Noname manuscript No.
(will be inserted by the editor)

Can a Social Robot Stimulate Science Curiosity in Classrooms?

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Received: date / Accepted: date

Abstract This study investigates whether the presence of a social robot and interaction with it raises children's interest in science. We placed Robovie, our social robot, in an elementary school science class where children could freely interact with it during their breaks. Robovie was tele-operated and its behaviors were designed to answer any questions related to science. It encouraged the children to ask about science by initiating conversations about class topics. Our result shows that even though Robovie did not influence the science curiosity of the entire class, there were individual increases in the children who asked Robovie science questions.

Keywords Robots for children, Science class, Social robot, Field study

Fig. 1 Social robot in an elementary school's science classroom.

1 Introduction

Previous studies have reported that robots are beneficial for children's learning. For instance, robot kits have been used for teaching mathematics, physics, and computer programming [1–3]. Interactive and social robots have been useful for vocabulary and language learning [4–7]. The presence of a social robot made a learner-centered class more enjoyable and encouraged children to participate again [8]. Future classrooms will offer many potential tasks for robots.

We wonder, however, what future robots will do when they are not being specifically used for their designed learning activities? Will they be stored in a closet? Will they be left out when their power is turned off? How can we exploit their free time? Robots engage children's curiosity by encouraging interaction [9]. Perhaps such curiosity might be turned into science curiosity, which is an important motivator for learning science [10]. In fact, in various field studies, we witnessed parents who thought their children would benefit from interacting with our robot. Can we design a social robot's behavior that fulfills these expectations and fuels children's science curiosity? To answer these questions, we conducted a field study in an elementary school science classroom (Fig. 1).

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2 Related works

2.1 Science curiosity

Extensive research exists on curiosity, which is a crucial factor in human's cognitive development and learning. Curiosity is associated with a preference for novel and unfamiliar objects, complexity, and uncertainty. Curiosity is the source of the desire to acquire knowledge and the motivation to explore unknown phenomena. It motivates children to learn in a self-regulated manner. In many domains, self-motivated students perform better than extrinsically-motivated ones [11,12]. Children with high ability exhibit more curiosity than other children, and their curiosity scores increase year after year while other children's curiosity decreased [13]. Even among above average students, children with autonomous inclinations were more curious and received higher grades [11]. Research has shown that teachers understand the importance of fostering curiosity in the context of science education [14].

One element of higher education is inquiry-based learning, which is related to curiosity, where learners develop in-depth scientific questions and find the answers by themselves. Such learning techniques direct learners to acquire experimental and analytical skills and foster self-regulated learning strategies, thereby encouraging curiosity [15]. Even though our study targets elementary school children, they are not too young for inquiry-based learning [16]; then we believe that prompting children to ask questions will fuel their curiosity.

2.2 STEM education using robots

The needs of Science Technology Engineering and Math (STEM) education are of large social interest. Researchers have considered robots for it, including small robot-kits like Lego Mindstorms. With its visual programming language, Lego Mindstorms was successfully used to help 5- to 8-year-old children build their own animated constructions [1]. With such learning, children's math scores improved [3]. It also helped university students connect theory and real-world applications [2]. While these studies used robots as a learning material to be constructed and programmed, our current study uses a social/interactive robot to intellectually stimulate children with its human-like interaction. Compared with previous STEM education activities with robots, ours is an unexplored challenge in the robotic domain.

Robots have been placed in scientific museums, expositions, and STEM education contexts to raise children's interest in science and technology. Early trials used tool-like robots that people can touch to retrieve information [17,18], and later studies used more interactive robots [19] and human-like robots [20]. Yet in these studies, robots were used as a kind of exhibit with advanced technologies, unlike our current study's novel aspect that stresses specific interaction designed to promote children's science interest or curiosity.

2.3 Social/interactive robots for learning and motivating

Recent researchers have designed several types of specific interactions to promote children's learning. In the context of vocabulary and foreign-language learning, robots engaged in various language-related activities, such as games [6] and reading [4]. A robot was used for "learning by teaching" activities so that children's intrinsic motivation to interact with it was successfully leveraged to motivate them to teach the robot [7]. Such activities typically fall within the domain of language-related education; this is reasonable because a positive effect is expected if children are interacting with language, and they are often motivated to interact with robots. In a previous work more relevant to STEM education contexts, Pereira et al. used a cat-like robot to stimulate children to learn chess [21].

Beyond learning, a couple of long-term studies used agents and robots as motivators. Bickmore et al.'s screen agent motivated people to exercise [22] by engaging in human-like daily conversations and asking users to exercise more. Kidd et al. employed a robot to motivate users to continue their weight-loss activities [23]. In these studies, agents and robots engaged in dialogues through which they quite explicitly motivated users.

Our current study does not resemble either of the above type. Unlike previous work, our target is science curiosity, which cannot be accomplished by repeating simple language-based dialogues. Our robot does not explicitly request children to be curious about science because such curiosity is unlikely to be stimulated by a robot's requests.

3 Robot as a Knowledgeable student

3.1 Design consideration of robot's behaviors

"Why is the sky blue?" Children are often curious about such basic questions. Asking them is a good opportunity for children to satisfy their science curiosity. If they acquire answers in a reasonable time frame, their curiosity will probably be more stimulated and they will ask further questions in a process that resembles inquiry-based learning [15].

We also believe that peer-like friendly robots would encourage motivation to interact with them for children, as shown in past research works [5, 9]. Thus, rather than a teaching assistant, we portrayed our robot as a transfer student who has considerable science knowledge and integrated it into the school by imitating a situation where a new student joins a class. Such a robot naturally behaves friendly to encourage approaches by children. Past HCI research reported the importance of building rapport, which is known as affective computing [25]. Considering such interactions would be important to avoid just short-sighted question-and-answer conversations with children, and increase social acceptance towards the robot in a real setting.

To observe what might be reasonable in near future situations, we designed a robot's behaviors to always respond correctly and provide easily understandable answers, like parents and teachers. For instance, when asked about centrifugal force, the robot described it as "the force that draws a moving body away from the center of the movement. You've probably felt it in a car when it turned a corner." Keeping these considerations in mind, we prepared a robot that provided simplified summary answers by a Wizard-of-Oz technique.

3.2 Robot

We used Robovie, who is 120-cm tall with two arms (4*2 DOF) and a head (3 DOF) (Fig. 1). It is equipped with cameras, microphones, and a speaker. Its utterances were generated using speech synthesis software [26]. For this study, the robot is semi-autonomous; gestures and pre-determined speeches are autonomously controlled, but an operator conducted speech recognition and chose them based on pre-determined rules or typed in new text by an interface.

3.3 Environments and setup

Robovie was installed in an elementary school science room (Fig. 2) that has eight desks in front of a blackboard, where children attend science classes. Four cameras were attached to Robovie for tele-operating it from the next room. Before the first lesson (about one month ago from it), we introduced Robovie to children and explained that Robovie is semi-autonomous and it will connect to network to find answers if needed.

At the first lesson when children met Robovie, we conducted an introduction session, where Robovie introduced itself as a transfer student and explained that it always stays in the science room and quietly learns from behind the children. It expressed a desire to talk with the children about science during breaks, and it also talked with the teachers about a motor mechanism to demonstrate its science knowledge. To increase opportunities for the children to interact with Robovie, the science room remained open before and after science lessons as well as during morning breaks (before the first class) and lunch time. During science classes, Robovie did not initiate conversation; if children talked to it or stayed more than ten seconds in the front of it, Robovie suggested, "let's talk later, because we're in class now." This feature was designed to avoid disturbing class activities.

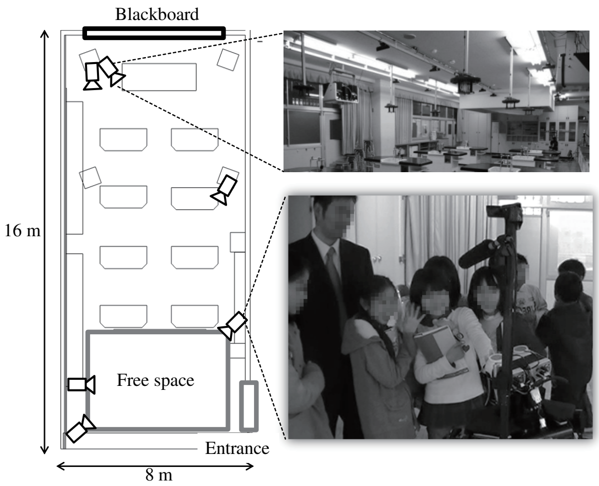

Fig. 2 Layout of science room.

During breaks, children were allowed to freely interact with Robovie in the free space. Children woke it up during morning and lunch breaks by pushing its wake-up button to start interactions. This created a reason for the children to visit the room.

Therefore, Robovie interacted with children only during breaks, unlike teachers. We note that this is not just an extension of the science classes to the breaks, because the interaction style of Robovie is quite different from common science classes and the teachers behaviors. For example, Robovie did not review their classes during breaks; it talked with children about various science topics, which are not limited to topics about their science classes, through behaviors described below.

3.4 Details of implemented behaviors

An overview of the dialogue flow is summarized in Fig. 3. When children lingered around Robovie during breaks, it turned to them and started conversations.

To establish peer-type relationships, Robovie exhibited such relational behaviors as greeting and self-disclosure dialogs (Section 3.4.1). While Robovie be-

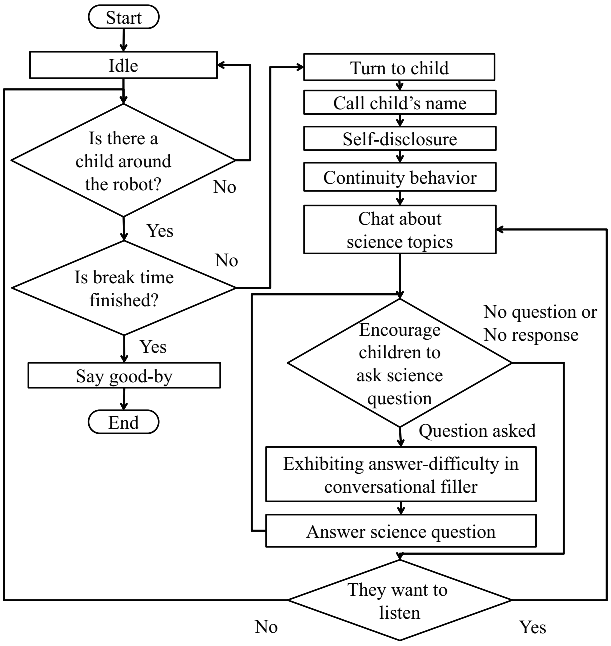

Fig. 3 Flow of Robovie's dialogue.

haved like a friend, it tried to elicit science curiosity by performing a series of behaviors for talking about science (Section 3.4.2), such as chat and question-answer behaviors. The operator controlled Robovie's locomotion, greeted children by name, and chose the behavior to be performed.

3.4.1 Relational behaviors

Calling children by their names In our previous studies, since we found that people appreciated their name being called by robots [5,9], we continued this strategy and prepared behaviors to greet the children by names, such as "Hello, Yamada-san (pseudo name)."

Self-disclosure with science topics

We followed a self-disclosure strategy that plays an important role in human-robot interaction [5,9] to encourage children to interact with Robovie. Chatting with a robot increased their desire to use robots as well as their perceived enjoyment toward them [27] Even though previous research focused on senior citizens, we believe that such interactions would make Robovie more accessible for children, too.

To convert the student curiosity in Robovie into curiosity for science, it discussed science during 68 self-disclosure behaviors (utterances accompanied by gazes, gestures, and arm motions) that we implemented to mention its personal favorites or its experiences. For example, Robovie asked the children about their school lunch and said, "I eat electricity and save it in my lithium-ion battery, like smartphones," and looked at its own stomach where its battery is.

Continuity behaviors

We implemented ten continuity behaviors with which Robovie mentioned that it investigated questions more deeply if a child asked at the last interaction or thanked the child who woke it up at the morning and at lunch breaks. For example, when a child asked a science question about the weight of a colt, the next day Robovie said, "Yamada-kun, I learned more about a colt's weight since we talked last. Want to hear what I learned?"

3.4.2 Behaviors that encourage science questions

Chatting about science topics Robovie aimed to establish a contextual background to talk about science by pretending that it failed to hear part of the lesson and asked children to explain what it missed. We expected that children could easily discuss the things they had just learned.

Robovie also initiated chats where it explained other relevant science topics. This behavior was used when children did not have a science question or became too quiet. Robovie first asked whether the children wanted to listen to a talk about science. For example, "By the way, I learned about a future battery that uses water to give an electrical charge. Want to hear more?" If the children were interested, Robovie explained the topic. We prepared 64 such behaviors.

Encouraging children to ask science questions

After such chats, Robovie directly asked the children whether they had any questions: "Any questions about today's science lesson? I'd like to answer them." Robovie explained how it felt happy when it talked about science. "As you know, I really like to talk about science. Please ask me some science questions." After answering them, Robovie said, "Thank you for asking me science questions. I really enjoyed answering them." Note that we did not review about the science class, e.g., do quizzes becuase it would be perceived as an extension of their classes by children. We implemented 33 such behaviors.

Answering science questions When a question was asked, the operator judged its relevance to science or Robovie. To answer it, the operator employed two strategies. When typical questions were asked, he selected from pre-implemented behaviors; otherwise, he directly typed utterances to implement new behaviors after the session.

In both cases, we tried to provide easy-to-understand answers. We initially prepared 60 behaviors that were related to the contents of the children's science lessons and exhibits in the science room. If the children asked

The final publication is available at
http://link.springer.com/article/10.1007/s12369-015-0303-1

about such exhibits, the robot used pointing gestures for confirmation and explanation. After adding some behaviors, the final number of answering behaviors was 100.

Avoiding deviation from science questions On the other hand, if children asked non-science questions, Robovie politely refused and redirected their attention to science. For example, if Robovie was requested to perform too simple math computations which did not relate to science topics, he would respond, "Sorry, I don't know much about non-scientific topics. But I do know science!". These behaviors were kinds of social behaviors to increase the total opportunity to interact with children, including conversations about science topics.

Exhibiting answer-difficulty in conversational fillers Because typing takes a few seconds, the operator used conversational fillers like "etto" or "well, let's see..." to buy time to type the responses [28]. With such conversational fillers, we motivated children to ask questions. We initially thought that the children would ask very easy questions to test Robovie's capabilities and accept that it can respond to their utterances. By providing feedback about the question's difficulty, we motivated the children to ask more difficult questions. Along with the question's difficulty, the operator chose conversational fillers to provide feedback about the difficulty. For example, Robovie said, "Wait a moment, that's a very difficult question... Let me search my memory" and scratched its head. If the question was easy, it only said, "Well, let me see..."

4 Field study

4.1 Hypotheses and predictions

In previous studies, robots increased children's curiosity and motivated mutual interaction in classrooms [5, 9]. Similarly, we expect that the children in the current school will actively interact with Robovie. Its behaviors were designed to talk about science and encourage children to ask science questions. Based on these designs, we hypothesized that its presence would influence all the children in the classroom and fan their science curiosity. We made the following prediction:

Prediction 1: Children's science curiosity will be increased by the robot's presence in the classroom.

We also speculated that it matters greatly whether a student asks Robovie a science question. Those who do not ask questions will passively observe Robovie and the interaction will have less influence on such passive observers. The science curiosity of those who actively ask science questions will be more influenced. Therefore, we made the following prediction:

Prediction 2: The more children ask science questions, the greater their science curiosity will increase.

4.2 Participants

Our study was conducted in a public elementary school science room used by 4th-6th grade students. We targeted four classes of 114 5th graders.

4.3 Procedure

Robovie was installed in the science room for a month. Science classes in this school are designed in a typical teacher-centered learning paradigm and last 45 minutes, followed by a ten to twenty minute break. Each class had seven lectures during the month. Pendulums and human birth were taught during the lectures. Each class had six morning breaks and six lunch breaks, which lasted ten minutes. Robovie was introduced to children at the first lecture.

We administrated questionnaires to the children. Pre-tests were conducted before the first science class, and post-tests were conducted after the final science class of the school term.

4.4 Measurements

4.4.1 Science curiosity: pre- and post-tests

In both the pre- and post-tests, we measured science curiosity using a scale, which consists of five items, developed for 5th grade students [10]. The questionnaire used 1-to-5 point Likert scales, where 1 is the most negative and 5 is the most positive. All five items were translated from English to Japanese. It includes such questions as "Science magazines and stories are interesting" and "I like touching different things to learn about them." The Cronbach's alpha at pre-test and post-test are 0.85 and 0.93, which were generally considered reliable. We note that children knew the participation of Robovie to their science classes before measuring the curiosity at pre-test; this information might have influenced to their science curiosity at pre-test.

4.4.2 Perception of robot: post-tests

We investigated the children's perceptions of Robovie in the post-tests. The questionnaire used 1-to-5 point

Likert scales where 1 is most negative and 5 is most positive. We kept the questionnaire short to match their limited attention spans by truncating many scales and used the questions weighted most highly by the factorial analyses described below in the corresponding papers. We prepared all other post-test items ourselves.

Likability: “I liked this robot” [29].

Enjoyment: “I enjoyed talking to the robot.”

Intention to use: we adapted three items including, “If I had the chance, I’d talk with the robot again” [13].(The Cronbach’s alpha was 0.94.)

Perceived friend-likeness: “I think the robot was my friend.”

Perceived value of knowledge: “The robot’s knowledge was valuable.”

Perceived helpfulness: “The robot was helpful.”

Perceived understandability: “I understood the robot’s explanations.”

Perceived science expertise: “The robot was a science expert.”

4.4.3 Number of questions to the robot

We counted how many times the children asked Robovie science questions (e.g., why is the sky blue?) and Robovie-concentric questions (e.g., what is your favorite food?). We analyzed the recorded audio and video, coded who asked the questions, and whether they were science or Robovie content.

Fig. 4 First week: children gathered around Robovie.

Fig. 5 Fourth week: Few children talk with Robovie, but others return to their room or talk with friends.

5 Results

5.1 General trends

The children’s interaction with Robovie gradually changed during our month-long trial. As observed at another field trial at elementary schools [5,9], in the first and second weeks many children seemed interested and gathered around Robovie (Fig. 4). The robot(s greeting-by-name behavior attracted their attention. Typically they asked, “Do you know my name?”

In contrast, during this time period, children seemed much less attracted to the behaviors related to science. They sometimes asked questions, but their purpose was more to test its capabilities; they often asked Robovie whether it knew the topic that had just been taught. For instance, in a break just after the lesson about pendulums, a child asked, “Do you know anything about pendulums?” In addition, they often ignored Robovie’s request for science questions and interrupted it by asking Robovie-related questions.

After the third week, the situation started to change. The size of the crowd around it reduced, maybe because the robot’s novelty had worn off. Although almost all of the children continued to greet Robovie before and after the lessons, only about half had follow-up conversations with it (Fig. 5). In a typical scene, when a break started, a group of active children ran to Robovie and interacted with it while relatively quiet children watched. After the active children left, these quieter children took turns interacting with it. The frequency of their requests to hear their names was less than the first two weeks. Instead, children more frequently listened to Robovie without interrupting it.

5.2 Verification of prediction 1

Regarding prediction 1 (children’s science curiosity will be increased), we ran an analysis to reveal whether Robovie contributed to changes in science curiosity using linear mixed-effect models with within-participant variables of science curiosity scale (pre- and post-test scores) as a fixed effect. We used class as a random effect due to the differences of teachers and children between them. However, there was no significant effect in science curiosity (F(1,109)=1.705, p=.194). Prediction 1 was not supported.

5.3 Verification of prediction 2

Regarding prediction 2 (children's science curiosity will increase if they ask Robovie questions) we ran an analysis to reveal whether interaction with Robovie contributed to changes in science curiosity using linear mixed-effects models with variables in the following equation as the fixed effect and the children's class as the random effect:

Model (curiosity at post-test - curiosity at pre-test) = intercept + curiosity at pre-test + number of science questions + number of Robovie questions.

There were significant effects in curiosity at pre-test (F(1, 104.945) =23.327, p <.001) and number of science questions (F(1, 105.505) =4.075, p=.046), but no significant effect in number of Robovie questions (F(1, 104.164))=0.140, p=.709) (Table 1). These results indicate that the curiosity at pre-test and number of science questions have significant effects towards the curiosity at post-test. Children who asked science questions were more likely to become more curious. It also indicates a trend where the curiosity of children who did not ask science question become lower. Note that the details of relationship between the science curiosity at pre-test and question asked will be discussed at the discussion section. Overall, prediction 2 was supported.

Table 1 Factor analysis results for increase of curiosity

	Estimate	p
Intercept	1.164	<.001
Curiosity at pre-test	-0.348	<.001
Science questions	0.083	.046
Robovie questions	-0.019	.709

5.4 Additional analysis

Since we focused on whether children asked science questions as an important factor in their increased science curiosity, we analyzed whether their perception of the robot changed using linear mixed-effects models with a factor whether children asked a science question as a fixed effect and the class as a random effect (Fig. 6).

Our analysis revealed significant differences in perceived likability (F(1, 111.415)=16.928, p <.001), enjoyment (F(1, 110.754) =11.905, p =.001), intention to use (F(1, 111.615)=10.590, p=.002), friend-likeness (F(1, 110.703)=11.295, p =.001), value of knowledge (F(1, 111.232)=5.588, p=.020), and helpfulness (F(1, 109.430)=8.239, p=.005). A significant trend was found in science expertise (F(1, 111.928)=3.558, p=.062), and no significant difference was found in understandability (F(1, 109.218)=2.300, p=.110).

These student ratings about perceptions suggest that the perceived pleasantness (e.g., likability, enjoyment, and friend-likeness) of the robot had a greater relationship with whether a student asked questions. The robot's perceived capabilities (e.g., understandability and science expertise) might have a relatively small relationship with whether children asked questions.

Moreover, as a supplemental analysis, we investigated whether questions about the robot change perception of the robot like science questions. For this purpose, we analyzed whether their perception of the robot changed using linear mixed-effects models with a factor whether children asked a non-science question (i.e., robovie question) as a fixed effect and the class as a random effect (Fig. 7).

Our analysis revealed significant differences in perceived friend-likeness (F(1, 109.900)=4.086, p =.046). A significant trend was found in perceived enjoyment (F(1, 109.974)=3.247, p =.074) and intention to use (F(1, 110.448)=3.107, p =.081). There is no significant difference was found in likability (F(1, 110.380)=1.962, p =.164), value of knowledge (F(1, 110.252)=1.059, p =.306), helpfulness (F(1, 108.867)=0.281, p =.597), science expertise (F(1, 110.878)=0.348, p =.556), and understandability (F(1, 108.809)=0.561, p =.455).

These student ratings about perceptions would suggest that the perceived pleasantness of the robot had a greater relationship with whether a student asked questions about the robot; this result seemed similar to the analysis of the students asked questions about the science. On the other hand, the robot's perceived capabilities might have no relationship with whether children asked questions about the robot.

These facts might indicate that the robot's presence had an influence on the increases of children who asked questions. However, impressions about the robot were measured at post-test only. Therefore it is difficult to judge whether they asked questions because they had high perceived pleasantness, or their perceived pleasantness was raised because they asked questions, even though the impressions about the robot might have a relationship with whether children asked questions.

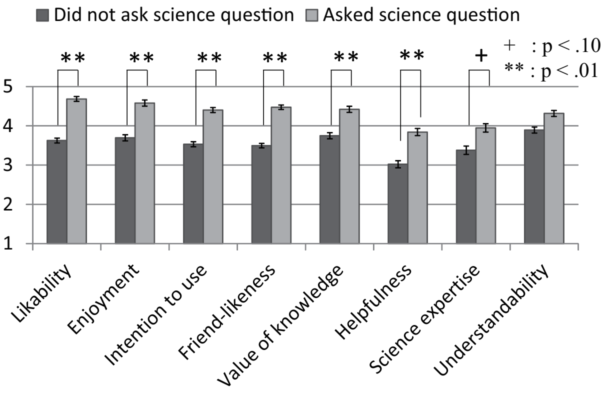

Fig. 6 Perception of robot (science question effects).

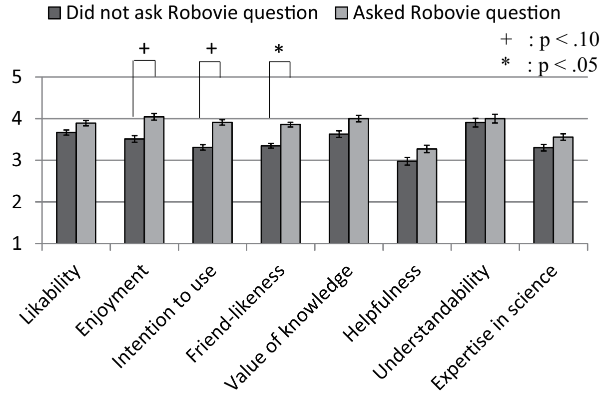

Fig. 7 Perception of robot (Robovie question effects).

Fig. 8 After class, a child ran to Robovie.

5.5 Observations

5.5.1 Effect of relational behaviors

We observed many scenes where relational behaviors seemed to motivate the children to interact with Robovie. As in past research works [5,9], children liked it when Robovie called them by their names. For instance, at the first lesson a child ran to Robovie (Fig. 8) who greeted him by name. The boy always asked, "Robovie, do you remember me?" and interacted with it during most breaks after the science lessons. Such greeting-by-name behavior motivated another child who approached Robovie and talked to it after it used his name in an interaction; this child was only a passive observer until the robot greeted him by name. Children requested to hear their names 46 times. Robovie used the names of 85 children (74.6%) and said children's names 257 times.

Fig. 9 Children tried to look under Robovie.

The robot's self-disclosure behaviors encouraged children's reciprocal self-disclosures toward it. For example, Robovie talked to a child about soccer because its brothers (other types of Robovie) won the Robocup championship. Then the child self-disclosed: "I like soccer, too." Next he asked Robovie, "How many friends do you have?" The robot explained about its friends and family (same versions of Robovie). In return, the student described his family: "There are four people in my family. My parents and my little brother, who's a second grader."

Self-disclosure behaviors with science topics raised children's interest in Robovie. For instance, Robovie explained its own locomotion abilities (Fig. 9, left): "I use wheels to move around instead of legs. Like a car!" Then children squatted and tried to look into Robovie's lower part (Fig. 9, right).

Even though the total number of the uses of continuity behaviors was relatively small (15 times), this behavior was well accepted. For example, at a break after a lesson, children crowded around Robovie and shouted at it to say their names. A child touched its shoulder and asked, "Do you know me?," and another child pointed to another student and asked, "Do you know his name?" (Fig. 10, left). However, continuity behaviors changed such noisy situations. Robovie talked to a child who had asked about Kepler's second law during a previous interaction: "Yamada-kun, I learned some more about your last question." All the children stopped their requests that Robovie say their names. They seemed surprised that it remembered previous questions. "Should I explain it?" the robot asked, and the questioner and the other children said "Yes" and "Please" and quietly listened to its explanation (Fig. 10, right).

Fig. 10 Children listening to Robovie after continuity behavior.

Fig. 11 Interaction during lunch break.

5.5.2 Did the robot encourage science questions?

Robovie conducted behaviors which talk about topics related to the children's science lessons 48 times, and children asked eight science questions after those behaviors in total. For instance, at a break after a science lesson about human birth, the children listened to Robovie talk about the abilities of unborn children. One child asked relevant science questions:

Robovie: "An unborn child can hear the voice of its mother from inside her body."

Child: "Why are unborn children only in their mothers?"

Robovie: "Well, because mothers have wombs."

Child: "Do fathers have wombs?"

Robovie: "No, they don't."

Overall, the children asked Robovie 57 science questions. 38 (66.7%) were relevant to their science lessons and 19 (33.3%) were on general topics beyond those taught in class, typically of three types: nature (e.g., what is the temperature of the sun's surface?), animals/human beings (e.g., how much does a colt weigh?), and engineering (What is eco-friendly energy?). 19 children asked science questions (3.00 questions per child on average, S.D is 1.60.). The numbers of each category through time is detailed in the table 2. As shown in the table, in the latter half period (third and fourth weeks), the number of science questions about their lessons were decreased, contrary to the number of science questions about general topics. This trend would indicate that, as time passes, children ask more question about general topics than questions which they already know answers.

During the field trial, Robovie exhibited the "encourage children to ask science questions" behaviors 36 times, and children asked science questions 12 times after those behaviors (note that the rest of science questions (45/57) were asked by children at different time). For instance, at a lunch break, a child visited the science room alone and asked a science question after being encouraged by Robovie (Fig. 11). Five days before he participated in a science lesson about human birth that did not include the abilities of unborn children:

Robovie: "If you have a science question, please let me know. I'l try to answer it."

Child: "Well, . . . can a fetus see anything in its mommy's womb?"

Robovie: "Hmm, a fetus has very poor eyesight, yet it can perceive brightness."

At another lunch break, another child visited alone and asked science questions:

Robovie: "Do you have any science questions? I can probably answer them."

Child: "I wonder. . . Why is the sky blue?"

Robovie: "Oh, that's a good question. Well, the atmosphere scatters blue light from the sunlight. That scattered blue light approaches the earth, and so the sky looks blue. That is also why the sea is blue. Water scatters blue light, too. "

Child: "I see. I understood the first time!"

After this exchange, he asked three other science questions: the source of the influenza virus, why ants and spiders have different numbers of legs, and why the earth is round. We thought that "Why is the sky blue?" could be a chance to start more difficult topics such as what happens to light when it crosses a refractive medium, but Robovie provided rather simple answer based on our behavior design policy. It might be difficult to judge whether Robovie's answer was better for child, but the child asked many kinds of questions after this answer; these questions seemed to reflect genuine science curiosity.

The avoiding deviation from science questions strategy worked well. Children sometimes asked questions

Table 2 The number of each category of science questions

	Related to lessons	General topics
The first half	22	8
The latter half	16	11

that were not related to science and robots. For example, such math questions as “What’s one and one?” were frequently asked. In such situations, Robovie politely declined and steered the topic back to science questions. As we expected, after such behavior from Robovie, children typically asked science questions. Another child also asked a math question as ”What’s four and four?” to test capability of Robovie, but the child stopped such question after a declining behavior by Robovie, and she asked science questions later. Note that Robovie declined only these too simple math questions during experiment, it would not restrain motivations of children to ask questions to Robovie. In addition, sometimes another child helped Robovie get science questions through this behavior. For instance, a child said to the child who asked a math question that Robovie wants science questions, and then another child said to the surrounding children that “Robovie wants to answer science questions, do you have any?”

Moreover, exhibiting answer-difficulty in conversational fillers also worked well. Children who watched these behaviors seemed to understand of Robovie’s state, and some of children seemed to be interested in asking more difficult questions to Robovie. A part of children said ”Maybe Robovie is connecting to Internet to find answers” when Robovie is exhibiting answer-difficulties.

6 Discussion

6.1 Which comes first: questions or curiosity?

Our study revealed that science curiosity increased more for the children who asked Robovie more science questions. This result begs a cause-and-effect relationship. In fact, it is difficult to judge whether they asked Robovie science questions because they had high science curiosity, or whether their science curiosity was raised because they asked them.

We believe that both are generally true. A kind of curiosity loop drives questions, which fuel more curiosity. The research question is how to cause such a positive spiral. On the other hand, based on our evidence from this study, we conclude that children who asked science questions had higher science curiosity (mean: 4.14, S.D.: 0.61) than children who did not (mean: 3.59, S.D.: 0.91). We conducted analysis with linear mixed-effects models with a factor whether children asked a science question as a fixed effect and the class as a random effect. The analysis revealed a significant difference (F(1, 107.986) = 6.657, p =.012), meaning that higher science curiosity is a required (but not sufficient) condition to ask science questions. Simply having higher science curiosity did not result in the increase; our analysis revealed that its influence had an opposite effect (Table 1).

Interaction with Robovie was the fundamental causal factor. For instance, some children asked many good science questions (see Section 5.5.2) that seemed driven by genuine science curiosity, and such question-asking was enabled by the interaction with Robovie. Knowing that Robovie could answer science questions motivated them to ask more questions and increased their science curiosity. We note that one limitation of this research work is the low number of question asked, which make it difficult to discuss the above question and the effects of children’s science questions towards their science curiosity. A longer duration experiment would increase such number then the effects of a social robot and children’s science questions towards curiosity would become clear. However, it was difficult due to limitation of installing a real robot to real environment.

Even though Robovie encouraged a positive spiral by motivating science learning or solving science questions for children who have high science curiosity, the question remains open how to motivate science learning for children with less science curiosity. This question would be difficult for human teachers too. For this purpose, human teachers would prepare a lot of ”new” items to attract such children because it is unknown what is interesting for them in advance. We think, Robovie could become one of such ”new” items; but it is difficult to statistically prove it from current results. Moreover, it is still open question how to reach out children who did not have interest in the robot.

6.2 Could an alternative entity cause a similar effect?

One remaining question is that whether other entities such as screen agents could cause a similar effect. In this research we only tested the effects of our social robot, thus we cannot estimate the effects of these entities. We thought that other than robots, such entities as tutor agents on a screen [21] would provide an easy-to-use interface for children to ask questions.

On the other hand, past research works showed the advantages of a use of physical robots by comparing screen agents. For example, Powers et al. compared a robot and a computer agent displayed on a monitor to investigate social interactions [29]. Shinozawa et al.

compared the effect of persuasions in a laboratory environment between a robot and a computer agent displayed on a monitor [30]. Bainbridge et al. also compared the persuasion effects between a computer agent and a robot for various tasks [31]. We also compared a robot and a computer agent displayed on a monitor to investigate persuasion effects in a shopping mall [32]. These research works reported that real robots affect subject decision-making more effectively or attract people than computer agents in real world environments. Moreover, Iris et al. have investigated the ease of asking question comparing between a robot and a human with different roles (helper and teacher) [33].

These research works would suggest that the physical existence and the social interaction of the robot encouraged children to ask questions; however, one limitation of our current study is its inability to answer this question from our experiment.

6.3 Can Robovie be autonomous?

Next we discuss the possibility of making our robot autonomous. Person identification is an essential function. In our past works we successfully identified children using RFID (Radio Frequency IDentifier) tags [5,9]. A system with such identification techniques and human tracking [34] would enable a robot to accurately identify children.

Speech recognition is another challenge. Current speech recognition systems, even those prepared for noisy environments, are only 21.3% successful in actual use with robots [35]. Many sources of difficulties exist: unexpected noise, background music, and children's speaking patterns, which are different from adults. On the other hand, similar to iPhone's Siri and Google speech recognition, the growth of data for training such systems might greatly improve performance in the near future. Perhaps there is a chicken-and-egg problem here: the more technology we use, the more data we gather, leading to greater improvements in performance. But to make technology usable in real settings, we need better performance. Starting to use robots, even tele-operated ones, is an important step toward gathering data and increasing autonomy.

Preparing easily understandable answers to children's questions requires very sophisticated intelligence, which is currently difficult for an autonomous robot. Even in the future, such answers will probably be prepared by human professionals. However, once enough answers are prepared, robots can be mostly autonomous because they can select answers from pools vetted by experts.

All of the above possibilities need further improvements of each technical component. Yet even with current technology a human operator might help in situations where a technology fails. With this shared autonomy approach and small efforts from human operators, robots might operate the tasks in this study.

6.4 How did children perceive the robot's role?

In this study, we decided the role of the robot as a transfer student, not a teacher (assistant). However, in the questionnaire, we did not ask to children to investigate whether they perceived the robot as a peer or a teacher assistant. Therefore, we did not have statistical results about whether children perceived Robovie as a teacher assistant, or a kind of friend as we designed. One limitation of our current study is its inability to answer this question.

However, we think that the questionnaire results about friendly-likeness would be one of evidences to support our statement. Because the average value of this item is more than three at one-to-five scale, if we designed the robot as a teacher assistant then this value would become lower value.

One of future works of this paper is to investigate the learning effects of different roles of the robot by considering the conjunction between the human teacher and the climates of classes. Appropriate roles of the robot in the school would be different depending on personalities of the human teachers and children, and the style of lectures.

7 Conclusion

Our field study investigated whether a social robot can stimulate children's science curiosity in an elementary school. Robovie was installed in a science room for one month, where children were allowed to freely interact with it during breaks. Although Robovie did not raise the entire class's science curiosity, the children's science curiosity scores increased more when they asked more questions. We conclude that an effect in Robovie stimulated the science curiosity of children who were very motivated to ask science questions. However, the science curiosity of children who were passively observing was not positively influenced.

Acknowledgements We thank the staff at the Higashi-Hikari elementary school, its students, and their parents for their cooperation. We also thank Prof. Naomi Miyake (Univ. of Tokyo) for her helpful advice and Kanako Tomita who helped conduct the experiment. This work was supported by JSPS KAKENHI Grant Numbers 21118001, 21118003, 21110008, and 25240042.

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