A Study of Collaborative Knowledge Construction in STEM via Educational Robotics

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Abstract: The educational robotics learning environment can integrate the benefits of robotics technology, computer supported collaborative learning (CSCL) and problem-based pedagogy, in an authentic learning space, simulating real-world problems. This study investigated primary school students' patterns of knowledge construction in STEM, as they engaged in collaborative problem-solving using educational robotics. Data analysis involved micro-level examination of students' discourse and interactions with their peers, the teacher and the robot, and students' delivered solutions (software programs and worksheets). The study presents three conditions that appear to relate to higher levels of knowledge construction: (i) embodied interaction with the robot; (ii) fair contribution by teammates adhering to predefined roles, and (iii) cognitive dissonance as a result of the robot's failure to perform the expected outcome. The study contributes to the design of educational robotics learning environments and conditions for collaborative knowledge construction in the STEM field.

Introduction

Since the beginning of the 21st century, there is a growing discussion about changes that should be made in the education systems in order to be able to meet the needs of the borderless, globalized and internationalized world. Problem-solving, critical thinking and collaboration are typically identified as key skills for success in the 21st century. Many reform efforts of the educational systems of advanced countries aim towards this direction. Frequently, learning in the science, technology, engineering, and mathematics (STEM) domains are cited as vehicles for the development of these skills for students (Ardito, Mosley & Scollins 2014).

Contemporary educational inquiry highlights the need to incorporate a technology-rich learning environment into the teaching of the STEM domains. The technology offers support for learning STEM-related school subjects or for enacting cross-curricular learning activities. Among flourishing arrays of technologies, educational robotics could be a highly effective learning environment for teaching STEM concepts (Barker et al., 2008). Educational robotics provides the opportunity for real-world application of science concepts, technology engineering, and mathematics, and helps to remove the abstractness of these fields (Nugent et al., 2010).

In this work, we present a learning experience using educational robotics, allowing students to engage in collaboration and co-construction of shared understandings in the fields of STEM. Our goal was to: a) field-test our design and explore patterns of collaborative knowledge construction, and b) explore the mediating role of educational robotics in our context. Below, we first present past papers on educational robotics and collaborative knowledge construction. Next, we present the theoretical grounding for our design and we detail the specifics of our activities and implementation procedures in a classroom setting. We conclude the section by presenting our findings from a field study with 14 student-participants and discussing possible links between the use of educational robotics and the observed outcomes.

Background work

Educational robotics

Our review of the literature reveals that educational robotics are used in education as a tool for achieving the following main objectives: a) to teach STEM, b) to develop learning skills such as problem solving, collaboration, scientific inquiry and critical thinking and c) to foster student motivation to engage in science and technology (Nugent et al. 2010). According to Eguchi (2010) most of the empirical work in education has focused on the first main objective. The majority of this work explores topics related to the field of physics and mathematics and emphasizes on skills that can be developed through robotics such as, problem solving skills, logic and scientific inquiry (Benitti, 2012). However, few studies have dealt with how knowledge is constructed and what elements of educational robotics can be associated with or can promote collaborative knowledge construction.

Many studies of educational robotics have been conducted in the recent years. These investigations have focused mainly on higher education; fewer studies have been conducted with secondary and elementary school students. Educational robotics with k-12 students have been implemented mainly out of schools, in summer or after-school programs and competitions (Barker et al., 2010). In general, there is limited empirical evidence to prove the direct impact of educational robotics on the k-12 curriculum. Many educators, researchers and educational theorists (e.g., Papert) believe that robotics can provide an enormous source of energy that can be used to stimulate children's learning. Overall however, while the arguments for the benefits of educational robotics in the classroom continue to grow, scientific inquiry in the area is sporadic and most of the literature is descriptive in nature. The processes and conditions under which any specific learning goals are achieved are far from being documented. Thus we need first to explore what educational robotics have to offer to education, before we arrive in overestimated and possibly wrong conclusions regarding their pedagogical value. Another main weakness in the area of educational robotics is the absence of clearly defined curriculum and educational material for teachers. Alimisis (2013) pointed out that there is no systematic introduction of robotics in school curricula within the European school systems.

Educational robotics and STEM-related outcomes

There are already a number of reports from robotics programs claiming that educational robotics can improve the performance of students in STEM (Bers & Portsmore, 2005; Nagchaudhuri, Singh, Kaur & George, 2002, as stated in Bilotta et al., 2009). For example, the use of educational robotics led to the enhancement of students (a) mathematics performance (Highfield, 2010; Nugent et al., 2009) (b) science performance and physics content knowledge (Mitnik et al., 2008) (c) engineering design skills (Larkins, Moore, Rubbo & Covington, 2013; Hong et al., 2011), and (d) STEM knowledge (Barker et al., 2010; Barker & Ansorge, 2007). Other benefits from the use of robotics include improvement in collaboration skills (Nugent et al., 2009; Mitnik et al., 2009) problem-solving skills (Nugent et al., 2009), creative thinking (Barak & Zadok, 2009), and scientific inquiry (Sullivan, 2008).

Educational robotics and collaborative knowledge construction

In the last 20 years, researchers have seriously studied learning in small groups and the nature of cooperation and interaction have turned into a focal issue for research on learning in social settings. Essential to collaborative learning is knowledge construction where the collaborative learning aims at co-constructing knowledge upon sharing information in groups for solving given tasks (Alavi & Dufner, 2005). In the recent years, the focus of knowledge construction moved from knowledge attainment to skill development knowledge in order to prepare students for the challenges of the 21st century (Wen, Zaid & Harun, 2015). The focus moved from simply gathering information to a more complex process of researching and thinking critically about the new information in order to use it in meaningful ways.

The joint construction of knowledge allows learners to experience a greater level of understanding (Kafai & Resnick, 1996) because they must construct their own knowledge to learn the truth (Tam, 2000). Knowledge is constructed by students when they participate and evaluate their own learning. Collaborative knowledge construction encourages students to investigate deeper about a subject so that can reach their highest potential level of development. The development of new understanding is coming as a combination of prior knowledge and skills with new experiences.

An educational robotics class can potentially contribute to the collaborative knowledge construction process. In a learning environment, educational robotics has the role of mindtools. The term "mindtools", as proposed by Jonassen (2000) in the sense of cognitive tools, represent the constructionism dimension of constructivism. Using educational robotics as mindtools, in a classroom, we apply constructivism -- students construct a physical object, while at the same time they construct problem solving knowledge. Learning is no longer teacher-centered but knowledge is actively constructed by the learner (Harel & Papert, 1991). Students can change or negotiate their existing knowledge into explicit knowledge. Knowledge construction is therefore, formed through a dual pathway; through interaction with the artifact and through interaction with peers. Several studies indicate that educational robotics can be used as mindtools supporting knowledge construction through the design of meaningful artifacts in authentic projects, learning by doing, facing cognitive conflicts and learning by reflection and collaboration (Mikropoulos & Bellou, 2013; Jonassen, 2000).

Learning design

Pedagogical aspects

Our work draws on social constructivism, which emphasizes the importance of social interaction in knowledge construction (Palincsar, 1998). Many popular educational formats such as problem-based learning and computer-supported collaborative learning (CSCL) have their roots in social constructivism, which states that group discussions can help students learn. In this work, we see educational robotics as fully compatible with the nature of collocated CSCL. The technology provides a way to infuse real world experiences to the CSCL setting, through the hands-on nature of collaborative activities they can facilitate. Also, in line with problem-based learning pedagogy, we aim for students, in groups, to engage in problem-solving processes such as defining the problem, developing a strategy, testing and experimenting, and reflecting in and on action (Ioannou, Vasiliou, Zaphiris, 2016). Problem-based learning helps situate learning in meaningful tasks and emphasises the importance of practical experience in learning (Hmelo-Silver, 2004; Ioannou, Brown, & Artino, 2015). In CSCL environments, participants are actively engaged in creating or co-constructing knowledge. Although in most CSCL studies, collaboration takes place through a computer network, face-to-face interactions have proven to be the richest communication media, conveying the greatest social presence (Newberry, 2001), and consequently, increasing the quality of learning and the achievement of learning objectives (Aspden & Helm, 2004).

Educational robotics activities and processes

Designing the technology-enhanced learning experience was a task undertaken by a teacher and an educational technologist. We used the Lego Mindstorms EV3 toolkit. Content for the activities came from: a) the national curriculum on mathematics and science education, and b) the EV3 STEM curriculum. Typically, the teacher presented students with a challenge and a mat. There was no clear path to the solution; students could adopt any strategy to come to a solution to the challenge. The teacher acted as a facilitator, supporting student's thinking without providing any answers. Upon completion of each task, a debriefing phase took place: groups demonstrated their strategies in addressing the challenge and they answered questions asked by the teacher and students in other groups. The teacher facilitated discussion on best strategies and reflection on what kinds of problem-solving and STEM skills were learnt. Sample activities are presented in Table 1 while Figure 1 summarizes the learning cycle.

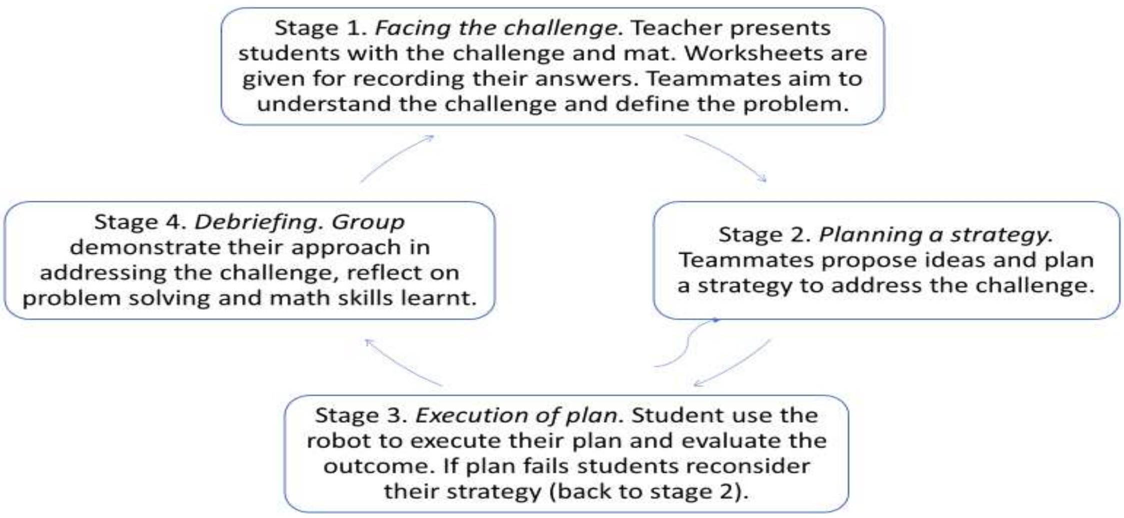
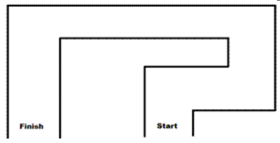
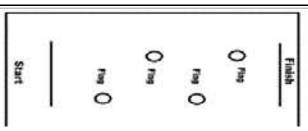
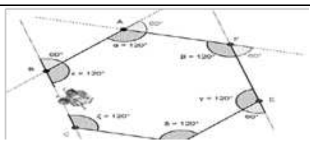


Figure 1. Typical problem-solving cycle of an educational robotics activity.

We further decided to assign roles within teams to encourage positive interdependence, interaction, and group processing and to ensure that everyone contributes and participates in the learning process. We assigned three distinct roles: the recorder (responsible for taking notes and keeping track of group data), the programmer (responsible for the programming and controlling the movements of the robot using a tablet), and the distance-measurer (responsible for measuring the position of the robot, putting the robot to the starting line, and observing carefully the robot moves in order to give feedback to the rest of the group). In practice, the roles are interdepended. That is, the programmer interacts with the distance-measurer to acquire relevant data through measurements or through distance-measurer's own observations on the robot's behaviour. The distance-measurer interacts with the recorder to report data for recording. The recorder interacts with programmer to indicate the readiness of the data collection for further action or give auxiliary data based on current data collection that may help with programming the robot. Roles were randomly assigned to students. From task to task the teacher ensured that the roles rotated amongst the team-members.

Table 1: Sample educational robotics learning activities

Activity	Explanation	Main STEM Pillars
	Maze challenge (80 min) Groups program the robot to move from its starting position through a without touching any walls.	Numbers & calculations, robot sensors, robot wheels diameter and speed vs. turns, loops, measurements
	Robot-slalom challenge (80 min) Groups program a robot to move along the outside of each flag and cross the finish.	Numbers & calculations, robot sensors, geometrical symmetry, swing turn and point turn, loops, measurements
	Draw a hexagon challenge (80 min). Students program their robot to draw a hexagon using a gyro sensor.	Numbers & calculations, polygons, supplementary & complementary angles, internal & external angles, design a pen holder, measurements

Field study

Participants, setting and data collection

Our sample was composed of 14 students (6 males) in Grades 4, 5 and 6 (9-11 years old) who attended a public elementary school in Cyprus. Students were divided into 4 groups, mixing gender, technological, and problem-solving abilities. There were two weeks of preparation activities to help students get familiar with the EV3 robot (e.g., move straight ahead, turn base on some angle, use sensors, robot decisions e.g., loops), followed by three 80-minutes sessions of STEM problem-solving activities. Two cameras were placed in the room to fully cover student interaction and technology use. Verbal contributions were captured separately via audio recorders next to each team; audio was later synced with the video.

Coding of video data and plotting chronological diagrams

All video data were transcribed verbatim and content analyzed. We used the coding scheme reported in Gunawardena, Lowe, & Anderson's (1997) Interaction Analysis Model, which conceptualizes the level of social and collaborative knowledge construction. The analysis focused on the "unit of meaning", each unit fitting into a sole category of the coding scheme (e.g., from minute 0:30 to 0:35 teammates share ideas on potential strategies). Overlapping talk was attributed to the most dominant category and team member. Around 30% of the video was coded by the first researcher, with a second researcher independently coding the same units. Reliability was high (agreement over 90%) and therefore, the first researcher finished coding the complete dataset. Table 2 presents examples of application of the coding scheme.

Table 2: Examples of application of the coding scheme of collaborative knowledge construction

Level	Operation	Example excerpts from the data
KC-1: Sharing/ comparing/ adding of information.	Statement of observation, opinion or a background information; Definition description or identification of a problem;	P2: "We will use the ultrasonic sensor to avoid the flags.

KC-2: Discovery and exploration of dissonance or inconsistency.	Identifying areas of disagreement; Asking and answering questions to clarify disagreement; Restating participant's position.	P3: "No, we tried using the ultrasonic sensor when we solved the maze challenge and took us a lot of time. What do you think"?
KC-3: Negotiation of meaning/co-construction of knowledge.	Negotiation or clarification of the meaning (building on previous statements); Synthesis-proposal, and negotiation of new statements (creating solutions);	P4: "I will draw a hexagon to find how many triangles are formed." P5: "So, 4 triangles multiplies by 180° equals 720° divides by 6 angles…(thinking) 120°".
KC-4: Testing and modification of proposed synthesis or co-construction.	Testing of new synthesis against existing cognitive knowledge, personal experience, and formal data with the prospect of finalizing it.	P5: "No, what is he doing? It is turning too much (while observing the drawing of the robot). What went wrong?" P6: "There is a problem with the gyro sensor. Let's remove it and put it back"
KC-5: Agreement/ application of newly constructed meaning.	Summarization of agreements; Application of new knowledge; Metacognitive statements illustrated changes of in knowledge	P13: "Yes, that's it. Bravo! The robot must turn as much as the supplementary angle of the internal angle. That was clever."

For a chronological investigation of within-group collaboration, we further plotted student's discourse and activity on chronological diagrams. We used the CORDTRA technique, initially suggested by Hmelo-Silver et al. (2011). This technique of visual representation enables one to combine the chronological visual of discourse with other types of coded data allowing for the examination of patterns and behavioral sequences.

Findings and discussion

Embodied interaction with the physical robot is linked to higher levels of knowledge construction

Based on Table 3, out of 172 coded units, the majority of verbal interactions (38,4%) was coded in the lowest level of knowledge construction (KC-1). This was followed by students' KC-4 level involving 43 verbal units (25%) and KC-3 level involving 37 verbal units (21,5%). KC-2, appeared with a relatively lower percentage than expected with only 18 coded units or 10,6%. The highest level of knowledge construction (KC-5), was difficult to achieve and was only represented by 8 units (4,5%). Gunawardena, Lowe, and Anderson's Interaction Analysis Model has been almost exclusively used only in online learning discourse in CMS and CSCL settings (e.g., Ioannou, Demetriou & Mama, 2014). According to these studies, KC-1 statements accounted for the largest percentage of the overall discussion and were prerequisite for subsequent higher levers of knowledge construction. The findings of the present study differ from typical results of online learning activity in that, KC-4 accounted for the second largest proportion of discourse units.

Table 3: Number of Codes Across Levels of Knowledge Construction and Groups

	Group 1	Group 2	Group 3	Group 4	Total (%)
Sharing/adding (KC-1)	20	15	12	19	66 (38,4%)
Exploration of dissonance (KC-2)	5	6	3	4	18 (10,6%)
Negotiating meaning (KC-3)	16	9	4	8	37 (21.5%)
Testing synthesis (KC-4)	13	9	6	15	43 (25%)
Applying co-constructed knowledge (KC-5)	3	2	0	3	8 (4.5%)
Total	57	41	25	49	172(100%)

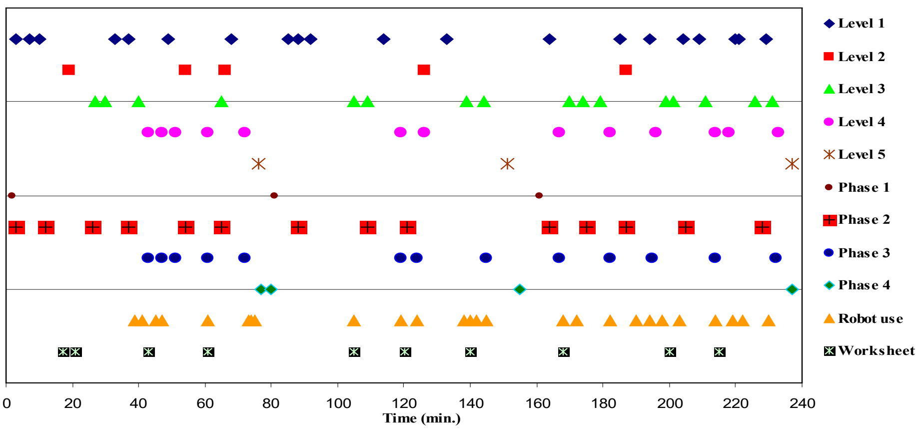
The increased KC-4, compared to previous CMC and CSCL studies, lead us to hypothesize that educational robotics might have encouraged knowledge construction at this level because of the hands-on experimentation and embodied interaction with the physical robot. We therefore, used chronological diagrams, to pinpoint what students were doing, when they exhibited KC-4 of knowledge construction. By zooming into the groups' chronological diagrams, we found that "Execution of Plan" was tightly coupled with higher levels of knowledge construction. That is when students interacted with the physical robot to execute their plan, they often engaged in KC3-KC5 (see Figure 2). Students were engaged in a process of “conversation with the robots”, through which they promoted self-directed learning and engaged in the construction of new knowledge. The physical and embodied interaction with the robot gave students the opportunity to test or modify their new synthesis (KC-4) against existing cognitive knowledge, personal experiences, and data.

Fair contribution by teammates adhering to predefined roles is linked to higher levels of knowledge construction

We found that collaborative knowledge construction was more evidenced in some groups than others. Groups 1, 2 and 4 appeared successful in engaging in the collaborative knowledge construction process, since their discourse involved contributions along all phases of knowledge construction. On the other hand, group 3 with only 25 coded units demonstrated limited engagement with the activities, whilst their discourse never reached the higher levels of knowledge construction. This case made us hypothesize that lack of within group interaction might have hindered collaborative knowledge construction. We therefore took a closer look at videos and chronological diagrams of all groups (see Figure 2; due to space limitations we present only the visuals of 2 groups) to pinpoint patterns of collaboration in relation to knowledge construction. We found that in groups 1,2 and 4 all teammates were active participants in the learning process, whilst they participated fairly, adhering to their predefined roles. Instead, members of group 3 did not serve their pre-defined roles and did not participate fairly in the tasks which seems to have led to failure in engaging in collaborative knowledge construction. It therefore appears that, assigning roles to teammates and serving these roles enabled fair contribution, individual accountability and social interdependence (Johnson et al., 1991) leading to better quality discourse and knowledge construction.

Cognitive dissonance is linked to higher levels of knowledge construction

A detailed examination of chronological visuals and associated groups’ discourse helped us understand the progressive interactions and breakdowns within each group. We noted that KC-2 (discovery and exploration of dissonance or inconsistency) was relatively rare in students’ contributions (only 10,6%). What’s more, when KC-2 type of discourse appeared, it took a while for the next level of contribution to appear. We therefore sought to understand cognitive dissonance and when it occurred. Zooming into the groups’ chronological diagrams and associated discourse, we found that cognitive dissonance was less often related to disagreement between the teammates and more often related to the robot’s failure to perform the expected outcomes during the execution of a planned strategy (stage 3 of Figure 1). In this case, students had to reconsider their strategies (i.e., going back to stage 2 of Figure 1). The finding suggests that the robot and its failure to deliver the expected result was a mediator to the discovery of cognitive dissonance or inconsistency; the latter was a time-consuming process which teammates struggled to overcome. Nevertheless, when the group overcame this stage, they engaged in higher levels of knowledge construction as evidenced in their chronological discourse. That is, inspection of the chronological diagrams of groups 1, 2 and 4 makes obvious that KC-2 contributions, i.e., cognitive dissonance mostly related to the robot’s failure to perform, are followed by contributions coded in the higher levels of knowledge construction (see Figure 2).



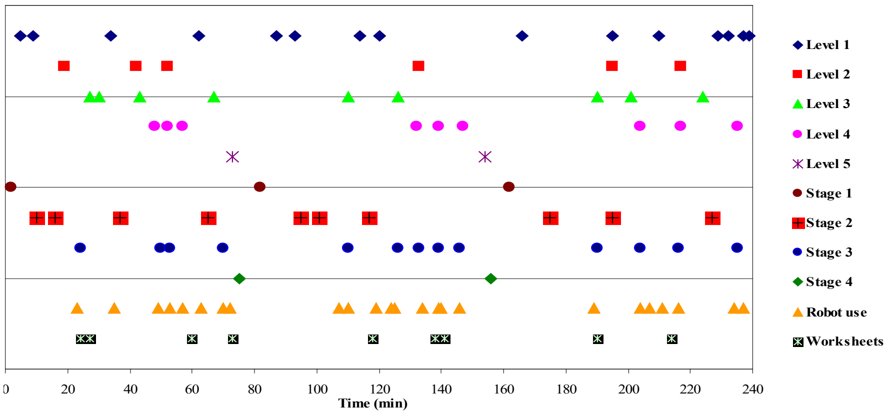


Figure 2. Chronological visual for group 1 and 2. The time of the contribution runs at the horizontal axis and the discourse-coded levels and the stages of the problem-solving cycle are listed on the vertical axis.

Conclusion

This work begins to collect the much-needed evidence around the practical utility and potential impact of educational robotics in school contexts. We described the design of a learning experience using EV3 educational robotics, allowing 14 students in the math and science classroom to engage in collaborative learning and problem-solving. We addressed the effectiveness of educational robotics in terms of collaborative knowledge construction in the STEM field. The findings demonstrated how knowledge is constructed and which elements of educational robotics and teamwork can promote collaborative knowledge construction in an educational learning environment. Overall, we offer a case study in which established pedagogy (problem-based pedagogy) blends with technological capabilities (robotics) to enable students to practically apply the key elements they are being exposed to in their STEM education curriculum. Educators can use these findings to develop interventions to assist students in engaging in higher levels of knowledge construction using educational robotics.

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