Explaining robotic behaviors: a case study on science education

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Abstract. Educational robotics laboratories typically involve building and programming robotic systems to perform particular tasks or to solve problems. Here we explore the potentialities of a class of robot-supported educational activities which are less discussed in the literature. In these activities, primary school children are asked to *explain* the behaviors of a robot which has been previously constructed by the laboratory supervisor, rather than to construct or program a robot. It will be argued that activities of this kind can play a significant role in science education: being engaged in a collaborative process of explanation of the behaviors of an educational robot, children have the opportunity to develop scientific research skills and competencies and to reflect on fundamental issues concerning the methodology of scientific research.

Keywords: educational robotics; science education; philosophy of science.

1 Introduction

Robots are often and fruitfully used as educational tools: from kindergartens to university courses all around the world, they have proven to facilitate the development of abstract thinking and collaborative problem solving abilities, and to support learning of various specific scientific, literary and artistic disciplines imposed by standard scholastic curricula [1], [2]. In a typical educational robotics laboratory, students are engaged in the *construction* of a robotic system, where the term "construction" refers to the physical assemblage of the robot from building bricks and to the design and implementation of a control program functional to achieving some spatial or sensory-motor objective [3–5]. The construction of a robot poses a number of problems to be solved: students are called to exploit their abstract thinking and problem solving abilities – which include reflecting on the available resources (in terms of building bricks and program instructions), predicting the outcome of their construction and programming choices, planning a sequence of instructions to achieve the desired objective, observing the results of their plans, comparing them with their objectives and eventually revising the algorithm or the physical structure of the robot to achieve more satisfactory results.

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In this paper we explore the potentialities of a class of robot-supported educational activities which are less discussed in the literature. In these activities, primary school children are asked to *explain* the behaviors of a robot which has been previously constructed by the laboratory supervisor, rather than to construct a robot in the sense discussed before. It will be argued here that activities of this kind can play a significant role in science education: being engaged in a collaborative, albeit supervised, process of *explanation* of the behaviors of an educational robot, children have the opportunity to develop scientific research skills and competencies and to reflect on fundamental issues concerning the methodology of scientific research, including those related to the concepts of "explanation", "hypothesis", "experiment". This idea has been rarely explored in the literature. Exceptions are [6], which discusses cases of explanation of robotic behaviors by children during program debugging, and [7] (and other studies carried out by the same research group at the Tel-Aviv University), which directly addresses children's understanding of robot behaviors. The objectives and results of these studies overlap to some extent with those presented in this paper. However, [7] addresses issues specifically related to children explanation of *robotic* behaviors (is it event-, script-, or rule-based? To what extent children of different ages adopt a psychological vocabulary?). Here we take a more general perspective: our primary interest is to reflect on the role of educational robotics laboratories in the development of scientific research skills at large, and, more relevantly, to identify *general* features of children's approach to explanation (not specifically related to the explanation of robotic behaviors) in the laboratory results. A more detailed analysis of the relationships between the results of the present pilot study and those reported in [7], and in the related literature, is ongoing.

The claims proposed here will be made more precise in section 2 with reference to the Curricular Guidelines defined by the Italian Ministry of Education concerning science education in primary schools. Section 3 will describe the structure of a robot-supported scientific research laboratory which is taken here as a case-study. Section 4 will provide some insights to reflect on the potentialities of educational robots for science education; Section 5 is devoted to some concluding remarks.

2 Robotics and science education in primary schools

Scientific disciplines differ from each other with respect to goals, methods of inquiry, technological instruments, symbolic and formal languages used to represent knowledge. However, as acknowledged by the Curricular Guidelines defined by the Italian Ministry of Education for primary schools (2007), they share a common methodological core: science involves "observing phenomena while they occur, both in the everyday life and in controlled laboratory settings …; describing and recording, with a proper language, what happens and what is made happen; interpreting facts and processes through models and theoretical frameworks; formulate predictions on what can (be made) happen and check their accuracy; enrich and revise previous interpretations on the basis of new experimental and conceptual instruments". According to the Guidelines, a reflection on these common methodological aspects of scientific research is of primary importance especially in the first years of primary

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school, as it facilitates proper learning of the specific contents of the curricular scientific disciplines. This can be read as prescribing that primary school students ought to learn and reflect on basic notions and concepts pertaining to *philosophy of science*, which is distinctively concerned with the methodology of scientific research and addresses issues related to the nature of scientific explanation, to the relationship between observation and explanation, to the relationship between theoretical hypotheses and the experiments designed to control them.

How to achieve this objective? The Guidelines recommend adopting a practical approach in which children are called to *investigate a concrete system*, thus acting as "scientists" under an expert supervision (consistently with the "man-as-scientist" metaphor proposed by the pioneer of constructive psychology George Kelly [8]). In this kind of approach children are asked to observe the target system, to describe it, to identify phenomena to be studied, to propose explanatory hypotheses, to make predictions based on those hypotheses, to design experiments, to compare experimental results with their previous predictions, and possibly to revise their hypotheses according to the results. While performing those activities children must reflect on what they are doing, in a metacognitive perspective.

In principle, various systems may be suited for that purpose: compounds making chemical reactions, mechanisms composed by gears and levers, plants, insects. We propose that *properly programmed robots* can be fruitfully selected as target systems for this kind of science laboratories. This idea will be illustrated and discussed with reference to the case-study which we are going to describe.

3 A case study

Structure of the laboratory. The educational robotics laboratory which we will refer to in the ensuing reflections has been held in a primary school in Milan, from March 29th to June 24th 2011. The laboratory consisted in 6 meetings, one per week, each one lasting approximately 1,5 hours. The classroom was composed by 18 children at their second year of primary school (they were mostly seven years old). The meetings have been supervised by one of the authors (Edoardo Datteri, who will referred from now on as "the supervisor"). Two of the school teachers were also present in all the meetings.

The robot and the activities. The laboratory activities involved a LEGO Mindstorms robot assembled as a small vehicle, provided with three ultrasonic sensors in front of it, one centered straight ahead, the other two at about 45° left and right respectively, and a LED multi-color light mounted on top (see Fig. 1 left).

Two kinds of activities have been proposed to the children. Some of them concerned *programming the robot*. Children had seven basic motor commands, defined qualitatively and identified with letters (e.g., A: go ahead; B: go ahead a bit more; F: turn right). Their goal was to find sequences of motor commands to make the robot solve mazes of increasing level of complexity (they were implemented and executed by the supervisor through the LEGO NXT-G visual programming language). The other kind of activities, on which this paper is focused, involved *explaining robot*

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behaviors. Children were allowed to interact freely with the LEGO robot which had been previously programmed by the supervisor, through the NXT-G software, as a Braitenberg-like vehicle [9]. Three vehicles have been involved in different meetings, each one with a different control program.

1) The first vehicle is a simple obstacle avoidance system: it goes straight ahead and triggers an avoidance reaction (it goes backward, steers to the right, steers to the left) when one of the sonars (front, left, right respectively) detects an obstacle closer than 20cm. The LED light is normally turned on and green; it becomes red while an obstacle avoidance motor action is being executed.
2) The second vehicle avoids obstacles closer than 20cm (as the first one) and goes towards objects farther than 50cm, thus simulating, in the spirit of Braitenberg's book, a sort of "curiosity". The light is normally green; it turns to red in case of obstacle avoidance; it turns to blue in the attractive stages.
3) The third control program generates an attractive behavior towards objects closer than 20cm. It displays no repulsive behavior: when no close object is detected, the robot remains idle.

The activities have been organized as follows. In the very first day of the laboratory, children have been asked to describe cooperatively the shape of the robot with the control system turned off. In this and in successive stages of the laboratory the supervisor has been careful to act as a mediator, recalling and re-proposing questions made by the children and calling attention to conflicts between hypotheses made by the children. He has kept to a minimum the number of technical information provided to the children concerning the robot and, in most cases, has avoided correcting wrong beliefs and hypotheses made by them [10]. After this initial observation/description step, the robot has been put on the classroom floor with the first control program activated (vehicles number 2 and 3 have been subjected to children's investigation in successive meetings, following the same approach).

In all the cases, children were asked to (A) *describe* what the robot was doing, and (B) *explain* why the robot was doing that. They were free to interact with the robot, e.g., to approach it and to put hands near to the sensors (note that the first vehicle was subjected to the children before any *programming* activity; especially in this case, and contrary to the explanation activities described in [6], children had no clear idea on the way the robot had been programmed by the supervisor: indeed, at the beginning, many of them thought that the robot was in fact tele-operated by the supervisor out of their sight).

Children became gradually and autonomously aware of the possibility to make experiments (e.g., putting a hand in front of the left sensor to evaluate the hypothesis according to which perceiving an obstacle on the left makes the robot steer to the right); they were asked to identify cooperatively the "proper" experiments to test a particular hypothesis and to reflect on the implications of the results.

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Fig. 1. Left: the assembled LEGO Mindstorms robot used in the laboratory. Right: a screenshot of the video-recordings showing the supervisor, some children, and the enclosure within which the robot has been observed in the first meeting.

Experimental monitoring. Five out of six meetings have been recorded with a video-camera (informed consent had been previously obtained to use video and audio recordings for research purposes only).

4 Robotics for science education: some insights

An empirical, qualitative analysis of this case study is ongoing, which involves interviews, discussions, and a close inspection of the audio and video recordings [11]. This analysis is guided by some research claims; here we focus on the following two.

1. Educational robots may contribute to the development of scientific research skills (observing; formulating explanatory hypotheses; testing them; revising them in light of the observed results) in primary school children.
2. Educational robots may stimulate children to reflect on fundamental issues concerning the methodology of scientific research, including those related to the concepts of "explanation", "hypothesis", "experiment".

4.1 Learning to explain

Research claim 1 is defended here by a general epistemic reflection on the nature of robots, supported by the results of the presently examined case study.

Flexibility. Unlike other potential target systems (e.g., chemical compounds or mechanical devices), educational robots can implement a virtually infinite number of sensory-motor control programs. Each control program makes the robot react differently to environmental stimuli and, in fact, poses a different "problem to be solved" (i.e., a different behavioral repertoire to be explained) to the students. In this sense, educational robots are *flexible*, thus particularly stimulating, tools for science education; this flexibility has been exploited in the presently examined laboratory where, as described, children have been asked to exercise and refine their "scientific research" abilities with three different agents implemented on the same robot.

Theoretical vocabulary. The investigation on chemical compounds, systems of pulls and levers or plants will naturally make appeal to chemical, physical, biological theories. On the contrary – at least, at some level of analysis – the explanation of the behavior of a Braitenberg-like robotic agent may involve formulating sets of rules or algorithms which need not make reference to, nor delve into the complexities of, concepts and theories pertaining to particular "standard" scientific disciplines. This has been actually the case in the present case-study where children, following the supervisor's request to explain robotic behaviors, have gradually formulated rules – defined in a non-technical vocabulary – connecting states of affairs, such as "whenever the robot is approaching an object, it steers away" (note in this respect that this case study and, more generally, the interaction with a robot may also provide interesting insights to reflect on what is for children "to explain" something, possibly in connection with the general epistemological literature on scientific explanation [12–14]). The possibility to explain robot behaviors without making reference to specific scientific disciplines enables one – at least in principle and under conditions to be carefully studied – to focus on the *methods*, rather than on the "contents", of scientific research; in particular, to encourage children to reflect on the fact that what characterizes science is not the reference to a particular corpus of expert knowledge but, rather, the adoption of particular methods of inquiry.

Epistemic vantage point. Under the reasonable assumption that the robot has been assembled and programmed by the supervisor (or by properly trained school teachers), she/he has a good knowledge of the mechanisms governing its behavior, i.e., of the mechanisms that children are called to discover. This places her/him in a particularly privileged position to evaluate the appropriateness of the explanations produced by children and to guide their process of discovery. Teachers may not be in a similar "epistemic vantage point" when operating with other, non-man-made systems, such as chemical compounds (which may be altered in ways that are difficult to understand without specialized instruments which are unavailable in classrooms), plants or insects. Clearly, this epistemic privilege does not guarantee accurate prediction in any case, as we are going to discuss.

Predictive and control limitations. Sensory-motor programs for robots are deterministic: at each step of their execution there is one and only one action to do next, which is clearly identified by the program. Obviously this does not imply that, on the basis of the program alone, one is in the position to make accurate *predictions* of the next motor action in a real setting, nor that the programmer – in light of her/him role – exerts full *control* on future robot behaviors (i.e., one cannot be sure that the future behavior of the robot will conform in any case to the programmer's expectations). Indeed, sensory-motor control programs typically prescribe that the motor behaviors of the robot are deterministically dependent on the sensory stimuli – but in ordinary environmental contexts it is typically hard to predict the next sensory stimuli. Moreover, as with any other physical system, the behavior of the robot can be perturbed by a high number of environmental and internal factors which are difficult

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to predict: for example, light or atmospheric conditions, or internal electronic damages, may alter the reading of ultrasonic sensors thus perturbing the "normal" robot behavior in ways that are hard to predict and control. The fact that even "simple" control mechanisms can give rise to an impressively wide behavioral repertoire, due to the richness of the environmental conditions, has been extensively discussed by Braitenberg [9], Simon [15], and Grey Walter in connection with his cybernetic tortoises [16].

This behavioral variability makes the process of explanation particularly stimulating, especially when the robot is observed – as in the present case-study – "in the wild", i.e., on the floor of a classroom full of children and environmental stimuli. Indeed, especially in these conditions it is very difficult to "guess" the control mechanism of the robot on the basis of the observed behavior (in the epistemological jargon, the former is significantly underdetermined by the latter one). Braitenberg has extensively discussed this point in connection with his vehicles, which illustrate what he calls the "law of uphill analysis": "It is pleasurable and easy to create little machines that do certain tricks. It is also quite easy to observe the full repertoire of behavior in these machines – even if it goes beyond what we had originally planned, as it often does. But it is much more difficult to start from the outside and to try to guess internal structure just from the observation of behavior" [9]. Indeed, especially in non-controlled environments such as classrooms, children will have very frequently to decide if unexpected robotic behaviors are due (a) to the fact that they have hypothesized the "wrong" mechanism, or (b) to the fact that an unexpected environmental or internal factor has perturbed the system – which would save the mechanistic hypothesis. This decision requires a considerable amount of theoretical reflection and a subtle analysis of the environmental circumstances; indeed, children may be subjected to the "bias" emphasized by Braitenberg and Simon, i.e., by the tendency to infer a "complex" internal structure from a "complex" behavior, whereas complex robotic behaviors may well be due to the richness and practical unpredictability of the environmental stimuli impinging on a relatively "simple" mechanism.

An interesting case in point is the following. In the first meeting of the laboratory children are sitting on the floor, around an enclosure of approximately 1×2m made of wooden bricks. The supervisor says: "Now I'm going to turn on the robot and to put it within the enclosure; look at what it does". Then he puts the robot within the enclosure with the first control program (simple obstacle avoidance) turned on. In fact, this question elicits two kinds of reactions: sometimes children describe the behavior of the robot (e.g., "the robot is moving", or "there is something on the display"), sometimes they hypothesize behavioral rules (e.g., "it checks with that camera if there are objects and try not to collide") which may be part of an explanation of the behavior of the robot (this point is extensively discussed in [7]). One of the children promptly proposes that the red light is associated with a collision: "I think that, if that light is green, it means that everything is ok; when it is red the robot is going to collide with something". This proposal is quite correct: as discussed in section 3, the robots steers to avoid obstacles with the red light on. When the coordinator asks whether everyone agrees on that hypothesis, children change their mind. In fact, the robot eventually starts to generate what seems to be a "wrong" obstacle avoidance behavior: it occasionally steers when there is no close obstacle and

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goes straight ahead when there are objects in front of the sensors. This may well be due to some kind of *external or internal perturbing condition*, e.g., light interfering with sensors distance readings, internal lags in the electronic transmission of the sensory signals or in their processing, irregularities in the shape of the wooden bricks making up the enclosure, which "confuse" the sensors. The occurrence of these perturbing conditions confuse the children as well, whose successive – wrong – hypothesis associates light color to *motor speed* and not to the presence of obstacles: one of the children proposes that "when the light is green the robots moves faster, when the light is red it moves slower".

The richness of potential environmental perturbations may lead children to reflect on a constitutive aspect of scientific research, i.e., on the need to control the experimental setting to understand the target phenomena. Indeed, scientists rarely observe and explain the behavior of their target systems "in the wild": they accurately constrain the experimental setting and try to neutralize undesired sources of disturbance (this has interesting implications on the relationship between explanation, generalizations and *idealization*, as discussed in [17] and [18] in connection with robot-supported investigations on biological behaviors). In the presently analyzed case-study children have progressively acknowledged the role of potential environmental disturbances; eventually, the supervisor has picked up the robot from the floor and asked the children to observe the motor behavior of the wheels while he was putting hands close to the sensors, to simulate the perception of an obstacle and, at the same time, to avoid potential perturbations occurring on the floor and in close contact with the children. In this case the choice to pick up the robot in order to segregate it from potential disturbances has been taken by the expert supervisor; it would be interesting to check whether, and to what extent, children themselves can develop autonomously this methodological strategy.

4.2 Explanation and the meaning of "why" in primary school children

Educational robots may stimulate children to reflect on fundamental concepts related to the methods and the foundations of science (claim 2). In particular, as we are going to discuss, properly controlled interaction with educational robots may trigger collaborative reflections on the meaning of "why", i.e., of the word which typically initiates explanation processes.

Philosophical analyses of the notion of "explanation" presuppose not only that there are various different types of explanation [19], but also that there are various types of *explanation requests* [20]. More precisely, a question such as "why system S generates behavior B" can be interpreted as a question on the *proximate* or on the *ultimate* causes of B. Under the first interpretation, a good answer may describe the mechanism M producing B; under the second interpretation, a good answer will describe the process which has made S possess exactly that mechanism (and not different mechanisms) and produce the behavior B (and not different behaviors). In biology and neuroscience, for example, proximate explanations typically describe the mechanisms underlying some behavior in a particular class of systems, while ultimate explanations typically describe the evolutionary or developmental process which has produced that mechanism [21].

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Educational robots may help children reflect on the distinction between these various interpretations of a "why" question (which reflect the distinction between different types of questions one can address about the external and inner world). Consider, by contrast, the explanation of a chemical reaction or of a physical mechanism. Why-questions on these phenomena, at least in a primary school classroom, will be naturally interpreted in the proximate sense (what are the chemical and physical laws governing those systems and responsible for those phenomena?); the "ultimate" interpretation would question on why the world is as it is now – i.e., why chemical and physical systems are governed exactly by those, and not by different, laws – which is an extremely challenging and thorny questions for primary school children. Robots, being man-made systems, do not pose similar challenges. Why the robot has turned to right in that circumstance? Under the "proximate" interpretation, one answers by describing the sensory-motor rules governing the behavior of the robot (e.g., the robot has turned to right because there was an obstacle on the left, and whenever there are obstacles on the left the robots turns to right). And the "ultimate" interpretation, contrary to the cases discussed before, is relatively easy to address too: the robot is governed by that (obstacle avoidance) mechanism because the programmer has implemented exactly that mechanism, and not another one.

Indeed, children have autonomously raised these two types of questions in the laboratory reported here. A case in point is when, during the first meeting, the supervisor has promoted a reflection on the steering mechanism of the robot. *Why* does the robot steer? Guided by the supervisor, the children have gradually acknowledged that the robot steers in a way that is very different with respect to cars, i.e., due to a difference between the speed of the right vs. the left wheel. After proposing this potential explanation one of the children has asked again: "Ok, but – why?". This question may be interpreted, again, as a proximate why-question: By virtue of what mechanism the right and left wheel move (or, have moved in some particular circumstance) at different speeds? However, a very plausible interpretation points to an ultimate why-question: Why this differential mechanism has been chosen, and not a mechanism which resembles more closely to the more familiar ones used in cars? Questions of this kind admit relatively unproblematic answers (unlike questions on why chemical or physical laws are just as they are) and can be exploited to promote a collaborative reflection on the variety of why-questions which drive our scientific understanding of the world.

5 Conclusion

The objective of this paper was to provide some insights to reflect on the potentialities of educational robots with respect to science education. We have proposed that properly programmed (educational) robots may be fruitfully selected as target systems in scientific explanation laboratories, and that they may enable children to reflect on crucial notions and methodological issues related to scientific research. The present discussion has been partly based on a robot-supported science laboratory. A closer analysis of the results of this laboratory is forthcoming, and will surely provide further, more precise insights to identify and exploit all the potentialities of robotics for science education.

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