Learning to explain: the role of educational robots in science education

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Abstract. Educational robotics laboratories typically involve building and programming robotic systems to perform particular tasks or solve problems. In this paper we explore the potential educational value of a form of robot-supported educational activity that has been little discussed in the literature. During these activities, primary school children are asked to explain the behaviors of a robot constructed in advance by the teacher or laboratory supervisor, rather than having to construct or program a robot themselves. It is argued that activities of this kind may have a significant role to play within science education: participation in a collaborative process aimed at explaining the behaviors of an educational robot provides children with the opportunity to develop scientific research skills and competencies and to engage in meta-cognitive reflection on fundamental issues surrounding scientific research methods.

Keywords: educational robotics, robotics in science education, philosophy of science

Introduction

Robots are frequently and fruitfully used as educational tools: from kindergarten to university contexts all around the world, they have been shown to facilitate the development of abstract thinking and collaborative problem solving abilities, as well as supporting learning in the various specific scientific, literary and artistic disciplines prescribed by standard school curricula (Bredenfeld et al., 2010; Catlin & Balmires, 2010). In a typical educational robotics laboratory, students are required to *construct* a robotic system, where "construction" is understood as both the physical assembly of the robot from building materials and the design and implementation of a control program enabling the robot to perform a spatial or sensory-motor task (Cincelli et al., 2010; Norton et al., 2006; Denis, 2001). Constructing a robot poses a number of challenges that require students to draw on their abstract thinking and problem solving abilities – for instance to reflect on the available resources (in terms of building materials and programming commands), predict the outcome of their construction and programming choices, plan a sequence of instructions to achieve the desired objective, observe the results of their plans, compare them with their objectives and, if necessary, adjust the algorithm or the physical structure of the robot to achieve better results.

In this paper we explore the potential of a type of robot-supported educational activity that has received little attention in the literature. During such activities, primary school children are asked to *explain* the behavior of a robot that has already been constructed by the teacher or laboratory supervisor, rather than having to construct a robot themselves as described above. It will be argued here that activities of this kind may play a significant role in science education: engagement in a collaborative, albeit supervised, process of *explanation* of the behaviors of an educational robot provides children with the opportunity to develop scientific research skills and competencies and to engage in metacognitive reflection on fundamental issues concerning scientific research methodology, including the concepts of "explanation", "hypothesis" and "experiment". This possibility has rarely been explored in the literature. Exceptions are (Sullivan, 2008), which discusses cases of explanation of robotic behaviors by children during program debugging, and (Mioduser et al., 2007) (as well as other studies carried out by the same research group at Tel-Aviv University), which directly examines children's understanding of robot behaviors. The objectives and the results of these studies overlap to some extent with those presented in this paper. However, (Mioduser et al., 2007) addresses issues specifically related to children's explanation of *robotic* behaviors (i.e., is it event-, script-, or rule-based? To what extent do children of different ages make use of psychological lexicon?). In this contribution, we take a more general perspective: our primary focus is on the role of educational robotics laboratories in the development of scientific research skills at a broad level, and, even more importantly, we aim to identify *general* features of the explanatory modalities deployed by children (not specific to the explanation of robotic behaviors) to justify the results of their laboratory experiments. A more detailed analysis of the relationships between the findings of the present pilot study and those reported in (Mioduser et al., 2007), and in the related literature, is in progress.

The hypothesis just outlined will be argued in finer detail in the "Robotics and science education in primary schools" section, with reference to the Curricular Guidelines provided by the Italian Ministry of Education for science education in primary schools. In the section entitled "A case study" we describe a robot-supported science laboratory held in a primary school in Milan (Italy) in spring 2011, using it as a case-study in support of the ideas discussed. In the section entitled "Robotics in science education: some insights", we reflect on the potential benefits of using educational robots in science education. The last section contains some concluding remarks.

Theoretical background

Scientific disciplines differ from each other with regard to goals, methods of inquiry, technological instruments and the symbolic and formal languages used to represent knowledge. However, as acknowledged in the Curricular Guidelines drawn up 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 everyday life and in controlled laboratory contexts; describing and recording, in appropriate language, what happens and what is made to happen; interpreting facts and processes in light of models and theoretical frameworks; formulating predictions on what can (be made) happen and checking their accuracy; expanding and revising previous interpretations on the basis of new experimental and conceptual instruments". According to the guideline document, it is of critical importance to reflect on these common methodological aspects of scientific research during the early primary school years in particular, in order to facilitate deep learning of the specific contents of the curricular scientific disciplines. This recommendation may be interpreted as prescribing that primary school students learn and reflect on basic notions and concepts pertaining to the *philosophy of science*, which is distinctively concerned with the methodology of scientific research and addresses issues relating to the nature of scientific explanation and the relationship between observation and explanation, as well as the relationship between theoretical hypotheses and the experiments designed to control them.

How may this objective be achieved? The Guidelines recommend adopting a practical approach whereby children are invited to *investigate concrete systems*, thus acting as "scientists" under expert supervision (according to George A. Kelly, one of the founders of constructivist psychology, "every man is, in his own particular way, a scientist", whose goal is to predict and control events, see Kelly, 1955; in pursuit of this objective, each individual formulates, in her/his own way, hypotheses to explain physical and social phenomena, developing a system of "personal constructs" through which s/he views the world of events). In the "hands-on" approach recommended by the Ministry, children are asked to observe a target system, describe it, identify the phenomena to be studied, propose explanatory hypotheses, make predictions based on these hypotheses, design experiments, compare experimental results with their predictions, and revise their hypotheses in line with the results. While carrying out these activities, children must actively think about what they are doing, adopting a metacognitive perspective that intrinsically involves epistemological and methodological reflection.

A variety of systems lend themselves to this kind of investigation, including compounds that set off chemical reactions, mechanisms made up of gears and levers, plants, insects. We propose that *appropriately programmed robots* may provide a suitable target system for science laboratories of this nature. We now illustrate this concept, discussing it with reference to the case-study outlined before.

Methodology

Laboratory structure

The educational robotics laboratory on the basis of which we shall discuss the potential for using robots in science education was held in a primary school in Milan, from March 29th to June 24th 2011. The laboratory took place over six sessions, one per week, each lasting approximately 1.5 hours. The class group was composed of 18 children in their second year of primary school (the majority were seven years old). The sessions were supervised by one of the authors (Edoardo Datteri, who from now on will be referred to as "the supervisor"). Two class teachers were also present at each session.

The robot and the activities

The laboratory activities involved a LEGO Mindstorms robot assembled as a small vehicle, equipped with three ultrasonic sensors at the front, one pointed straight ahead, and the other two set at about 45° left and right respectively, and a LED color light mounted on top (see Figure 1 left) which could be shone red, green or blue.

The children were invited to take part in two different types of activity. The first type involved *programming the robot*. Children were supplied with some basic motor commands, defined qualitatively and identified by letters (e.g., A: go forward; D: turn left; F: turn right). The set goal was to identify sequences of motor commands (implemented and executed by the supervisor using the LEGO NXT-G visual programming language) that would enable the robot to solve mazes of increasing complexity.

The other type of activity, on which this paper is focused, involved *explaining the behavior of the robot*. Children were allowed to freely interact with the LEGO robot which the supervisor had programmed in advance with NXT-G software to function as a Braitenberg-like vehicle (Braitenberg, 1986), designed along the lines of Brook's subsumption architecture (Brooks, 1986). Three different vehicles, each with a different control program, were used at three different sessions: they may be informally described according to the following sets of rules.

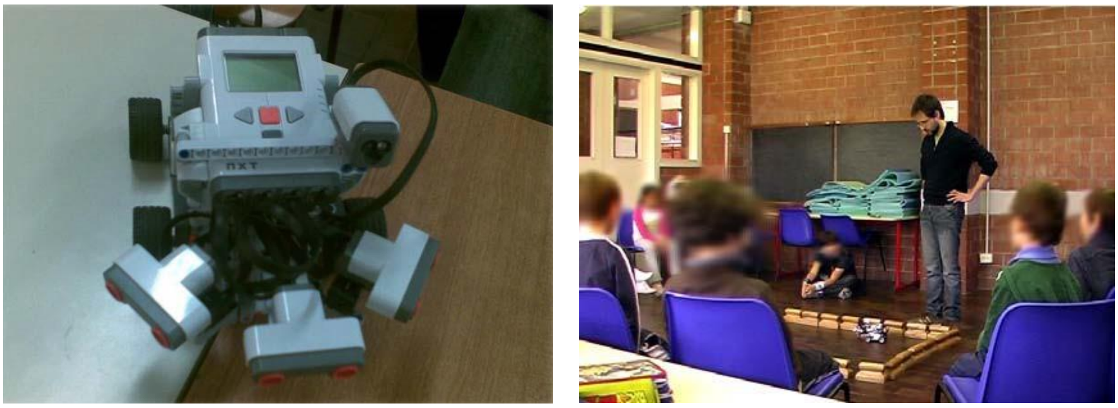

Figure 1. Left: the assembled LEGO Mindstorms robot used in the laboratory. Right: a screenshot of the video-recordings showing the supervisor, some children, and the enclosure within which the robot was observed at the first session.

1. The first vehicle was a simple obstacle avoidance system.
   a. If the {front | left | right} sonar detects an obstacle at a distance of under 20cm, the robot {goes backwards for a while | steers to the right | steers to the left};
   b. otherwise, it goes straight ahead.

   The LED light is programmed to normally shine green; it only becomes red while the robot is executing one of the motor actions imposed by rule *a*.
2. The second control program is an extension of the first.
   a. If the {front | left | right} sonar detects an obstacle at a distance of under 20cm, the robot {goes backwards for a while | steers to the right | steers to the left}; otherwise,
   b. if the {front | left | right} sonar detects an obstacle at a distance of over 50cm, the robot {goes forwards for a while | steers to the left | steers to the right};
   c. otherwise, it goes straight ahead.

   Rule *b* makes the robot turn towards far-away objects – thus simulating, in the spirit of Braitenberg's book, a sort of "curiosity". When this kind of attraction reaction is generated, the light – which by default shines green, as in the previous vehicle – becomes blue. However, when only close objects are detected, the robot issues an avoidance reaction, similarly to vehicle 1 (and the light becomes red).
3. The third control program is designed to generate an *attraction* behavior in the presence of close objects with no repulsion rules applying at any stage; the robot, in this case, is idle when no close object has been detected; the light is always off.
   a. If the {front | left | right} sonar detects an obstacle at a distance of under lower than 20cm, the robot {goes forward for a while | steers to the left | steers to the right};
   b. otherwise, it remains idle.

The activities were structured as follows. At the first laboratory session, the children were asked to collaboratively describe the robot's physical structure with the control system turned off. At this and at the following stages of the laboratory, the supervisor was careful to act as a mediator, recalling and reiterating questions posed by the children, as well as drawing their attention to conflicts between different hypotheses that they had put forward. He kept the amount of technical information provided to the children about the robot to a minimum and, in the majority of cases, avoided correcting mistaken beliefs and erroneous hypotheses proposed (Nigris, 2009). After this initial observation/description step, the robot was placed on the classroom floor and the first control program activated. At each of the two subsequent laboratory sessions, vehicles 2 and 3 respectively were presented to the children for observation and investigation.

In all 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 their hands near the sensors.

Note that the first vehicle was presented to the children before they had been privy to, or involved in, any *programming* activity. Consequently, (in contrast with the explanation activities described in Sullivan, 2008) they had no clear idea of how the robot had been programmed by the supervisor: indeed, in the beginning, many of them thought that the robot was being secretly tele-operated by him).

As at the preliminary observation stage, the supervisor mainly acted as a mediator. In particular, he avoided correcting wrong answers/explanatory hypotheses; rather, he asked the children to reflect on their tentative explanations and to justify them autonomously. The children gradually became aware that they could make experiments (e.g., putting a hand in front of the left sensor to evaluate the hypothesis predicting that detection of an obstacle on the left leads the robot to steer right). They were then asked to collaboratively design "appropriate" experiments to test a particular hypothesis and subsequently to reflect on the implications of the results obtained.

Experimental monitoring

Five out of six sessions were recorded using a video-camera (informed consent had been previously obtained to use video and audio recordings for research purposes only).

First results

An empirical, qualitative analysis of this case study is ongoing. Specifically, our analysis uses an ethnographic approach based on grounded theory; it includes interviews and discussions as well as in-depth examination of the audio and video recordings (Goldman et al., 2007). The analysis is guided by some broad research claims including the following two, which we go on to develop in the ensuing paragraphs.

1. Use of educational robots may contribute to the development of scientific research skills (observation; formulation of explanatory hypotheses; testing of these hypotheses; revision of hypotheses in light of the observed results) in primary school children.
2. Use of educational robots may stimulate children to reflect on key issues surrounding the methodology of scientific research, including those related to the concepts of "explanation", "hypothesis", "experiment".

Learning to explain

Our first claim is substantiated here by a general epistemic reflection on the nature of robots (supported by the results of the current case study) that illustrates the potential of educational robotics to foster the development of scientific research skills in primary school children.

Flexibility: A first reason for selecting an educational robot as the target system in a science laboratory is pragmatic. Unlike other potential target systems (e.g., chemical compounds or mechanical devices), educational robots can be used to 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 students with a different "problem to be solved" each time (i.e., a different behavioral repertoire to be explained). In this sense, educational robots are *flexible* tools for science education; this flexibility was exploited in the current laboratory case study in which, as described, children were invited to exercise and refine their "scientific research" abilities by investigating three different robotic agents implemented using the same LEGO Mindstorms device.

Theoretical vocabulary: The investigation of chemical compounds, systems of pulls and levers or plants will naturally appeal to chemical, physical or biological theories, respectively. On the contrary – at least, at some level of analysis – explaining the behavior of a Braitenberg-like robotic agent such as those described in the previous section involves formulating sets of rules or algorithms which need not make reference to, nor delve into the complexities of, concepts and theories belonging to particular "standard" scientific disciplines. This was the case in the present study, in which the children, in responding to the supervisor's request to explain robotic behaviors, gradually formulated rules – expressed using non-technical vocabulary – to connect states of affairs, such as "whenever the robot is approaching an object, it steers away" (in this regard, note that this case study, as well as interaction with robots in general, may also provide interesting insights into what it is for children "to explain" something – such insights could usefully be discussed in relation to the general epistemological literature on scientific explanation, see Psillos, 2002; Ladyman, 2002; Brockman, 2004). The fact that robot behaviors may be explained without making reference to specific scientific disciplines promotes a focus – at least in principle and under conditions to be carefully defined – on the *methods*, rather than on the "contents", of scientific research; in particular, this may encourage children to reflect on the fact that what characterizes science is not reference to a particular corpus of expert knowledge but, rather, the adoption of particular methods of inquiry.

Epistemic vantage point: On the reasonable assumption that the robot will usually have been assembled and programmed by the supervisor (or by adequately trained school teachers), it follows that the person presenting the robot to the children will have a good knowledge of the mechanisms governing its behavior, i.e., of the mechanisms that children are invited to discover. This places the supervisor/teacher in a particularly privileged position to evaluate the appropriateness of the explanations produced by the children and to guide their process of discovery. In contrast, teachers may not enjoy a similarly privileged "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 unavailable in classrooms), plants or insects. Clearly, however, this epistemic advantage does not guarantee accurate prediction in all cases, as we are about 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 be performed next, which clearly identified by the program. Obviously this does not imply that, on the basis of the program alone, it is possible to accurately *predict* the robot's next motor action in a real-life setting, or that programmers – thanks to their role – have full *control* over the future behaviors of the robot (in the sense that robot's future actions will conform in every case to their expectations). On the contrary, although sensory-motor control programs typically prescribe that the motor behaviors of the robot be deterministically dependent on sensory stimuli, in ordinary environmental contexts it is typically difficult to predict the next sensory stimuli. Moreover, as with any other physical system, the behavior of the robot may be perturbed by a large number of environmental and internal factors that are also difficult to predict: for example, light and atmospheric conditions, or internal electronic damages, may alter the reading of ultrasonic sensors thus perturbing "normal" robot behavior in ways that are difficult 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 environmental conditions, has been extensively discussed by Braitenberg (1986) and Simon (1969), and by Grey Walter in connection with his cybernetic tortoises (Walter, 1950).

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", that is to say, on the floor of a classroom full of children and environmental stimuli. In these conditions, it is very difficult to "guess" the control mechanism of the robot on the basis of observed behavior (in epistemological jargon, the former is significantly *underdetermined* by the latter). 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" (Braitenberg, 1986). Thus, especially in non-controlled environments such as classrooms, children will frequently have to decide whether unexpected robotic behaviors are due (a) to the fact that the group has hypothesized the "wrong" mechanism, or (b) to the fact that an unexpected environmental or internal factor has perturbed the system, thereby saving the hypothesis. This decision requires a considerable amount of theoretical reflection and a subtle analysis of the environmental circumstances; indeed, children may be subject to the "bias" emphasized by Braitenberg (1986) and Simon (1969), that is to say, by the tendency to infer a "complex" internal structure from "complex" behavior, although complex robotic behaviors may well be due to the richness and practical unpredictability of the environmental stimuli acting on a relatively "simple" mechanism.

An interesting case in point is the following. At the first laboratory session, the children were sitting on the floor around an enclosure of approximately 1×2m made of wooden bricks. The supervisor said: "Now I'm going to turn on the robot and put it down inside the enclosure; look at what it does". Then he placed the robot in the enclosure with the first control program (simple obstacle avoidance) turned on. Interestingly, this question elicited two kinds of reaction: sometimes children described the behavior of the robot (e.g., "the robot is moving", or "there is something on the display") and sometimes they hypothesized behavioral rules (e.g., "it's checking with that camera if there are objects and trying not to collide") which may be part of an explanation of the robot's behavior. One of the children promptly proposed that the red light was 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 suggestion was correct: as discussed in the previous section, the robot steers away from obstacles with the red light on. When the supervisor asked whether everyone agreed with this particular hypothesis, children changed their mind. And indeed, the robot seemed to generate "mistaken" obstacle avoidance behaviors in relation to this explanation: it occasionally steered when there was no close-range obstacle or went straight ahead when there were objects in front of the sensors (one child observed that it was trying to break out of the enclosure and escape). This may well have been due to some kind of *external or internal perturbing condition*, e.g., light interfering with the distance readings effected by the sensors, internal lags in the electronic transmission of the sensory signals or in the processing of same, irregularities in the shape of the wooden bricks making up the enclosure that "confused" the sensors. The occurrence of these perturbing conditions confused the children too, to the extent that their subsequent hypothesis associated light color with motor speed rather than with the presence of obstacles: specifically, one child proposed 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 bring children to reflect on a constitutive aspect of scientific research, that is to say on the need to control the experimental setting in order to acquire understanding of 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 Datteri & Laudisa, 2010, and Datteri, 2010, in connection with robot-supported investigations of biological behaviors). In the current case-study, the children progressively acknowledged the role of potential environmental disturbances; eventually, the supervisor picked up the robot from the floor and asked the children to observe the motor behavior of the wheels while he put his hands close to the sensors, to simulate the detection of an obstacle and, at the same time, to avoid potential perturbations occurring on the floor and close to the children. In this case, the decision to pick up the robot in order to take it away from potential disturbances was made by the expert supervisor; it would be interesting to check whether, and to what extent, children are capable of independently developing this methodological strategy.

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

Educational robots may stimulate children to engage in metacognitive reflection on key concepts pertaining to scientific research (claim 2). In particular, as we are about to discuss, controlled interaction with educational robots may trigger collaborative reflection on the meaning of "why", that is to say, of the word that typically initiates explanation processes.

Philosophical analyses of the notion of "explanation" presuppose not only that there are various different types of explanation (Nagel, 1961), but also that there are various types of *explanation requests* (van Fraassen, 1980). More precisely, a question such as "why does system S generate behavior B?" may be interpreted as a question regarding the *proximate* or the *ultimate* causes of B. Under the first interpretation, a good answer would describe the mechanism M producing B; under the second interpretation, a good answer would describe the process that has caused S to possess exactly that mechanism (and not other mechanisms) and produce the behavior B (and not other behaviors). In biology and neuroscience for example, proximate explanations typically describe the mechanisms underlying behaviors in a particular class of systems, while ultimate explanations typically describe the evolutionary or developmental process which has produced that mechanism (Craver, 2007).

Educational robots may help children reflect on the distinction between these alternative interpretations of the "why" question (that reflect the distinction between the different types of questions that may be posed regarding 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 naturally be interpreted in the proximate sense (i.e., what are the chemical and physical laws governing these systems and responsible for the phenomena?). In contrast, the "ultimate" interpretation would question why the world is as it is now – that is to say, why are chemical and physical systems governed exactly by those, and not by different, laws – which is an extremely challenging and thorny question for primary school children. Robots, being man-made systems, do not pose similar challenges. In responding to the question "Why did the robot turn right in that particular circumstance?", if children opt for the "proximate" interpretation, they will answer by describing the sensory-motor rules governing the behavior of the robot (e.g., the robot turned right because there was an obstacle on the left, and therefore whenever there are obstacles on the left the robot turns to the right). If on the other hand, the "ultimate" interpretation is favored, contrary to the cases discussed above, the question is relatively easy to address: the robot is governed by a particular (obstacle avoidance) mechanism because the programmer has implemented exactly that mechanism, and not another one.

Indeed, the children independently raised both types of questions in the laboratory sessions reported here. A case in point was when, during the first meeting, the supervisor tried to encourage reflection on the steering mechanism of the robot. Why does the robot steer? Guided by the supervisor, the children gradually recognized that the robot steered in a different way with respect to cars, that is due to a difference in speed between the right and left wheels. After proposing this potential explanation, one of the children asked again: "Ok, but – why?". This question may be interpreted as a further proximate why-question: By virtue of what mechanism do the right and left wheels move (or, moved in some particular circumstance) at different speeds? However, a very plausible interpretation points to an ultimate why-question: Why was this differential mechanism chosen rather than a mechanism resembling more closely the familiar ones used in cars? This type of ultimate-why question generates relatively unproblematic answers (unlike questions on why chemical or physical laws are just as they are) and may be exploited to promote collaborative reflection on the variety of why-questions that drive our attempts to gain scientific understanding of the world.

Conclusions

The aim of this paper was to provide some insights for reflection on the potential to use educational robots in science education. We propose that suitably programmed (educational) robots may be ideal target systems for scientific explanation laboratories, and may encourage children to reflect on crucial notions and methodological issues relating to scientific research. The present discussion has been partly based on a robot-supported science laboratory held in a primary school in Milan in 2011. A more in-depth analysis of the results of this laboratory is forthcoming, and will surely provide further, more precise insights enabling us to identify and exploit the potential advantages of using robotics in science education.

References

Braitenberg, V. (1986). *Vehicles. Experiments in Synthetic Psychology*. Cambridge, MA: The MIT Press.

Bredenfeld, A., Hofmann, A., & Steinbauer, G. (2010). Robotics in education initiatives in Europe: Status, shortcomings and open questions. In E. Menegatti (ed.), *Proceedings of SIMPAR 2010 Workshop, International Conference on Simulation, Modeling and Programming for Autonomous Robots* (pp. 568-574). Darmstadt, Germany.

Brockman, J. (ed.) (2004). *Curious mind. How a child becomes a scientist*. New York: Pantheon.

Brooks, R. A. (1986). A robust layered control system for a mobile robot. *IEEE Journal of Robotics and Automation*, 2(1), 14-23.

Catlin, D., & Balmires, M. (2010). The e-Robot project: A longitudinal on-line research collaboration to investigate ERA principles. In E. Menegatti (ed.), *Proceedings of SIMPAR 2010 Workshop, International Conference on Simulation, Modeling and Programming for Autonomous Robots* (pp. 411-420). Darmstadt, Germany.

Cincelli, S., Festi, G., Finotti, F., Lenzen, D., & Monfalcon, S. (2010). Teaching with robotics: different experiences at school after the TERECoP courses. In E. Menegatti (ed.), *Proceedings of SIMPAR 2010 Workshop, International Conference on Simulation, Modeling and Programming for Autonomous Robots* (pp. 429-438). Darmstadt, Germany.

Craver, C. F. (2007). *Explaining the brain: Mechanisms and the mosaic unity of neuroscience*. Oxford University Press.

Datteri, E. (2010). Simulazioni, spiegazioni e generalizzazioni nelle scienze cognitive [Simulations, explanations and generalizations in the cognitive sciences]. *Sistemi Intelligenti*, 3, 459-466.
Datteri, E., & Laudisa, F. (2010). Simulazione e spiegazione: il ruolo delle leggi nei modelli neuroscientifici [Simulation and explanation: the role of laws in neuroscientific models]. *Sistemi Intelligenti*, 12(1), 98-118.
Denis, B. (2001). Collaborative learning in an educational robotics environment. *Computers in Human Behavior*, 17(5-6), 465-480.
Goldman, R., Pea, R., Barron, B., & Derry, S. (eds.) (2007). *Video research in the learning sciences*. New York: Routledge.
Kelly, G. A. (1955). *The psychology of personal constructs*. New York: Norton.
Ladyman, J. (2002). *Understanding philosophy of science*. New York: Routledge.
Mioduser, D., Levy, S.T., & Talis, V. (2007). Episodes to scripts to rules: concrete-abstractions in kindergarten children's explanations of a robot's behaviour. *International Journal of Technology and Design Education*, 19(1), 15-36.
Nagel, E. (1961). *The structure of science*. New York: Harcourt, Brace & World Inc.
Nigris, E. (2009). *Le domande che aiutano a capire* [*The questions which help children understand*]. Milano: Bruno Mondadori.
Norton, S. J., McRobbie, C. J., & Ginns, I. S. (2006). Problem solving in a middle school robotics design classroom. *Research in Science Education*, 37(3), 261-277.
Psillos, S. (2002). *Causation and explanation*. Acumen - McGill Queens University Press.
Simon, H. A. (1969). *The sciences of the artificial*. Cambridge, MA: The MIT Press.
Sullivan, F. R. (2008). Robotics and science literacy: Thinking skills, science process skills and systems understanding. *Journal of Research in Science Teaching*, 45(3), 373-394.
van Fraassen, B. C. (1980). *The scientific image*. Oxford: Clarendon Press.
Walter, W. G. (1950). An imitation of life. *Scientific American*, 182(5), 42–45.

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