A Self-Competitive Method for the Development of an Educational Robot for Children

Fumihide Tanaka[1] and Shizuko Matsuzoe[2]

***Abstract*— To accelerate the developmental process of robots interacting with humans in the real world, we propose the simultaneous introduction of two competing robots into the test field. One robot moves autonomously using a preprogrammed behavior set, while the other is remotely controlled by a human operator. The operator attempts to improve the robot by exploring new behavioral elements. Concurrently, the preprogrammed behavior set is tested by the first robot. The main concept is that by allowing the two robots compete against each other, we aim to accelerate the development process. By applying this methodology, we developed an educational robot for children. Herein we report the functioning of this methodology and how behavioral elements were explored and improved through field development.**

I. Introduction

In designing a robot for interacting with humans, the robot's desirable behaviors are usually not evident before conducting test trials. Therefore, developers have to repeat such test trials for determining better behavior, which is a time-consuming process. However, sometimes it is not possible to conduct sufficient number of test trials. For example, designing robots that interact with young children require child participants, who are usually more difficult to recruit than adult participants. Furthermore, when conducting field trials in real environments (e.g., classrooms) there are limitations such as difficulty in coordinating schedules. Therefore, we need to optimize the available opportunities.

In this paper, we propose a methodology that accelerates the abovementioned developmental process. The main idea is to introduce two robots simultaneously into a classroom, explore desirable behaviors and evaluate previous behaviors. One robot moves autonomously using a preprogrammed behavior set; the other is remotely controlled by a human operator. The human operator explores new desirable behaviors by which the controlled robot outperforms the autonomous robot. Meanwhile, the autonomous robot exploits behaviors discovered in the previous trials. By competing with the autonomous robot as the *previous-self*, the human operator can quickly explore and test several behaviors and find the best behavior. Comparative experiments on all of these behaviors would require a huge amount of time; instead, we accelerate the developmental process by admitting the operator's judgment. At set stages, the autonomous robot is upgraded to encourage new exploration by the human operator. The upgrade is made by incorporating the previously found behaviors into the robot. By this approach, the operator's previous judgment can also be retested in the next run of the autonomous robot. The contribution of this paper is to present the methodology of this self-competitive development, and demonstrates its feasibility in developing an educational robot for children (aged 4–6) in a classroom.

[1]Fumihide Tanaka is with Faculty of Engineering, Information and Systems, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki, Japan fumihide.tanaka@gmail.com

[2]Shizuko Matsuzoe is with Graduate School of Systems and Information Engineering, University of Tsukuba shi25tty@gmail.com

II. Educational Robots

A. Need for a Rapid and Continuing Developmental Cycle

Educational robots are gaining attention in the social robotics field. Studies have shown that robots can be useful educational agents that attract students' interests and positively impact on learning. Kanda and his colleagues introduced the English-speaking robot, Robovie into a Japanese elementary school and investigated its effect on students' English skills [1]. This group also studied the long-term relationships between the robot and elementary school children [2]. Other researchers have introduced teaching assistant robots [3], [4] and tutor robots [5] to elementary school children in field trials. A comparative study between a robot and other educational media such as books and web-based instructions further demonstrated the effectiveness of educational robots [6].

All the above educational robots were developed as teaching assistants or robotic tutors, whose behaviors were designed and programmed prior to the field trials. However, most of these studies ended once the trial was completed, rather than continuing the developmental cycle. The few exceptions include grand projects such as the abovementioned Robovie project, and the RUBI project [7], [8] in the US, which investigated the use of social robots in early childhood education. Compared with previously mentioned studies, the target age group was younger in these studies; for example, early studies investigated socialization between toddlers (aged 18–24 months) and robots at an early childhood education center [9], [10], [11]. The RUBI project required two years to repeat the early developmental cycle [7], [8] and a further two years to complete the next cycle [12]. These previous works show the difficulty of developing educational robots for children, particularly the long timeframe of repeated field trials, which are crucial for the development of educational robots. As explained in Section I, recruiting child participants for experiments is more difficult than recruiting adult participants. Moreover, field trials at educational facilities must be coordinated around many standard schedules. Therefore, we require a methodology that optimizes the available opportunities to continue the developmental cycle.

B. *Care-Receiving Robot*

This subsection explains an educational robot called the *care-receiving robot* (CRR). The CRR is adopted in a case study that demonstrates the feasibility of our methodology in accelerating the developmental cycle of educational robots, as described in the following sections.

In the previous section, we mentioned that most educational robots act as teaching assistants or tutors, providing either instructions or care to children. In 2009, Tanaka proposed the opposite type of an educational robot [13], namely, a robot that is taught or cared for by children, eliciting their "learning by teaching;" hence the name *care-receiving robot*. The CRR was tested in a field study at an English learning school for Japanese children, and was found to promote spontaneous learning. Thus, the CRR provides an effective enrichment tool in childhood education [14].

Because the CRR's behavior elicits caretaking or teaching activities in children, it is a crucial factor in the robot design. Previously, a CRR was designed to respond incorrectly to some questions asked by the human teacher in a classroom [14]. To implement the incorrect response, random preprogrammed behaviors were triggered and executed by a human operator (Wizard-of-Oz control). Clearly, this approach was limited, and additional desirable behaviors could be identified in further developmental cycles. However, as indicated in other studies mentioned in the previous subsection, the research group could not continue the developmental process beyond one iteration.

III. Self-Competitive Robot Development

The proposed methodology uses two robots that are introduced simultaneously into a test field. One robot (R1 in Fig. 1) moves autonomously using a preprogrammed behavior set, while the other (R2) is remotely controlled by a human operator. Using R2, the human operator explores desirable robot behaviors. Concurrently, the preprogrammed behavior set implemented in R1 is tested through interactions with participants. The main concept here is that by allowing the two robots to compete against each other, we aim to accelerate the process of the behavior development.

R1 is programmed to act autonomously using a behavior set determined from its previous test results. This behavior set is determined according to the objectives of the robot. For example, the objective of the CRR is to elicit caretaking actions in humans.

R2 explores new desirable behaviors, which is essential because such behaviors are usually not evident before the test trials. For effective exploration, we utilize a Wizard-of-Oz (WOZ) control, in which a human operator remotely controls the robot, and attempts to improve its performance over R1. By this approach, we anticipate the discovery of new desirable behaviors. From experience, we consider that desirable robot behaviors are best revealed in field trials. Therefore, we encourage discovery by the human operator

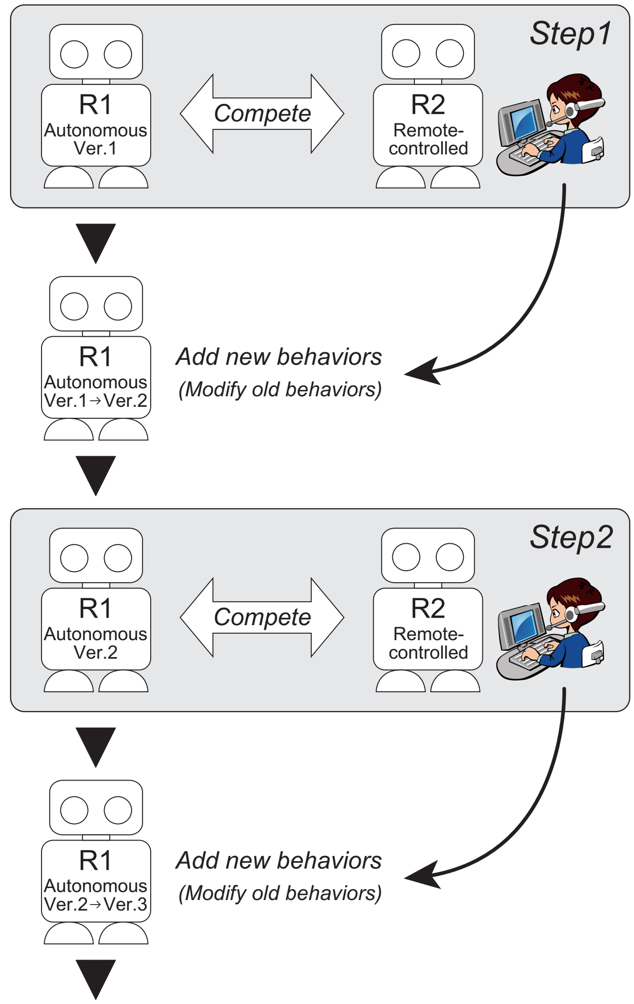

Fig. 1. Self-competitive development of robot behaviors: using two robots (R1 and R2) that compete against each other, desirable new behaviors are expected to be discovered and tested effectively, resulting in the development of robot behaviors. R1 is an autonomous robot, and R2 is remotely controlled by a human operator.

within the WOZ framework. In practice, it is useful to provide the human operator with a recording device, such as a speech recorder, to capture his/her thoughts during the WOZ control.

Once a trial is complete, R1 is updated by the new behaviors discovered during the trial. In the next trial, the operator competes R2 again against the updated R1 and seeks further behaviors. In one sense, the state of the autonomous robot (R1) can be considered as a *previous-self*. Through this process, we expect to realize effective exploration and development of robot behaviors.

Note that this approach does not necessarily find the optimal solution (behaviors). To formally assess the utility of each behavior, comparative experiments are needed. Instead, we rely on the quick judgment of the operator, which might be incorrect. However, if this approach accelerates the process of the behavior development, it should prove valuable when fast test trials are crucial; for example, in

Fig. 2. Kindergarten classroom in which the field trials were conducted.

the development of a robot for young school children, as explained in Section I.

IV. Field Trials

In this section we describe field trials in which we applied the self-competitive methodology (Section III) in developing an educational robot for children. The target robot was a CRR, as described in Section II-B. Recall that the CRR is taught or cared for by children; therefore, its behaviors must be designed to elicit children's teaching/caretaking.

The field trials were conducted in two kindergartens in Tsukuba city, Japan. A classroom is photographed in Fig. 2. The classroom environment was kept as usual during the trials; that is, toys remained in the classroom and children were allowed to play with them alongside the two robots to maintain the regular classroom atmosphere. Two robots, set an appropriate distance apart, were simultaneously introduced to the center of the classroom. The trials were recorded by two camcorders installed in the corner of the room. A monitoring system (a camera and a microphone: LifeSize Passport) were also installed for the human operator, who remotely controlled one of the robots from another room.

A total of 63 children (aged 4–6) participated in the field trials. This study was approved by the Ethical Committee of the University of Tsukuba. We explained our study goals and field trials to the children's parents, and received written consent from each parent before starting the field trials.

First, we conducted pilot trials to identify the base elements for the main field trial. From these pilot studies, we selected appropriate materials (in this case, animal cards) and classroom activities (an animal gesture game), and the timing of each game session in the main trial.

A. Goals

The main objectives of the field trials were twofold: (1) to apply and test the feasibility of the self-competitive methodology in the development of a CRR and (2) to develop an effective CRR. More specifically, in (1) we wanted to determine whether self-competitive development was feasible in a daily classroom environment, and whether exploring desirable CRR behaviors was a repeatable process. In (2) we wanted a CRR that expressed more diverse behaviors

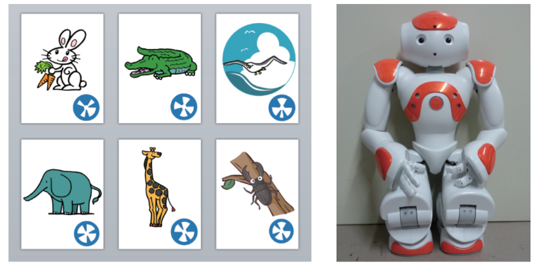

Fig. 3. (Left) Animal cards used in the study. Naomarks are printed on the bottom right of each card. (Right) Aldebaran Robotics' NAO.

Fig. 4. Direct teaching: children teach elephant gestures to a robot by guiding its hand in a step-by-step fashion.

than the original implementation reported in [14], which was equipped with a single behavior (making incorrect answers), and which was remotely controlled by a human operator. Here we aimed for an autonomous CRR equipped with multiple behaviors.

B. Materials and Tasks

The robot used in this study was NAO (Aldebaran Robotics; see right panel of Fig. 3). The WOZ control of NAO was implemented through a standard GUI and a puppet robot interface. This interface offered a master-slave control that synchronized the movement of the target robot (slave) with that of the puppet robot (master). Thus, if the operator lifted the arms of the puppet robot, the target robot moved its arms in the same manner.

The methodology was trialed on an animal gesture game. Children were allocated animal cards (left panel in Fig. 3) while interacting with two robots. There were six cards, each depicting a different animal: rabbit, elephant, alligator, giraffe, sea gull, and stag beetle. Each group of children was randomly allocated three cards, counterbalancing the difficulty level of the English names of the animals. When the children showed an animal card to the robot, the robot attempted to imitate the gesture of the animal on the card. All the gestures were predefined, and typified the gestures regularly seen in classrooms. If the robot demonstrated an incorrect gesture, the children were able to take its hand and teach the gesture step by step (direct teaching; Fig. 4). The robot then correctly demonstrated the animal gesture.

Fig. 5. Snapshot of a pre-test for assessing a participant's English level.

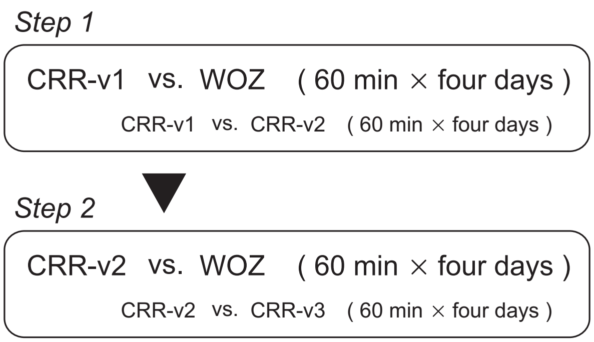

Fig. 6. Overall flow of the field trial. Each condition was maintained for four days with independent participant groups.

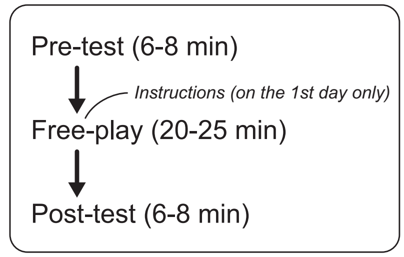

Fig. 7. Session time flow (on each day).

Two robots were simultaneously introduced to the classroom. One robot was remotely controlled by a human operator through the above-described controlling interface. The other robot moved autonomously. The autonomous robot visually recognized the animal cards using Naomarks (left panel of Fig. 3), special landmarks for NAO provided by Aldebaran Robotics. In addition, by observing all joint angle information in real time, we could recognize direct teaching by the children.

A tablet PC with earphones was used for pre/post-testing the participants (Fig. 5). Each participant listened to a native speaker pronouncing the animal words on the tablet PC in English. In the pre/posttest, we assessed the participants' knowledge of the animals.

C. Procedure

The main field trial was conducted over 16 days (four sets of participants, each assessed over four days: see Fig. 6). Each session lasted for approximately 60 min. A total of 48 participants were divided into four groups, each of which attended one of the four-day sessions.

In the first four-day sessions, CRR-v1 (version 1) and WOZ (remote-controlled robot) competed against each other, constituting the first step of the self-competitive development described in Fig. 1. Like the original CRR [14], CRR-v1 simply gave incorrect responses; in this case, a wrong gesture when shown an animal card. If the robot then learned the correct gesture by direct teaching, it performed that gesture once only (forgetting it in subsequent trials). CRR-v1 remained at one position in the classroom and did not move around by itself. Next, CRR-v1 was updated to CRR-v2 (version 2) by adding the newly discovered behaviors. To assess the performance difference between the two CRRs, we compared the two autonomous robots CRR-v1 and CRR-v2 in additional four-day sessions with a new participant group. During the third four-day sessions, we introduced and competed CRR-v2 and WOZ. After adding further new behaviors to CRR-v2 to create CRR-v3, we conducted the last four-day sessions to assess the difference again.

Fig. 7 shows the overall flow of a single day's session. In the pre-test, each participant was asked to play a card game. The participant heard the English name of an animal and was instructed to pick up a corresponding animal card from eight cards on the floor. This test was repeated six times (six animals), including the animals used in the succeeding gesture game.

During the following free-play period, participants freely played the animal gesture game (Section IV-B) with the robots. On the first day of their session, all participants were instructed on the game play by an experimenter. The experimenter demonstrated how to show a card to the robot, and how to teach the corresponding gesture to the robot. The experimenter also encouraged participants to play with both robots. These actions were performed only during the first few minutes of Day 1; during the remaining three days, the experimenter looked after the safety of the participants.

V. Results

A. Observations from Step 1: CRR-v1 vs. WOZ

When the WOZ robot started walking, it attracted participants' interest as well as the attention of others who had been playing with other toys further away. A bowing motion (as if the robot was disappointed) was found to be effectively encourage the participants to return to the robot and play the animal gesture game. Moreover, after the first four-day sessions, we decided to let the robot fall down. We expected that this new behavior would evoke the participants' caretaking actions. In fact, at one time during the first sessions, CRR-v1 accidentally became stuck and fell onto the floor. We observed that children came to care for the robot. A quite similar case, in which young children enjoyed helping a fallen robot regain its footing, has been reported [11]. However, no studies of deliberate falling by a robot have been reported. The operator of the WOZ robot considered these falling behaviors to be quite promising during the sessions. Also, the operator considered that the safest falling regime for the robot was falling backward after sitting down. Based on these considerations, we added the following three behaviors to create CRR-v2 from CRR-v1:

- B-11: Circling around a spot and looking around
- B-12: Sitting down and bowing its head
- B-13: Sitting down and falling backward

If no participant interacted with CRR-v2 for 30 s, these behaviors were executed in sequence, following a request for animal cards spoken in English.

B. Observations from Step 2: CRR-v2 vs. WOZ

During the next trial, CRR-v2 was compared with the WOZ robot. Observing that a backward-walking behavior was effective (Fig. 8), the operator explored the best timing of this behavior, and found it to be especially effective when there was nobody in front of the robot. In fact, it became clear that the robot should behave differently when there was somebody present in front of the robot than when there was nobody present in front of the robot. This was particularly noticeable when the operator tried mirroring CRR-v2's movements through the WOZ robot. This example highlighted the success of introducing two robots for self-competitive development. Based on these considerations, we updated CRR-v2 to CRR-v3, with the following new behaviors:

If there was nobody in front of the robot, do either of

- B-21: Circling around a spot and looking around or
- B-22: Walking 45 cm backward.

If there was somebody in front of the robot, do either of

- B-23: Sitting down and bowing its head or
- B-24: Sitting down and falling backward.

The presence or absence of humans in front of the robot was judged by an infrared sensor embedded in the robot.

C. Evaluation of the CRR Development

To evaluate the feasibility of the self-competitive development and assess the performance of the developed CRRs, we analyzed the behavior of the participants from the videos shot during the trials.

First, we classified the interactions between the robots and participants into two categories. The first category included game-relevant interactions such as showing an animal card to the robot, teaching an animal gesture to the robot, and praising the robot. The second category included all other (game-irrelevant) interactions. We double-checked the reliability of the behavioral classifications (video coding) by three external coders, and the inter-observer reliability was 0.91. Fig. 9 shows the average percentages of the game-relevant interactions for the four robot types. Each bar was calculated from each of the four-day sessions using the corresponding robot. *Base* refers to the baseline robot used during the pilot trial. This robot performed only the animal game, and made no mistakes. The game-relevant interactions steadily increased, indicating that the CRR had evolved toward attracting participants' interests in the learning activity.

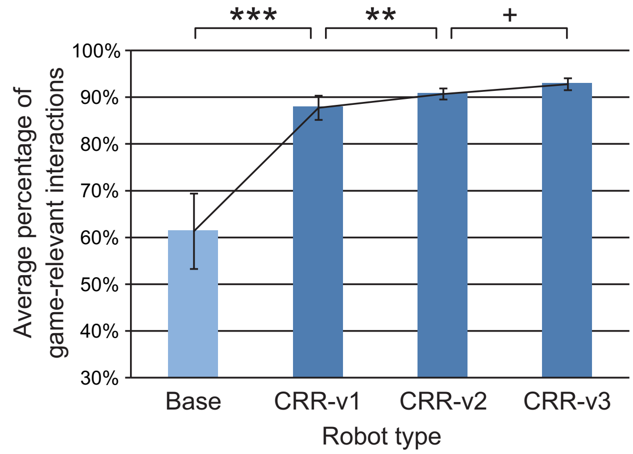

Fig. 9. Average percentages of game-relevant interactions for the four robot types. Bars indicate the attraction of the participants to the learning activity in each trial. The percentages steadily increase as the robot evolves. ($***: p < 0.001$, $**: p < 0.01$, $+: p = 0.05$)

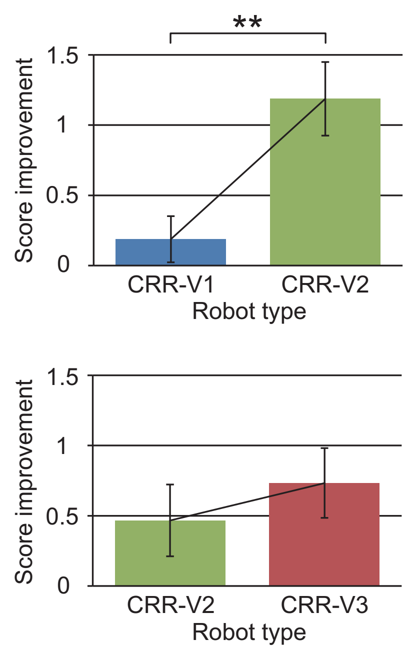

Fig. 10. Average score improvement of the participants in post-tests. ($**: p < 0.01$)

As shown in Fig. 10, the participants' learning was accelerated by the newer version of the CRR. The graphs plot the improvement in the average score, calculated from the results of the pre/post-tests. The data were collected during the second day of the four-day sessions, and were specific to a given robot type (other data were excluded).

D. Effectiveness of the New Behaviors

As described in Section IV-A, we aimed to discover more behaviors than expressed in the original CRR implementation [14]. The seven new behaviors were listed in Sections V-A and V-B. In this section, we investigate the participants'

Fig. 8. Children were intrigued by backward-walking behavior of the robot, even those who were initially playing with the other robot.

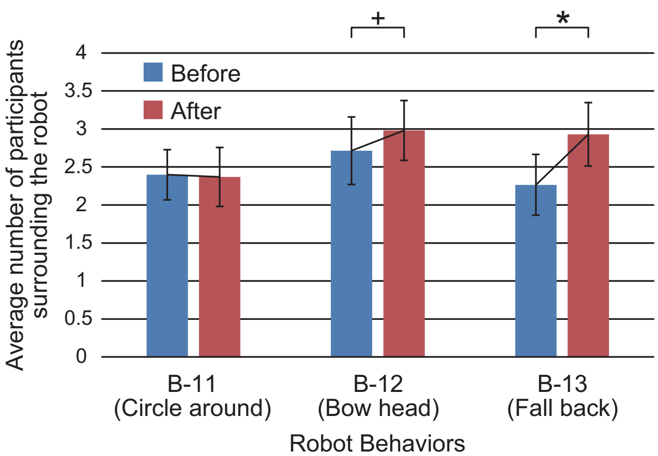

Fig. 11. Average number of participants surrounding the robot before and after (10 s window) executing each behavior. ($*: p < 0.05$, $+: p = 0.06$)

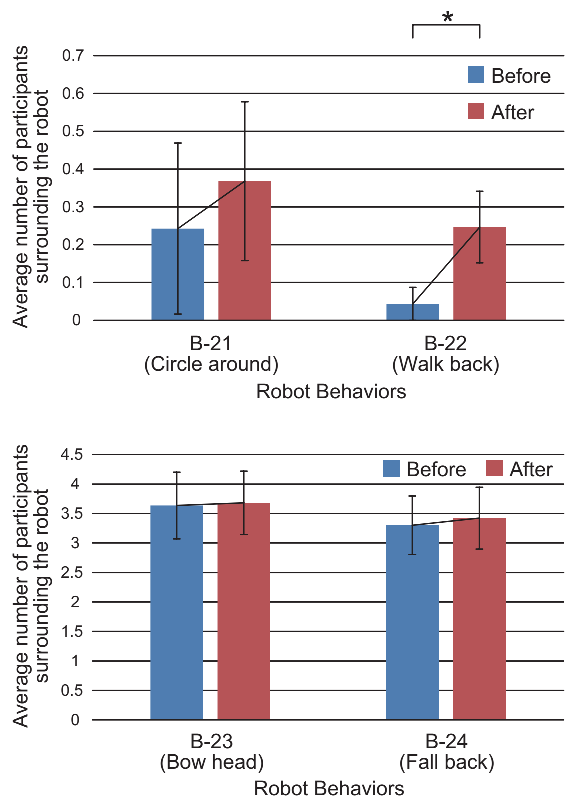

Fig. 12. Average number of participants surrounding the robot before and after (10 s window) executing each behavior. ($*: p < 0.05$)

reactions toward each behavior.

To this end, we observed the number of participants surrounding the robot. We asked coders to extract this information from the videos (inter-observer reliability: 0.96). If a child was within touching distance of the robot, the child was counted as surrounding the robot. We next investigated the change in the number of surrounding participants before and after each behavior was executed. The results are presented in Figs. 11 and 12.

Fig. 11 shows the results from Step 1, in which three new behaviors (B-11, B-12, and B-13; Section V-A) were tested in CRR-v2. Behavior B-13 (sitting down and falling backward) triggered the largest increase in participant attraction.

Fig. 12 shows the results from Step 2, which introduced four new behaviors (B-21, B-22, B-23, and B-24; Section V-B) into CRR-v3. Two graphs are presented, because B-21 and B-22 were executed if there was nobody in front of the robot, whereas B-23 and B-24 were executed if somebody was in front of the robot. This distance factor causes the large difference between the two vertical scales. Behaviors B-23 and B-24 elicit insignificant effect, probably because of a ceiling effect, i.e., the initial values (blue bars) were already large (exceeding 3.0 or 3.5, indicating that more than three children surrounded the robot before it executed the behavior), leaving little room for further improvement. On the other hand, behavior B-22 (walking 45 cm backward) exerted a clear positive effect. The impact of behavior B-21 is obscured by the large deviation.

VI. Discussion

The results demonstrated the feasibility of the proposed self-competitive method. The developed CRRs steadily improved their performances (Fig. 9) through their newly acquired behavioral elements. The performance of each found behavior was evaluated by observing the number of participants surrounding the robot (Figs. 10–12). Apart from the ceiling effect, the behaviors overall increased the number of participants surrounding the robot, indicating that they effectively engaged the children's interest. Some of these behavioral elements were difficult to anticipate before conducting the field trial. As reported in Section V-

B, the operator discovered improvements and gained ideas by comparing the two concurrent robots in real time. The autonomous robot functioned as a reference for the operator who remotely controlled the other robot to outperform the autonomous (reference) robot. Meanwhile, the autonomous robot served as a "previous-self" of the operator and its performance was checked.

Our experience highlighted the importance of a logging interface for the operator. The operator would require a device for recording ideas easily and quickly while remotely controlling the robot. Although no recording device was set up during the current trials, future trials could include a camcorder set up behind the operator. The camcorder would capture the spoken thoughts of the operator as well as videos of the interactions.

This method may be inapplicable to robot development involving verbal communication tasks, because simultaneous utterances from two robots would probably annoy the participants.

In this study, the components of the animal gesture game were fixed; i.e., the game was unchanged throughout the trials. Because some of the results exhibited a ceiling effect, we should improve the game components along with the robot behaviors in further continuations of the trials. We predict that if the game was changed or rendered more difficult, the results would further improve.

It should be noted that the field trials were not a well-controlled experiment. Because we simultaneously introduced two different robots, we could not strictly separate the factors and effects. It was possible that some interaction effects between them existed, although they were not apparent in our observations.

Also important is the large dependence of this method on the operator's decision. The operator chooses the explorations and new behaviors. The decision could be wrong, and in that case the operator would recognize it during the next step, where the selected behavior is implemented in the autonomous robot, and corrected thereafter. Although this method accelerates the developmental process, there is no ground truth for an external assessment. Instead, the method can only be assessed internally by confirming the progressive increase in the robot's performance, as shown in Fig. 9. Thus, we can confirm only the feasibility of the method.

VII. Conclusions

Rapid development of robots that interact with humans in the real world is highly demanded. To this end, we proposed a self-competitive methodology, and tested it on the development of an educational robot for children. As seven new behavioral elements were introduced in the field trials, the performance of the care-receiving robot steadily increased, confirming the feasibility of the proposed methodology.

Applying this methodology to wider cases would provide more specific and useful protocols for developers. As discussed in Section VI, the current methodology largely depends on the operator's decision. Wider applications would accumulate a body of knowledge on use of the methodology (for example, effective ways of exploring behaviors).

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