Educational robotics and inquiry learning: Assessing learning products across iterations

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Abstract
Educational robotics provides an excellent opportunity for orchestrating open-ended learning activity sequences in inquiry learning that involve a trajectory with questioning and exploration instead of the more close-ended trajectory with hypotheses and experimentation. In the present study, we developed and implemented an educational intervention in real classroom contexts, which intended to integrate inquiry-based learning and educational robotics. We planned for multiple iterations, where students were engaged in subsequent cycles of design, programming, testing, and revision. To monitor and evaluate student performance, we assessed the quality of learning products delivered by students. Our objective was to examine if student performance improved within and across iterations. Participants were 46 Cypriot primary school students, who worked in groups of two (5 groups) or three (12 groups) to design routes of a robotic vehicle in a hypothetical neighborhood, translate these instructions into block-based programming creating flow diagrams, test the movement and behavior of the GINOBOT and improve their flow diagrams so that the observed movement and behavior match their instructions. The same cycle was repeated in four iterations with increasing programming complexity. In contrast to previous research, which has documented a decreasing trend in achievement when young children were engaged in multiple lessons of block-based programming of increasing difficulty, our results indicate that students progressed within each iteration as well as from one iteration to the next. Our constructionist approach can be exploited for assessing student performance in open-ended learning settings with few participants, where control groups cannot be easily compared to experimental groups, and where pre-post tests would most probably fail to grasp the richness of student actions and paths.

Introduction
There have been several calls to integrate inquiry-based learning and educational robotics (Altin & Pedaste, 2013; Blancas et al., 2020). Educational robotics provides an excellent opportunity for orchestrating open-ended learning activity sequences in inquiry learning that involve a trajectory with questioning and exploration instead of the more close-ended trajectory with hypotheses and experimentation (see Pedaste et al., 2015). In this case, it would be insightful to track student performance within an inquiry cycle as well as from one inquiry cycle to the next. A crucial consideration is how to evaluate such open-ended learning environments, where implementations involve few students, where control groups could hardly be established to be compared to experimental groups, and where pre-post tests may not grasp the richness of student actions and paths (see Hamner et al., 2010). In the frame of the present study, we developed and implemented an educational intervention in real classroom contexts, which intended to integrate inquiry-based learning and educational robotics. We planned for multiple iterations, where students were engaged in subsequent cycles of design, block-based programming, testing, and revision (for the need of iterations in educational robotics see Chevalier et al., 2022). To monitor and evaluate student performance, we assessed the quality of learning products delivered by students. We define learning products as physical or digital artefacts constructed by learners during learning activities by means of physical or digital tools (e.g., flow diagrams used to program

robots) (Hovardas, 2016; Hovardas et al., 2018). Our objective was to examine if student performance improved within and across iterations.

Methods

Participants were 46 Cypriot primary school students, 45.7% female, distributed in three classes: Group 1, N = 19, mean age = 7.74 years; Group 2, N = 16, mean age = 8.31 years; Group 3, N = 11, mean age = 8.27 years. Students worked in groups of two (5 groups) or three (12 groups) to design and execute routes of the GINOBOT (https://www.engino.com/w/index.php/products/innolabs-robotics/ginobot), which was operationalized as a wheelchair moving in a hypothetical neighborhood modelled on a two-dimensional track (Figure 1). After a first set of familiarization activities (manual programming of the GINOBOT; transition from manual programming to software programming), students designed routes for the GINOBOT (e.g., move from home to school along the pavement and pedestrian crossings and recognize obstacles, e.g., tables and chairs on the pavement, by making a sound). Students then translated these instructions into block-based programming creating flow diagrams in KEIRO (https://enginoeducation.com/downloads/), tested the movement and behavior of the GINOBOT and improved their flow diagrams so that the observed movement and behavior match their instructions. The same cycle was repeated in four iterations. In each iteration, students added new functions of the GINOBOT, which increased programming complexity. The whole intervention lasted for 360min and was implemented by three teachers, one in each class, trained by the authors to follow the same protocol. The role of the teachers was to explain the working scenario and guidelines given to students, when necessary, as well as offer technical assistance, for instance, when transferring flow diagrams from KEIRO to the GINOBOT through Bluetooth or cable. We coded learning products (instructions; initial and revised flow diagrams) employing the following scheme: 0 = not delivered/irrelevant/out of scope; 1 = incomplete, students would need to repeat the activity to complete the learning product; 2 = incomplete, students could complete the learning product with a few amendments without having to repeat the activity; 3 = complete, no further action required (ordinal variables). Interrater reliability (Cohen's Kappa) between two independent coders amounted to 0.86. For each route, we also recorded if the initial flow diagram corresponded to written instructions (binary variable) and counted debugging actions, i.e., the number of changes made in the initial flow diagram to deliver the revised diagram (scale variable). We used non-parametric statistics to examine trends in data.

Results

Table 1 presents the variables describing the quality of learning products delivered by student groups in different iterations (routes executed by the GINOBOT). When observing each iteration separately, median values for revised diagrams were higher than median values for initial diagrams. This denotes an improvement of the quality of flow diagrams within each iteration. For iterations 1, 2 and 4, the quality of initial flow diagrams correlated significantly with the quality of revised flow diagrams (Iteration 1: Spearman's rho = 0.66, $p < 0.01$; Iteration 2: Spearman's rho = 0.66, $p < 0.01$; Iteration 4: Spearman's rho = 0.58, $p < 0.05$). In iteration 3, we had the highest average number of changes made by students to the initial flow diagrams in order to deliver the revised flow diagrams. Indeed, number of changes here was significantly lower for student groups with correspondence between instructions and initial flow diagrams (Mann-Whitney Z = -2.13, $p < 0.05$). These results are in line with the increasing difficulty in learning tasks. When observing data in Table 1 from one iteration to the next, correspondence between instructions and initial flow diagrams doubled from the first to the second iteration and then doubled again from the third to the fourth iteration. The above trends imply that the coherence between learning activities had a gradual increase. Throughout iterations, students were capable of providing adequate instructions when designing the routes of the GINOBOT (median value across iterations = 3, with min value = 2). From the second iteration onwards, correspondence between instructions and initial flow diagrams increased quality of initial flow diagrams (Iteration 2: Likelihood ratio chi-square = 11.85, $p < 0.01$, Phi = 0.84, $p < 0.01$; Iteration 3: Likelihood ratio chi-square = 15.84, $p < 0.001$, Phi = 0.91, $p < 0.001$; Iteration 4: Likelihood ratio chi-square = 10.62, $p < 0.01$, Phi = 0.70, $p < 0.05$). These findings suggest that students were able to align their designs to programming after the first iteration. Age, gender, prior experience with robotics or group size did not significantly influence any parameter examined.

Discussion

Analyzing learning products can provide valuable data and insight for monitoring student performance within and across iterations (inquiry cycles) in educational robotics. In contrast to previous research, which has documented a decreasing trend in achievement when young children were engaged in multiple lessons of block-based programming of increasing difficulty (Bers et al., 2014), our results indicate that students progressed within each iteration as well as from one iteration to the next. Our constructionist approach can be exploited for assessing student performance in open-ended learning settings with few participants, where control groups cannot be easily compared to experimental groups, and where pre-post tests would most probably fail to grasp the richness of student actions and paths (see Hamner et al., 2010). Learning products can be employed by teachers for formative assessment (see Hovardas, 2016), by students themselves for peer assessment (Hovardas et al., 2014; Tsivitanidou et al., 2011) as well as by stakeholders for structuring a dialogue on the cross-fertilization of inquiry-based learning and educational robotics (Tasiopoulou et al., 2020). Future research should shed more light on examining debugging not as a technical exercise but as a design challenge (see Socratous & Ioannou, 2021) and it should showcase how educational robotics can be used to improve transformative and regulating inquiry skills (Pedaste & Sarapuu, 2014).

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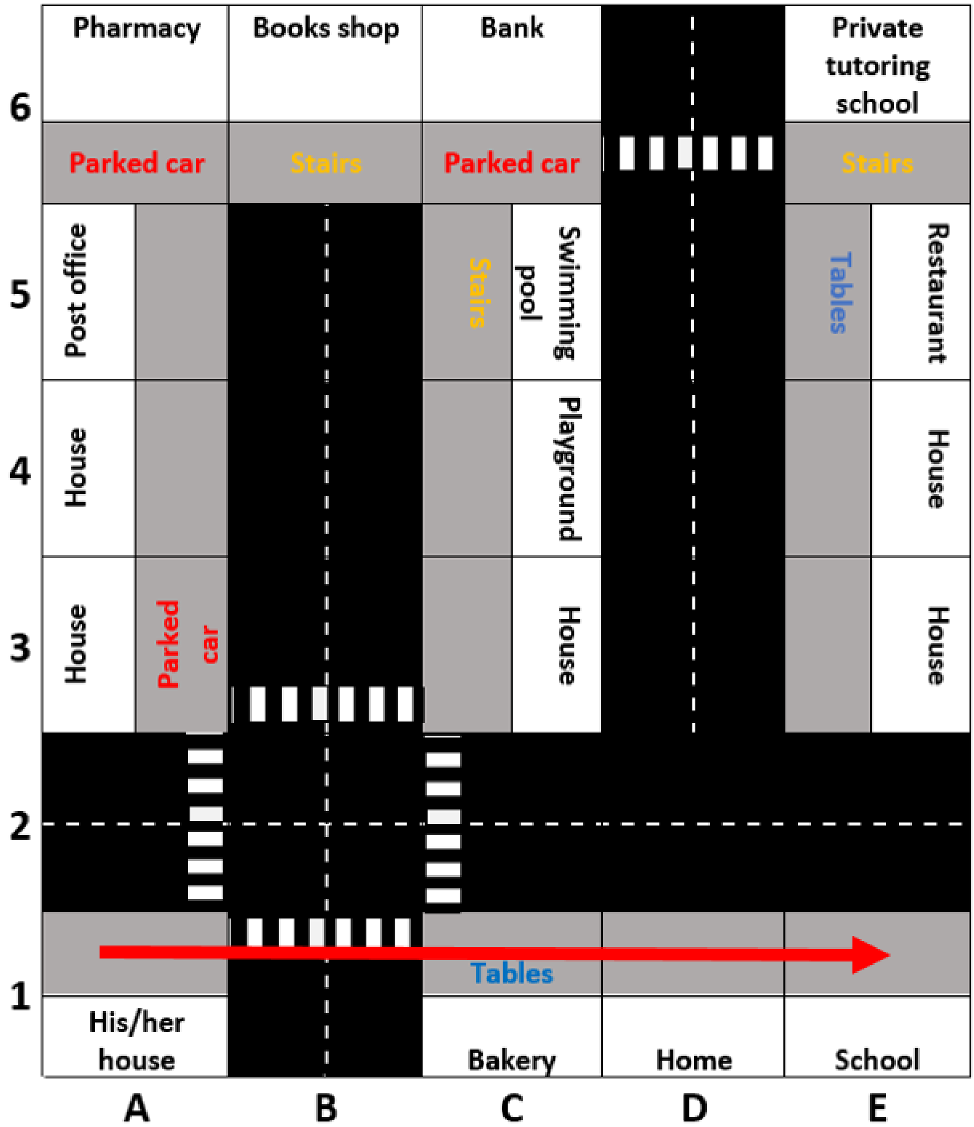

Figure 1. Route designed by students for the GINOBOT in the two-dimensional hypothetical neighborhood.

Table 1. Quality of learning products delivered by student groups in different iterations (routes executed by the GINOBOT)

	Iteration (route) 1	Iteration (route) 2	Iteration (route) 3	Iteration (route) 4
Instructions for the GINOBOT to execute a desirable route (ordinal variable; median values presented and min/max values in parentheses)	3 (min = 2; max = 3)	3 (min = 2; max = 3)	3 (min = 2; max = 3)	3 (min = 2; max = 3)
Flow diagram for the GINOBOT to execute the route (ordinal variable; median values presented and min/max values in parentheses)	2 (min = 0; max = 3)	2 (min = 0; max = 3)	2 (min = 2; max = 3)	2 (min = 1; max = 3)
Correspondence between instructions and flow diagram (binary variable; percentage of student groups presented)	11.8%	23.5%	17.6%	47.1%
Revised flow diagram for the GINOBOT to execute the route (ordinal variable; median values presented and min/max values in parentheses)	3 (min = 0; max = 3)	3 (min = 0; max = 3)	3 (min = 2; max = 3)	3 (min = 1; max = 3)
Number of changes in the initial flow diagram to deliver the revised diagram (scale variable; average values presented and min/max values in parentheses)	1.53 (min = 0; max = 5)	2.82 (min = 0; max = 11)	3.06 (min = 0; max = 9)	1.71 (min = 0; max = 7)

Note: N = 17 student groups; values for ordinal variables: 0 = not delivered/irrelevant/out of scope; 1 = incomplete, students would need to repeat the learning activity to complete the learning product; 2 = incomplete, students could complete the learning product with a few amendments without having to repeat the learning activity; 3 = complete, no further action required.