic visualization with mathematical features (left) and pictorial with mathematical features (right).

The scoring procedure was simple. Students got one point for each correct prediction or postdiction judgment and zero points for each uncertain or incorrect prediction or postdiction judgment regardless of whether they had solved the problem correctly or not (i.e., if a student predicted that he could solve the problem and indeed did it, he got 1 point; or if he predicted that he could not solve the problem and indeed didn't, he again got one point). For the visualizations, students got zero points if they made pictorial or irrelevant sketches without showing any important aspects or relationships of the problem, they got 0.5 if their sketches were partly pictorials with some schematic or mathematical features and they got one point if their sketches were primarily schematic visualizations with mathematical features (see Fig. 2). The maximum score for each student was 12 points (4 problems x 3 points each). The first 30 visualizations (17.9%) were evaluated with two judges until a consensus about scoring rules was reached. Reliability was high (agreement over 90%) and, therefore the first researcher finished the scoring procedure alone.

Pre-post mathematics test. For assessing mathematical knowledge gains, we used the data from the four problem-solving tasks from the two administrations of the VisA instrument. We also looked for the correctness of their solutions (not their judgments and visualizations). Each correct task was scored with 25 marks, and the maximum possible score was 100 marks. The four tasks were adapted from the released 4th-grade assessment questions from previous studies of Trends in International Mathematics and Science Study (TIMSS).

5 Findings

5.1 MAI Questionnaire

First, Cronbach's coefficient alpha reliabilities were computed for the MAI scales, both for pre- and post- administrations; the scales had strong internal consistency for pre and post (Cronbach's alpha >.81). Then, un-weighted mean scores were calculated for scales and subscale. Paired-sample t-test analysis showed statistically significant differences on "regulation of cognition" [t(21)= -7.83, p< .001] with students exhibiting higher levels of "regulation of cognition" in the post-test (M=4.02;

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SD=0.21), compared to the pre-test (M=3.70; SD=0.29) with large effect size (Cohen's d = 1.71). Instead, there was no statistically significant difference in "knowledge of cognition", t(21) = -.61, p = .55 from pre-testing (M=3.68; SD=0.46) to post-testing (M=3.72; SD= 0.32). With respect to the subscales of "regulation of cognition", the results demonstrated statistically significant differences with a large effect in three of the five subscales: Planning [(t(21)= -9.28, p= .000, d = 2.05], Comprehension Monitoring [t(21)= -3.65, p= .002, d = 0.80)] and Debugging Strategies [t(21)= -6.97, p< .001, d = 1.52] (see Table 2).

Table 2. Comparing pre- and post-MAI scores for each variable.

Variables	Pre-test M(SD)	Post-test M(SD)	t-test Statistics (Effect Size)
Knowledge of Cognition	**3.68 (0.46)**	**3.72 (0.32)**	**t(21)= -0.61, p= .55**
Procedural Knowledge	3.79 (0.30)	3.83 (0.50)	t(21)= -0.38, p= .71
Declarative Knowladge	3.55 (0.59)	3.59 (0.57)	t(21)= -1.30, p= .208
Conditional knowledge	3.78 (0.69)	3.85 (0.48)	t(21)= -0.36, p= .73,
Regulation of cognition	**3,70 (0.29)**	**4.02 (0.21)**	**t(21)= -7.83, p< .001 d = 1.71**
Planning	3.47 (0.59)	4.01 (0.44)	t(21)= -9.28, p< .001 d = 2.05
Comprehension Monitoring	3.79 (0.64)	4.18 (0.39)	t(21)= -3.65, p= .002 d = 0.80
Evaluation	3,77 (0.60)	3.98 (0.36)	t(21)= -2.63, p= .016
Debugging Strategies	3.74 (0.64)	4.26 (0.44)	t(21)= -6.97, p< .001 d = 1.52)
Information management strategies	3.75 (0.42)	3.80 (0.45)	t(21)= -1.17, p= .255

5.2 Students' visualization and accuracy (ViSa)

Once again, the scales had strong internal consistency for pre and post (Cronbach's alpha >.80). Paired t-test analysis indicated that students improved their performance from pre to post-testing; this difference was statistically significant [t(21)=-2.96, p<.005)] with medium effect size (d=0.797). Furthermore, the analysis showed a statistically significant increase in students' accuracy on prediction judgments and postdiction judgments (Table 3) from pre-testing to post-testing with medium effect size (d=0.65 and d=0.70 respectively for both variables). However, there was no statistically significant difference in students' visualizations from pre- to post- testing.

Table 3. Comparing pre- and post- VisA scores

Variables	Pre-test M (SD)	Post-test M(SD)	t-test Statistics (Effect Size)
Visualization & Accuracy	2.03(0.66)	2.33 (0.59)	t=(21)= -3.65, p= .002, d= 0.797
Prediction	2.33 (0.73)	2.71 (0.64)	t(21)= -2.96, p= .008, d=0.65
Visualization	1.43(0.88)	1.45 (0.72)	t(21)= -0.204, p= .84
Postdiction	2.33(0.73)	2.81 (0.68)	t(21)= -3.21, p= .004, d=0.70

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5.3 Learning Gains

A total pre and post-test score was computed for each participant, by summing up the correct answers and adjusting to 100. A paired-samples t-test was conducted using students' data from the two administrations of ViSa. The analysis showed a statistically significant increase, t(21) = 2.65, p = .016, from pre- (M=59.52%; SD=16.73) to post-testing (M=67.86%; SD= 19.59), with medium effect (d = .58).

6 Discussion

Despite the widespread use of robotics in education, their role as a metacognitive tool remains ambivalent. This study investigated the hypothesis that ER can serve the learning process as metacognitive tools, supporting and promoting students' MC in the context of elementary STEM education. Prior studies mainly observed metacognitive behavior in ER activities. To our knowledge this is the first investigation of the matter of MC via ER using a quantitative dataset and therefore, it represents an extension of previous work in the area.

Four significant breakthroughs have emerged in the present study. In accordance with prior empirical studies [e.g., 3, 7, 8] our research has provided evidence supporting the positive impact of ER activities on students' metacognitive thinking (RQ1). Our teaching procedure can be considered as a low coercion approach for students' metacognitive training. In contrast with the study of [8] which they found an improvement on students' metacognitive skills only in "strong guidance" groups, we found that MC can also take place with a minimal guidance approach. This finding further emphasizes the instrumental role of the technology in supporting students' metacognitive processes. The improvement in students' metacognitive thinking is seen as a collective result of the technology use, group work, teacher's interventions and the nature of the activities. However, we think that the role of the technology was instrumental since it enabled a spontaneous 3-stages problem-solving process (understanding the problem, planning, executing & evaluating) which can be considered by itself as a metacognitive learning protocol.

The collection of evidence of students' metacognitive processes by assessing students' judgments of their own performance (calibration), demonstrated that there was a statistically significant increase for students' accuracy on prediction judgments and postdiction judgments from pre-testing to post-testing (RQ1). The ability to judge one's performance has been conceptualized as an expression of metacognitive monitoring [23]. We, therefore, confirm previous findings about the positive impact of ER activities on students' abilities to monitor their own learning [1, 7]. Perhaps, that is because ER activities are based on procedural knowledge and engage students naturally in the process of exploration for solving a problem; yet, further research is needed to fully understand what elements of ER contribute to students' metacognitive thinking.

Furthermore, we found that ER activities have no impact on students' abilities to visualize a problem scenario. The latter contradicts to the previous finding of students' improvement on performance accuracy as someone would expect students to

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improve their visualizations. However, we know that the accuracy of performance judgments gives information into a limited part of metacognitive processes (only in monitoring by looking forward or backward about a solution plan for a problem). Also, to visualize a problem scenario is an activity that may need further skills or something that may require a longer time to be improved.

Moving a step forward, our study provides evidence that ER activities have a greater positive impact on three regulatory subcomponents of MC such as planning, monitoring, and debugging strategies (RQ2). These subcomponents are related to “regulation of cognition,” and ER seem to tackle these aspects of MC well. This finding can be considered as crucial knowledge for educators who see their elementary students struggling in solving multi-step problems. Training these aspects of MC can help their students become more effective in solving multi-step problems in several disciplines and in general, to become more effective problem-solvers. Since a low level of guidance was applied, this improvement cannot be explained beyond the role of ER as “scaffolding embedded technological tools” [24]. These findings are in line with previous work by the authors [7] showing that students’ discourse over ER activities included a large volume of regulatory and self-control elements such as metacognitive monitoring and planning.

Last but not least, in agreement with the prior work (e.g. [25]), the present study demonstrated a statistically significant increase on students’ ability to solve logical-mathematical thinking problems from pre to post-testing (RQ3). It should be noted that our ER activities were not specifically aimed at improving students' abilities in mathematical problem-solving; instead, they were more about STEM and programming concepts. Therefore, it becomes evident that positive results in mathematical problem-solving can be documented via an interdisciplinary approach to ER activities in elementary education, capable of expanding the curricular space [17].

Depside the encouraging results of the study, some limitations of this work are also important to note. First, the study is based on a small sample size, although comparable with relevant studies in the literature [3, 7, and 8]. Second, the sample was drawn from a population of convenience. Third, the duration of the study (two-months) might have caused a maturation effect in the study, linked to the students’ development of MC. Future research could replicate this study with a larger (and preferably random) sample of participants, whilst aiming for a control group helping to address a possible maturation effect.

7 Conclusion

This study provides empirical evidence on the added value of ER for learning. We examined the hypothesis that ER can serve the learning process as metacognitive tools, supporting and promoting students’ MC. Our results suggest that ER activities can improve students' metacognitive and mathematical problem-solving skills. Specifically, the study demonstrated that: (a) students developed their metacognitive and problem-solving skills through ER activities, (b) students’ accuracy on performance judgments was significantly improved, as yet another piece of evidence of metacogni-

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tive development, (c) regulation and self-control components of MC such as planning, monitoring, and debugging strategies were activated more than knowledge components of MC, (d) students' abilities in mathematical problem-solving were significantly improved. Given the encouraging results of the study, one might suggest that ER activities can be a vehicle to the development of MC skills in elementary education, although further research is needed to support this argument. We hope this work will motivate further research in the area of educational robotics for metacognition and learning.

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