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LONG PAPER

B. Robins · K. Dautenhahn · R. Te Boekhorst
A. Billard

Robotic assistants in therapy and education of children with autism: can a small humanoid robot help encourage social interaction skills?

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Abstract This article presents a longitudinal study with four children with autism, who were exposed to a humanoid robot over a period of several months. The longitudinal approach allowed the children time to explore the space of robot–human, as well as human–human interaction. Based on the video material documenting the interactions, a quantitative and qualitative analysis was conducted. The quantitative analysis showed an increase in duration of pre-defined behaviours towards the later trials. A qualitative analysis of the video data, observing the children's activities in their interactional context, revealed further aspects of social interaction skills (imitation, turn-taking and role-switch) and communicative competence that the children showed. The results clearly demonstrate the need for, and benefits of, long-term studies in order to reveal the full potential of robots in the therapy and education of children with autism.

Keywords Autism therapy · Longitudinal study · Robotic assistant · Imitation · Social interaction

1 Introduction

The work described in this article is part of the Aurora project [2], which investigates the potential use of robots as therapeutic or educational 'toys' specifically by children with autism [36]. This approach is based on the findings revealing that people with autism enjoy and benefit from interactions with computerized systems (see below). This article presents a longitudinal study with four children with autism, who were repeatedly exposed to a humanoid robot over a period of several months, using basic imitative and turn-taking games. The aim was to encourage imitation and social interaction skills. Different behavioural criteria (including eye gaze, touch, near and imitation) were evaluated based on the video data of the interactions. The results clearly demonstrate the crucial need for long-term studies in order to reveal the full potential of robots in therapy and education of children with autism.

1.1 Autism

Autism, here, refers to the term autistic spectrum disorders, with a range of manifestations that can occur to different degrees and in a variety of forms [21]. The exact cause or causes of autism are still unknown. Autism is a lifelong developmental disability that affects the way a person communicates and relates to people around them. People with autism often have accompanying learning disabilities [1]. The main impairments that are characteristic of people with autism, according to the National Autistic Society [30], are impaired social interaction, social communication and imagination (referred to by many authors as the triad of impairments, e.g. [52]):

1. Impairments in social interaction—this refers to an inability to relate to others in meaningful ways. It comprises a difficulty in forming social relationships and an impairment in understanding others' intentions, feelings and mental states. For a person with autism, it is perfectly reasonable to answer a friend's question "How do you like the colour of my new car?" with, e.g. "I think the colour is awful".

B. Robins (✉) · K. Dautenhahn · R. T. Boekhorst
Adaptive Systems Research Group,
School of Computer Science, The University of Hertfordshire,
College Lane, Hatfield, Hertfordshire, AL10 9AB, UK
E-mail: b.robins@herts.ac.uk
Tel.: +44-1707-281150
Fax: +44-1707-284185

A. Billard
EPFL, Lausanne, Switzerland

[1]For detailed diagnostic criteria, the reader is referred to DSM-IV, the Diagnostic and Statistical Manual of Mental Disorders, American Psychiatric Association, (1995).

2. Impairments in social communication, including verbal and non-verbal communication. This manifests itself, e.g. in difficulties in understanding gesture and facial expressions, and a difficulty in understanding metaphors or other 'non-literal' interpretations of verbal and non-verbal language (for example, for a person with autism the most reasonable answer to the question "Do you know where I can find the train station?" is likely to be either "Yes, I do." or "No, I do not", illustrating an inability to interpret what people say or do with respect to the person's intentional, motivational and emotional states.
3. Impairments in imagination and fantasy—the development of play and imagination activities is limited. For example, children with autism do not get engaged in role-play or pretend play (e.g. pretending to be a princess, a knight or football star) as intensely as typically developing children.

Moreover, people with autism show little reciprocal use of eye contact and rarely get engaged in interactive games. Generally, autism affects more males than females [30]. The above mentioned impairments can lead to a substantially decreased probability of being able to lead an independent life. Even high-functioning people with autism might encounter great difficulties in learning the everyday 'social rules' that guide our lives, including an understanding of humour, white lies, and deception (see examples of 'mind-reading errors' given in [19] and first-person accounts of Temple Grandin, e.g. in [15]).

1.2 Imitation and the case of autism

Imitation plays an important part in social learning both in children and adults. From birth, imitation plays a critical role in the development of social cognition and communication skills, helping an infant in forging links with other people [29]. Imitation and turn-taking games are used in therapy to promote better body awareness and sense of self, creativity, leadership and the taking of initiative both in children and adults (as used in Dance Therapy by [22], [23], [33]). There are currently contradictory findings concerning imitative deficits in autism. Some researchers suggest autism-specific impairments in imitation ([40, 25]) while others show that autistic children are able to engage in immediate imitation of familiar actions [16].

Nadel explored the use of imitation as a communicative means in infant with autism [29] and found significant correlation between imitation and positive social behaviour. Her findings indicate that imitation is a good predictor of social capacities in children with autism. In addition, it was also found that autistic children improve their social responsiveness, when they are being imitated ([11, 46, 29]). In therapy too, imitation, reflection and synchronous movement work has been used with autistic children to develop social interactions ([5, 1]).

1.3 Computers and robot technology in autism therapy and education

Research suggests that people with autism generally feel comfortable in predictable environments, and more specifically, enjoy interacting with computers (e.g. [4, 34, 27]). One possible explanation has been put forward by Murray [28], who noted that the attention of people with autism tends to be fixed on isolated objects apart from the surrounding area. According to Murray, computers can break into this world by focusing the individual's *attention tunnel* on the screen, so that external events can be ignored more easily. She argues that computers in the education and therapy of people with autism can be beneficial for the development of self-awareness and self-esteem. Moreover, they motivate an individual to speak, read or share achievements with other people, which can greatly facilitate communication. Hershkowitz strongly argued for the use of computer-based learning in therapy and education as an effective aid in teaching language and academic skills to children with autism ([17, 18]).

In recent years, interactive learning environments (software or robotic based) have been studied increasingly in the therapy or education of people with autism, cf. review in [9]. Software-based systems include highly structured virtual environments (e.g. [43, 44,32]) to be used by therapists and teachers as tools in order to teach social and other life skills (e.g. recognizing emotions, crossing the road, learning where and how to sit down in a populated cafeteria).

Since the early 1980s, the usage of robots in education has become popular (e.g. [31], for more recent work compare e.g. [12]). The application of autonomous robots in therapy and education of children with autism has been studied only more recently (e.g. [6, 8,51, 50, 26, 47]), although early work with a remote-controlled robot suggested positive effects on a 7-year-old boy with autism [48]. Michaud and Théberge-Turmel investigated whether various robotic designs with different interactive capabilities could engage children with autism in playful interactions. The designs included, e.g. an elephant, a spherical robotic 'ball', and a robot with arms and a tail. The work was carried out as an engineering project, focusing on the development of the robots. Results of the playful interactions are described as narratives, and little is known about any specific benefits or even the history of the children. Similarly, Wada et al. [47] developed a pet robot called 'Paro', trying to mimic the appearance and some of the behaviours of a baby seal. Paro has been proposed as a tool for robot assisted activity that could benefit elderly people, hospitalized children, as well as children with autism. However, in this work, too, very little has been documented about the particular history of the children and the specific nature of therapeutic effects that can be linked to the robot.

Different to using computer software or virtual environments, interactions with an interactive physical robot contribute important real-time, multi-modal, and *embodied* aspects, which are characteristic of face-to-face social interaction among humans, cf. Dautenhahn and Werry's discussion of advantages and disadvantages of using different types of computer technology in education and therapy of children with autism [9]. Ultimately, various types of virtual or robotic interactive systems are likely to fulfill different roles and niches in the spectrum of possible applications for children with autism that can potentially enhance their quality of life and contribute to their social integration. This is an important step towards enabling them to share the benefits of human culture and society, as well as empowering the skills necessary for living independently.

1.4 Robots in the aurora project

People behave in a manner that is not easy to interpret, unless you share a common understanding of how goals, motivations, intentions and emotions impact people's behaviour, let alone a great amount of social and cultural norms and conventions to be considered. Without such mind-reading skills you might feel like an 'anthropologist on Mars' (a phrase coined by Temple Grandin, a Professor of animal science and a person with autism, when describing the situation of dealing with other people, cf. [15]). Human–human interaction is multi-modal, involving not only verbal language, but a rich body language, gestures etc., many of these expressed in a subtle and unconscious manner. Human evolution and development has tuned our perceptual and cognitive system to perceiving a multitude of social cues. Different from how we deal with physical objects, we develop into skilled mindreaders during our first 4 years of childhood, learning to predict and interpret human behaviours in terms of mental states. Deficits in mind-reading skills, as they have been shown in people with autism, make people's social behaviour, from the perspective of a person with autism, widely unpredictable. Different from human beings, interactions with robots can provide a simplified, safe, predictable and reliable environment where the complexity of interaction can be controlled and gradually increased. Similarly, psychological studies have shown that children with autism prefer simple toy designs and predictable environments (e.g. [14]) that can provide starting points for therapeutic intervention where the complexity of the therapeutic toys can be slowly increased.

The work reported in this paper is part of the Aurora project [2]. A core aim of the performed studies is to investigate if and how simple imitation and turn-taking games with a robot can encourage social interaction skills in children with autism. Specifically, the robot's role is considered as an object of shared attention, encouraging interaction with peers (other children with or without autism) and adults. Humanoid as well as non-humanoid robots have been used in previous studies ([6, 7, 8, 36, 41, 49, 50, 51]). Quantitative and qualitative techniques for evaluating interactions of single children with autism with a mobile robot were presented, e.g. in [10], [49], [50]. Also, a comparative study was carried out in order to compare the impact of the robot with a non-robotic toy. The statistical analysis of behavioural observations revealed that children with autism directed significantly more eye gaze and attention towards the robot, supporting the hypothesis that the robot represents a salient object suitable for encouraging interaction. In a later study, with pairs of children with autism [51], Werry et al. illustrated the robot's ability to provide a focus of attention, and shared attention (see Fig. 1, right photo). The robot's role as a *mediator* became clearly apparent in how the children interacted with other people present in the same room, including child–

Fig. 1 Robots as social mediators in the Aurora Project's trials. Right: a pair of children with autism both attracted by the mobile robot [51]. Here, three pairs were studied in total. The children were paired by the teacher's according to their level of social skills. These two boys were the least social. Nevertheless, the robot provided a salient object that lead to competition for access to the robot. Thus, the children, driven by their strong interest in the robot, were required to acknowledge each other and coordinate their behaviour. To our knowledge this was the first study aimed at investigating the potential use of robots as social mediators. *Middle and left*: scenes from the trials discussed in this paper, showing child–child as well as child–carer interaction in situations where the robot's movements provided salient stimuli and a focus of attention

teacher, child–investigator and child–child interactions. The robot's role of a mediator emphasizes that the primary aim is not to replace, but to *facilitate human contact*. Recent work by Robins et al. [39] showed how a small humanoid robot can provide an enjoyable focus of (joint) attention that can reveal communicative and social competencies of children with autism, cf. Fig. 1 (middle and left photos). Here, the robot served as a salient object mediating joint attention between the children and an adult. Furthermore, this work highlighted the fact that the skilful interaction on the part of the children occurred not just in the presence of the robot, but was specifically concerned with features of the robot's behaviour (the autonomous and predictable pattern of moving head and limbs).

In other work carried out as part of the Aurora project, the need for robots to recognize different interaction styles and to adapt to individual behaviour of children has been identified, cf. preliminary work with typically developing children reported in [41].

A precursor of the work presented in this paper is the study conducted by Dautenhahn and Billard [7], who reported a first set of trials with 14 children with autism interacting with a humanoid robotic doll called Robota. The central theme of these trials was imitation games between the robot and the children. A computational vision system analysed gross arm movements of the children that in turn could trigger the robot to imitate the child. Also, Robota performed movements on its own in order to encourage the children to mirror the robot's movements. It was thus hoped to initiate imitative interaction games between Robota and the children. However, the results were inconclusive, and a number of drawbacks in the original setup can be identified. First, the set up required the children to sit still at a table, facing the robot, and to move their arms in a very distinct manner, due to limitations of state of the art vision systems that cannot identify subtle movements. Secondly, the children's participation in the interaction games substantially depended on explicit encouragement by a teacher, who sat next to them (see Fig. 2). Overall, the acquired experiences showed that the particular set up did not seem to facilitate the emergence of *spontaneous*, *proactive*, and *playful* interaction games. Lastly, in these previous trials each child was only exposed once to the robot, a situation where accidental parameters can potentially have a significant effect on the interactions observed. A small number of exposures to the robot is also not likely to give any indications with regards to any therapeutic or educational effects.

Based on the initial set of trials, for the purpose of the present study it was therefore decided: (a) to use a much more unconstrained setup, posing only very few constraints on the children's behaviours and postures that are allowed during the interactions, (b) to pursue a longitudinal study and expose each child a number of times to the robot, and (c) to reduce the intervention of carers so as to focus on spontaneous and self-initiated behaviour of the children.

2 Research hypothesis

The primary aim of this study is to investigate to what extent repeated exposure to a humanoid robot, over a long period of time, has an impact on basic social interaction skills in children with autism. The underlying hypothesis is that repeated exposure to an interactive small humanoid robot will increase basic social interaction skills. Also, varieties of interactions that can be observed will be documented.

Fig. 2 Examples of trials from an early study with Robota [7]. In order for the robot to detect vertical arm movements performed by the children with autism a very restricted setup had to be used where the children needed to stay very close to the robot. The robot could only detect gross arm movements. It was observed that the children needed a lot of encouragement from the teacher. Teacher–child interactions were less playful and more instruction oriented. In order to provide a more naturalist setting for playful interactions we decided for future studies to use the robot remotely-controlled by the experimenter who had extensive experience in behaviour observation and could easily identify and respond to even subtle movements of the children who could be located anywhere in a large room

2.1 Longitudinal research

As mentioned above, the longitudinal repeated measure design reduces the influence of variables that could lead to ‘accidental outcomes’, because the same subjects are used. For example, it was noticed that unplanned changes in the schedule of activities prior to a trial, such as canceling the school’s assembly, can significantly affect the children’s behaviour because of the change to their routine. Also, in longitudinal studies, there are fewer cases of random variation to obscure the effects of the experimental conditions.

It is very common in therapy to design programs of intervention/treatment to take place over a period of a year or longer. For example, 50 or more sessions of Art Therapy are not unusual [13], and in Dance Movement therapy (e.g. [42, 1]) case studies show that it might take 6 months or more for the first breakthrough in the interaction between the therapist and an autistic child to occur.

Similarly, in education there is increasing use of the qualification and curriculum authority’s (QCA) P-scales assessment method [35] to assess pupils’ performance and to support monitoring of progression and target setting for pupils with learning difficulties. This is usually done once a year and although in many cases the pupils move up a level at the end of a year, often pupils show very slow progress in some developmental areas and stay at the same level for more than a year, simply covering more ground at that level.

A common approach in therapy involves the therapist gradually attuning to the client. This slow process reduces anxiety and distress levels and allows the gradual development of the therapeutic relationship. For these reasons, and because of the long-term projection that is used in education, the trials reported in this study were designed to take place over a longer period of time. On the one hand, this aimed at minimizing the anxiety and distress the autistic children might find themselves in, caused by a change of routine, being in a novel situation with a new and unusual toy (the robot), and a new person (the investigator). On the other hand, it was deemed important to allow enough time for the children to use any interaction skills they might already possess (e.g. eye contact, turn-taking, imitation), in a reassuring environment, where the predictability and repetitiveness of the robot’s behaviour is a comforting factor. Another requirement was to allow enough time and opportunity for the children to improve their social interaction skills by attempting imitation and turn-taking games with the robot while slowly increasing the unpredictability of the robot’s actions.

Additionally, monitoring of the children’s reaction to different appearances of the robot was necessary. In a previous study, where children with autism played with different non-robotic toys, it has been shown that the children approached social objects more readily if they were simple in appearance [14]. In investigating the effects of the robot’s design, a preliminary study with a life size ‘Theatrical robot’ (i.e. a person who was dressed and acted like a robot) was first conducted. Results of this study showed that the children responded notably more socially towards the life-size robot when it had a plain/robotic appearance when compared to an appearance with full human features (see Fig. 3, left). Based on these encouraging results, the children’s reactions to a small humanoid robot’s appearance were monitored. This involved two different appearances of the robot, namely a ‘pretty girl doll’ as opposed to plain clothing with a featureless head. Figure 3 (right) illustrates these trials. The results of the trials indicated that initially, the children showed preference for interaction with the robot with its plain robotic appearance over the ’pretty doll’ appearance, although over time during the longitudinal study, they became accustomed to both appearances of the robot (for completeness purposes, details of all robot appearances used in the trials can be found in Appendix 2, while a detailed comparison of

Fig. 3 Appearances of the Theatrical Robot (*left*) and of the Humanoid Robot (*right*), cf. Robins et al. [38],[37]. *Left*: pro-active behaviour towards a mime artist dressed up as a robot, followed by a photo showing the aversive or ‘alof’ reactions towards the same person in his normal clothing, a reaction typical of how children with autism react towards strangers. *Right*: the photos show pro-active behaviour towards the robotic doll with a plain dress, as opposed to the reactions towards the same robot in a ‘pretty girl dress’

these two experimental conditions with the 'theatrical robot' and with the humanoid robot can be found in separate publications, i.e. [38] and [37], respectively).

Overall, this approach has been designed to allow the children to have unconstrained interaction with the robot with a high degree-of-freedom and on their own terms (providing it is safe for the child and safe for the robot), as can be seen in Appendix 1. This approach has also been designed to build a foundation for further possible interactions with peers and adults using the robot as a mediator [51, 39].

3 The trials

The trials took place in Bentfield Primary school in Essex, UK, a mainstream school with approximately 220 typically developing pupils. The school also has an Enhanced Provision unit to cater for nine pupils with various learning difficulties and physical disabilities. These pupils, each accompanied by a carer, pursue their own unique curriculum and are integrated in the mainstream classes, according to their age group. They participate in any class activity that they are able to.

3.1 The setup

The trials were conducted in the light and sound room at the school. This is a familiar room for the children, as they often use it for various activities. The light and sound area, which is an extended part of the room, was closed off by a curtain leaving a large empty area of approximately 5.5×4.5 m, with a carpeted floor. The room had one door and several windows overlooking the school playgrounds.

The robot was connected to a laptop and placed on a table against the wall at one side of the room. Two stationary video cameras were placed in the room, one at the side to capture the area in front of the robot and the children when approaching the robot, and the other camera placed behind the robot in order to capture the facial expressions of the children as they interacted with the robot in close proximity. It was felt that having manned cameras (with yet more adult strangers in the room) would be too intrusive and would cause additional stress to the children. However, despite having two cameras in most of the trials, there were periods of time when the children moved outside the range of the cameras, as the nature of the trials gave them the freedom to move around in the large room.

3.2 The robot

The robot used in these trials is Robota—a 45-cm high, humanoid robotic doll (see Fig. 4). The main body of the doll contains the electronic boards (PIC16F870, 4 MHz and 16F84, 16 MHz) and the motors that drive the arms, legs and head giving 1 DOF (degree-of-freedom) to each. The robot also has the capability to be connected to various sensors such as infrared emitters/receivers, light detectors and more, which were not used in these trials. The arms, legs and head of the robot are plastic components of a commercially available doll. The robot can react to touch by detecting passive motion of its limbs and head (i.e. when the user is moving the robot's limbs or head from one position to another, during the interaction) For a more detailed description of Robota see [7].

Robota is connected through a serial link to a PC and can use speech synthesis, speech processing and video processing of data from a quick-cam camera. Using its motion tracking system, Robota can copy upward movements of the user's arms, and sideways movements of the user's head when the user sits very still and close to the robot, looking straight at it, engaging in turn-

Fig. 4 The robot in its two different appearances (the centre figure shows the 'undressed' version revealing the robotic parts that control its movement)

taking and imitation games with the robot. Machine learning algorithms allow Robota to be taught a sequence of actions, as well as a vocabulary.

Robota had originally been developed as a robotic toy that supports a rich spectrum of multi-modal interactions with typically developing children, involving speech, music and movements. However, many behavioural qualities that are required in situations of social interaction are less natural to children with autism. Such qualities would include being still, having a long enough focus of attention, and maintaining gaze on other's face. These are advanced tasks for children with autism to perform as it lies directly in one of the main areas of their impairment—communication and social interaction. Therefore, in the current trials, Robota's features of speech processing, motion tracking, and learning were not used. As explained above, the trials are designed to be unconstrained, with minimal structure, to allow the children to have the greatest DOF. Possibly other features of Robota could be used in future experiments where more structure and complexity will be gradually introduced, allowing the children time to build their confidence and increase their social interaction skills according to their abilities.

In the current set of trials, the robot has been programmed to operate in two basic modes:

1. As a 'dancing toy' moving its arms, legs and head to the beat of pre-recorded music. Three types of music were used, namely children's rhymes, pop music and classical music, following the teacher's advice as to the children's liking.
2. As a puppet, whereby the investigator is the puppeteer and moves the robot's arms, legs or head by a simple press of buttons on his laptop. This approach is related to the Wizard-of-Oz technique used in human–computer interaction (HCI) and more recently in human–robot interaction (HRI) research, e.g. [24], [20].

3.3 The children

Four autistic children age 5–10 from the Enhanced Provision unit at Bentfield primary school were selected by their teacher to participate in the trials. Each child participated in as many trials as was possible during that period, with an average of nine trials each. The children are:

EM—age 5, in the reception class. EM uses only two or three words but is beginning to communicate using the picture exchange communication system (PECS).

BB—age 6, in year one. BB has some limited verbal expression, which he uses to express some needs, likes and dislikes. He understands simple directions associated with routines.

BS—age 10, in year 5. BS has autism combined with severe learning difficulties. He has no verbal language and uses symbols and signs to make choices and to express basic needs. He will generally attempt whatever task he is presented with unless he is feeling unwell when his behaviour deteriorates. In this situation, BS is restless, moving from one activity to another and may refuse to perform any task if asked, protesting with loud vocal noise.

TM—age 10, in year 5. He has verbal language, which he may use to express needs but often elects not to do so. He can be very difficult to motivate and it is sometimes very difficult to channel his attention towards a particular task.

Once a year the school assesses the pupils' performance using the QCA's P-scale method. It is important to view the children's behaviours during the trials in the context of their personal development level, which was assessed by their teacher 6 months prior to the trials.

According to the assessment of their personal and social development level, in the subject of attention, EM and BB have been assessed at a level where they pay rigid attention to their own choice of activity, and are highly distractible in activities or tasks led by others. BS and TM have been assessed at a level where they can attend to an adult directed activity but require one-to-one support to maintain their attention. In the area of interacting and working with others, EM was assessed at a level where he engages in solitary play or work and shows little interest in the activities of those around him. BB, BS and TM were assessed at a level where they might take part in work or play with one other person and take turns in simple activities with adult support.

3.4 Trial procedures

Before each trial, the robot was placed on a table ready to start with a click of a button from the laptop. The investigator was sitting next to this table operating the laptop when necessary. The cameras, operated by a remote control, were set to 'standby' mode ready to record.

The children were brought to the room by their carer, one at a time. Each trial lasted as long as the child was comfortable with staying in the room. The trials stopped when the child indicated that he wanted to leave the room or if he became bored after spending 3 min already in the room. The average duration of trials was approximately 3 min. A few of the trials lasted up to 5 min, a few others were just under 3 min, and two ended very shortly after they started when the children left the room after 40 s and 60 s.

The trials were designed to progressively move from very simple exposure to the robot to more complex opportunities for interaction. There were three phases to this:

Setup A—During the first three trials, the robot was placed inside a large open box painted black inside, similar to a puppet-show setting (see Fig. 5 left). At this stage in the trials the robot was operating in its 'dancing' mode, moving its limbs and head to the rhythm of pre-recorded music. This was simply intended to attract the

Fig. 5 The three phases of the trials: setup A—left, setup B —middle, setup C—right

children's attention to the robot. The children mostly watched while sitting on the floor or on a chair, but occasionally left the chair to interact with the robot more closely (watching closely, touching etc).

This section of the trials was designed mainly for the children to familiarize themselves with the robot (a new toy) and so the carer gave no instructions or tasks for the children to do, simply minimal verbal encouragement if and when this was needed (e.g. 'look, there, what is it?' etc). The children were left to do what they chose to do. The carer and the investigator were generally only observing, intervening only if the child was about to harm the robot (i.e. pushing or pulling the robot's limb using excessive force). The investigator did not initiate communication or interaction with the child, but did respond when addressed by the child.

Setup B—In later trials, the box was removed, the robot was placed openly on the table and the children were actively encouraged to interact with the robot. In this stage, the carer introduced physical encouragement, standing with the child near the robot and moving the child's limbs to show him how the robot could imitate his movement (see Fig. 5 centre). The children could then continue the interaction with the robot on their own. In this situation, the robot was operating in its 'puppet mode', where the investigator as puppeteer caused the robot to accurately respond to the child's arm, leg and head movements (even when the child was not facing the robot directly or was not in close proximity to the robot). Note that the investigator's control of the robot was hidden from the children.

Setup C—In the last couple of trials, whenever possible, the children were not given any instructions or encouragement to interact with the robot, and were left to interact and play imitation games on their own initiative if they chose to do so. On these occasions, the robot was again operated as a puppet by the investigator. The investigator was able to recognize even subtle expressions of the child and to quickly respond to the child's movements, and also to introduce further complexity of turn-taking and role-switch into the simple imitation game.

4 Interaction profile analysis

Four elementary behaviour criteria were defined in our trials that were evaluated throughout the period of trials, based on the video footage. These behaviours were:

1. Eye gaze (when directed at the robot).
2. Touch (when the child touched any part of the robot).
3. Imitation (this included direct imitation of the robot's movements, delayed imitation and response to the robot's movement, and attempted imitation of the robot's movement).
4. Near (this included the child approaching the robot and staying in close proximity to the robot regardless of the child's other behaviours). Quantitative and qualitative analysis of the data creates an interaction profile [2] for each of the children who participated in the trials.

4.1 Quantitative analysis

The video data from each and every trial for a given child was segmented into 1-s intervals. The trials were coded by scoring the above defined elementary behaviours every second of the trial, cf. [45, 10]. The scores for each trial were then summed up and yielded the total number of occurrences of each behaviour during a specific trial and the total duration of the child's engagement in each behaviour during that trial. The trials varied in duration, therefore the duration of a behaviours was standardized by expressing it as a proportion of the trial duration.

To verify the reliability of the coding of the children's various behaviours and to ensure interrater reliability, a subset (10%) of the trials' video data for each of the

[2] We would like to thank an anonymous reviewer for suggesting the term interaction profile analysis.

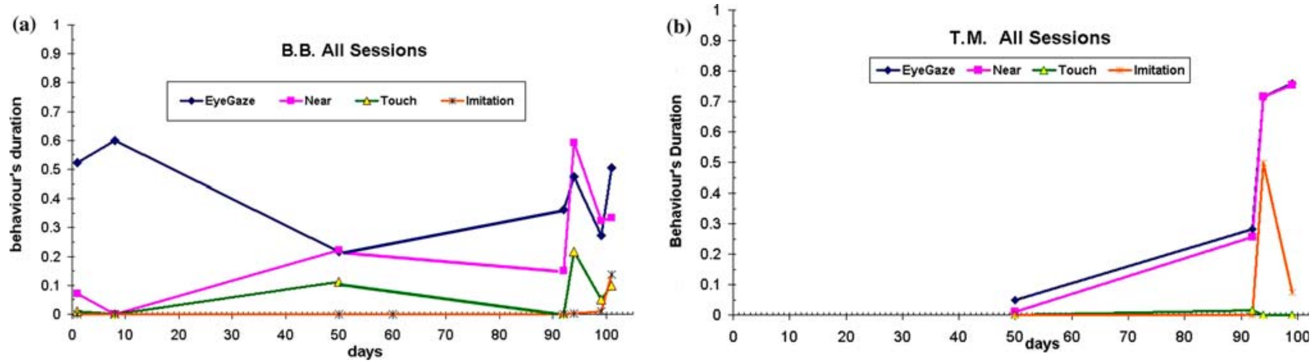


Fig. 6 Scores for the four behavioural elements of the subjects B.B (*left*) and T.M (*right*)

children, randomly selected, was coded independently by a second researcher. The average percentage of *agreement* between the two observers for the pre-defined elementary behaviours of the children was 96. This level of percentage of agreement between observers is commonly thought to be 'good'. In order to check the *reliability* of scoring Cohen's kappa coefficient was used. A value of 0.60 or higher is generally considered sufficient to indicate that chance alone is not accounting for the agreement. Some researchers, as described in [3], are going further and characterize kappas of 0.40–0.60 as fair, 0.60–0.75 as good, and over 0.75 as excellent. The kappa scores obtained in the test of the subset of trials for the four children were on average 0.79 (0.74 for BB, 0.78 for BS, 0.83 for TM, and 0.84 for EM).

4.1.1 Results and discussion

The data analysis produced various graphs showing changes in the children's behaviour (during child–robot interaction) over a period of time. For each child, the trend of each of their behavioural criteria was followed from day 1, when the first trial took place, to day 101 when the last trial was conducted.

The graphs in Figs. 6 and 7 show the changes in behaviour for each of the children during the period of the longitudinal study. Figure 6 (left) shows that the values for the behaviours of touch, imitation and near all increase considerably towards the later trials, i.e. from day 92 onward. For eye gaze, the highest scores occur during the first two trials on day 1 and day 8. This could be attributed to the novelty of the situation and to the fact that the carer decided to offer the child a chair to sit in front of the robot to watch this new toy. Naturally, a high score for eye gaze can be expected in this situation. However, if these first two trials are disregarded, it can be noticed that the trend for eye gaze, too, increases from the third trial onwards, resulting in a relatively high score on the last trial on day 101.

Figure 6 (right), which shows the behaviour of TM during the trials, demonstrates a considerable increase of the scores for near, eye gaze and imitation toward days 92 and 94. Touch, although with a very low score, also occurred only on day 92.

When interpreting the graphs, it is important to remember that autism, being a spectrum disorder, can occur to a different degree and in a variety of forms. Furthermore, the children that took part in the trials are of different ages and different levels of development.

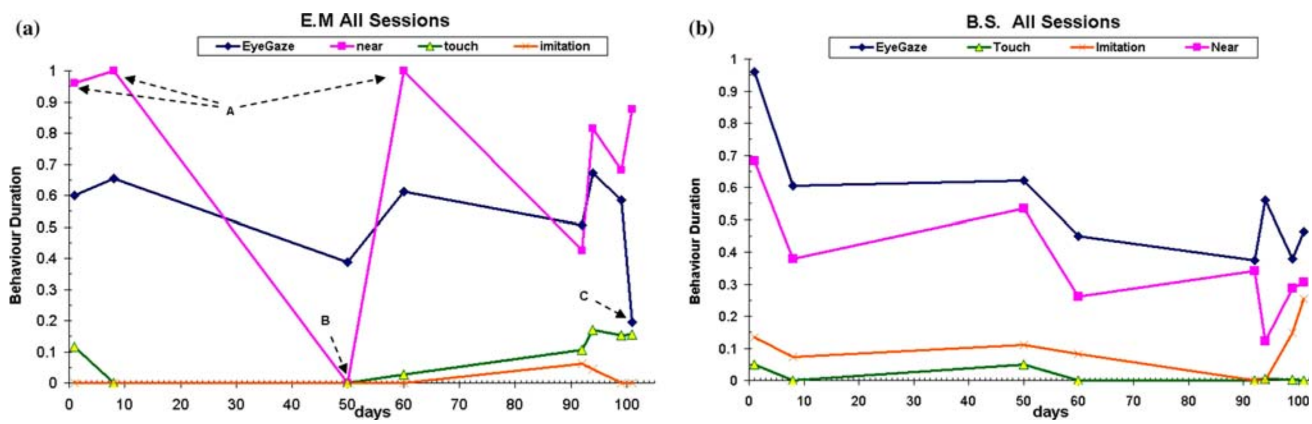


Fig. 7 Scores for the four behavioural criteria during all the trials that E.M. (*left*) and B.S. (*right*) participated in

Therefore, these graphs can provide only a very general view of what it might be possible to achieve with some children with autism. As stated earlier, it is important to view the children's behaviour during the trials in the context of the assessment of their personal and social development level which brought other influences to the trials, such as having a chair to sit on in early trials, or a constant encouragement the child needed to receive from his carer in order to remain focused.

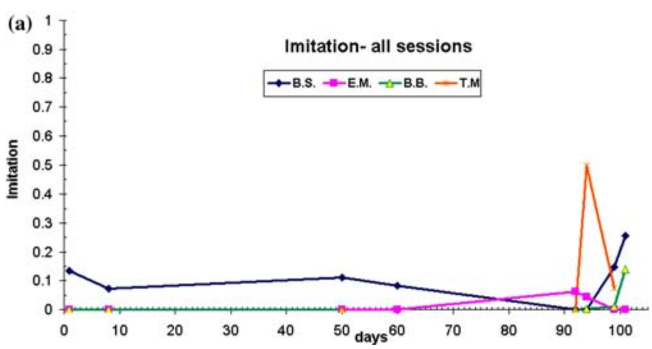
Figure 7 (left) shows the behaviour of EM during the trials. EM, being only 5 years old, is highly distractible in activities or tasks led by others (see assessment above) and during the familiarization phase of the trials he needed constant encouragement from his carer to remain focused. Point A in the graph above refers to trials 1, 2, and 4, where the carer placed a chair next to the robot for EM to sit on and watch the robot, hence the very high score in the *Near* criterium. During the third trial (point D- day 50), EM was sitting on the carer's lap throughout the trial and as the carer herself was sitting some distance away from the robot, the score for EM for *Near* equals zero. Point C marks a considerable drop in eye gaze towards the robot. However, it highlights again the need to view the results in the context of what actually happened in the trial itself. In this trial, once the long period of familiarization was passed, EM surprised the carer and experimenters involved: he initiated a long interaction with the investigator, using the robot as an object of shared attention. EM showed at this point unexpected communicative skills (described in a separate publication [39]) and the entire episode with this particular child provided very positive indications as to the possible role of the robot as a mediator in interactions between autistic children and other people.

As the children differed in their personal development levels, for some the main interactions with the robot were by means of eye gaze or touch only. Developmentally, according to their teacher, it was too early for the younger children EM and BB to comprehend imitation. For others, imitation was an achievable goal after the period of familiarization and learning (this applies to BS and TM—the older boys) while touch did not play a major part in their interaction with the robot. An example of this can be seen in Fig. 7 (right). BS touched the robot only rarely. He rather explored the new 'toy' in his own way, walking freely in the room, approaching and walking away from the robot frequently in each trial. In one trial, he even performed what seemed to be a 'dance', directed at the robot (see Fig. 10 and description below). However, his main achievement was that the longitudinal approach allowed him enough time to get familiar with the robot, to learn imitation games, and to engage with the robot *on his own initiative* (as can be seen in the graph for the behavioural criteria of *Imitation*).

The data also allowed monitoring each behavioural element separately, over the entire period of the trials, across all the children. The graphs in Fig. 8 show examples of the results. As it becomes clear from the discussion above, even when a larger sample size of children had been available, averaging behaviour scores across children is not appropriate in this study since our study focuses on the individual interaction histories of each child.

4.2 Qualitative analysis

As stated earlier, one of the overall questions that we are investigating within this project is whether exposure to and interaction with the robot can help to increase the autistic child's social interaction skills using imitation and turn-taking games for this purpose. During the analysis of the video recordings of this set of trials, several occasions were noticed in which the children also interacted with the adults in the room (i.e. their carer, or the investigator). Sometimes this occurred in relation to the robot, when the robot acted as a mediator or an object of shared attention, but at other times these interactions were not robot related. To understand the events that take place in such interactions requires attention to the autistic child's activities in their interaction context. The quantitative analysis alone, based on the frequency and duration of the basic behaviours,



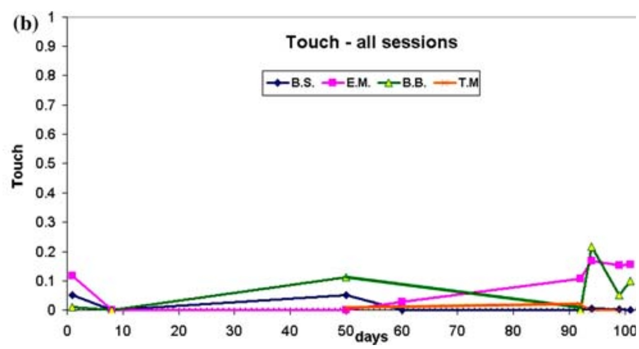


Fig. 8 *Figure on the left* shows the trend of Imitation scores as it appeared in all children throughout all the trials with a visible increase at the end of the trial period—from day 92 onwards. *The figure on the right* shows the scores for Touch that increase for some of the children in the last trials, days 92–101

Fig. 9 autistic children sharing with an adult their experience with the robot

cannot reveal some important aspects of social interaction skills (imitation, turn-taking and role-switch) and the communicative competence that the autistic children showed during the trials.

4.2.1 Results and discussion

A comprehensive qualitative analysis of some of those segments of the trials where the children showed such interaction skills and communicative competence is being discussed in a separate publication [39]. However, the following provides a description of a very short segment (duration of 32 s) taken from one child's trial on the second to last day, which reveals such interaction skills:

Action	Response
Robot raises left arm	Child mirrors and raises right arm
Robot raises left arm	Child mirrors and raises right arm
Robot raises left arm	Child mirrors and raises right arm
Robot raises right arm	Child mirrors and raises left arm
Robot raises right arm	Child mirrors and raises left arm
Pause (under 1 s)	
Child raises right arm	Robot mirrors and raises left arm
Robot raises left arm	Child starts to raise left arm, quickly drops it and raises right arm
Child raises left arm	Robot mirrors and raises right arm
Robot turns head to the right	Child mirrors and turns head to left
Robot turns head to the right	Child mirrors and turns head to left
Child shakes head up and down	Robot turns head to left
child pauses	
Robot raises right arm	Child starts to raise right arm, quickly drops it and raises left arm

It can be observed that during this segment the child showed the following social interaction skills: (a) straightforward imitation of various body parts' movements (lines 1–5, 9–11,14), (b) the child realized when he made a mistake in imitation and corrected himself (lines 8, 14), (c) the child initiated interaction as part of the imitation and turn-taking game without any pre-determined cue, thus causing a role-switch (lines 7, 9), and (d) the child tried to initiate interaction using a new movement, shaking the head up and down. The child indicated a comprehension that this movement is beyond the robot's capability and so moved on without insisting on that movement (line 13).

5 Conclusion

This paper presented a novel study of longitudinal research on the exposure of children with autism to a humanoid robot. Relatively little work has been done on using autonomous robots in autism therapy, cf. [10] for a comprehensive overview on related work. Usually, the same children are only exposed once or a few times to a robot. In contrast, the approach reported in this paper, based on repeated trials over a long period of time, allowed the children time to explore the interaction space of robot–human, as well as human–human interaction. Supporting evidence was obtained for the initial hypothesis, namely that repeated exposure to an interactive small humanoid robot will increase basic social interaction skills in children with autism.

In some cases, the children started to use the robot as a mediator, an object of shared attention, for their interaction with the teachers, carers and the investigator (cf. [51, 39, 36]). Furthermore, once they have become accustomed to the robot, in their own time and on their own initiative, they all opened themselves up to include the investigator in their world, interacting with him, and actively seeking to share their experience with him as well as with their carer. In Fig. 9, the photo on the right, taken from a trial conducted during the longitudinal study, is a still shot taken out of a sequence where, for the first time, the child acknowledged the presence of the investigator (in prior trials the child completely ignored him) and came and sat on the investigator's lap for few moments before standing up and moving towards the robot while holding the investigator's hand. It is important to note that the investigator did not initiate any part of this interaction. The photo on the left, from a trial that took place during an extension to the study, some months later, depicts a moment when the child (who has very limited verbal communication skills) turned his head toward his carer and said: " toy fun...-fun...fun".

Fig. 10 B.S responding to the robot's movement with a 'dance' of his own

We believe that this sharing of experiences is an important aspect of the work, since human contact gives significance and (emotional, intersubjective) meaning to the experiences with the robot.

Fig. 11 B.S says 'goodbye' to the robot

The approach of repeated exposure of the children to the robot over a long period, in a stress free environment, with a high degree of freedom, allowed the children, as hoped, to have unconstrained interactions, which facilitated the emergence of spontaneous, proactive, and playful interactions. Figure 10 below depicts how BS, during the last trial of the original longitudinal study, was encouraged to respond to the robot's movements with what looks like a dance of his own ("he is dancing to the robot" said the carer). At the end of that session, when it was time to leave the room, BS (who has no language skills at all) surprised his carer by turning and walking towards the robot making his own unique 'goodbye' sign with his hand (see Fig. 11). The carer made a point that this was a significant act and should be noted in his monitoring book.

It is not clear yet whether any of the social and communicative skills that the children exhibit during interaction with the robot would have any lasting effect and whether they could be generalized and used in the children's day to day life outside the trials scenario. More longitudinal studies are required, together with continued monitoring of the children in their classroom and home

Fig. 12 Six month later, B.S respond to the robot's movement with a dance similar to the dance performed previously. It is difficult to interpret this single observation. One might speculate whether B.S. remembers the earlier interactions with the robot, and whether his very particular 'dance' could represent a means of attempted (non-verbal) communication with the robot

environments. However, it is interesting to note that when this study was extended 6 months later, to continue the investigation on the effect of the robot's appearance, BS responded in one of the trials with a similar dance towards the robot (see Fig. 12), a behaviour that, according to his carer, he generally does not exhibit.

Future work will continue the development of new interaction games with Robota as well as with other robots, including a mobile robot (cf. Fig. 13). The role of the robots as social mediators encouraging the interaction of autistic children with other humans (e.g. peers and adults) will be further investigated. Encouraging social interaction skills in children with autism is a challenging aim addressing deep issues into the nature of social interaction, social relationships and the 'meaning' of human–human contact. Studying robotic assistants in this domain introduces an additional level of complexity. However, in the authors' view, the potential benefits could justify these efforts. For example, a robotic assistant could at least partially relieve carers or parents of intensive one-to-one sessions with a child with autism. It would allow the adults to take a perspective where they can decide to observe and monitor the children's play behaviour and possible progress. Also, in the role of a mediator, the robot might facilitate adults' participation in the otherwise often solitary play of children with autism. Last but not least, specific therapeutic goals could be systematically addressed with a programmable robotic assistant, e.g. imitation or joint attention. Robots to be used for such purposes would need to be very robust and easily re-programmable by parents and teachers without extensive computer science or robotics training, and would have to be affordable. Taking it one step at a time, current research focuses on providing evidence for a positive role of robots in therapy and education of children with autism.

Fig. 13 A child with autism playing with a mobile robot used in the Aurora project. Different from interactions with Robota, small mobile robots encourage unconstraint full body interactions, movements in space, and touch

Fig. 14 E.M

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6 Appendix 1

Varieties of interaction: The four children that participated in the trials showing unconstrained interactions with a small humanoid robot (Figs. 14, 15, 16, 17).

Fig. 15 B.B

Fig. 16 B.S

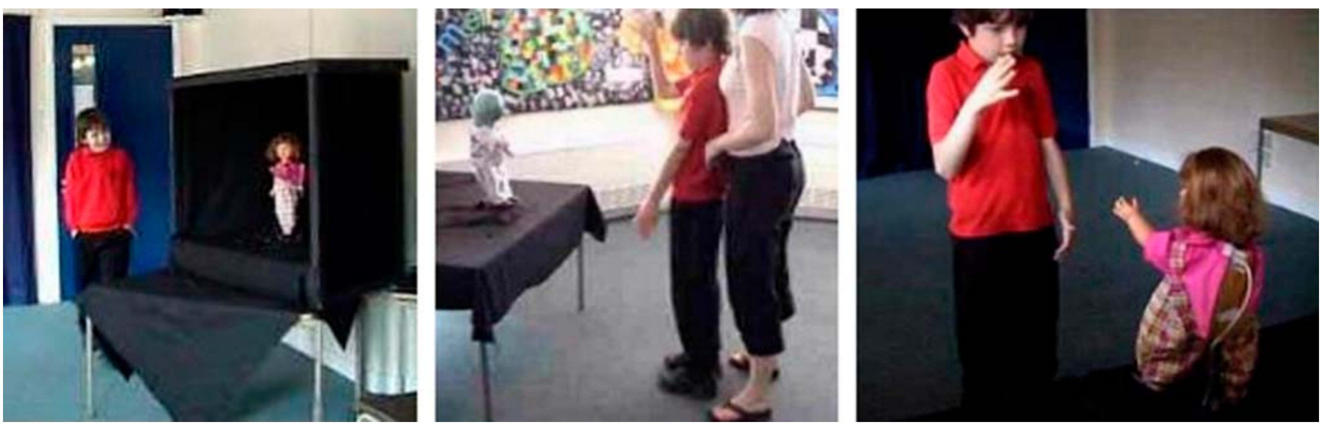

Fig. 17 T.M

7 Appendix 2

The two different robot's appearances used in the longitudinal study:

G—Robot with a 'pretty Girl' appearance.

P—Robot with a Plain appearance.

G&P—On these days, two sessions were conducted with the children, one using the robot with a 'pretty girl' appearance, and a second session with the robot in plain appearance. The combined results of these trials were used in the analysis of the data for that particular day.

Note, on certain days sessions with particular children were not possible (empty entry in Table below).

Child	Day no.							
	1	8	50	60	92	94	99	101
E.M	G	G	G	G	P	G&P	G&P	P
B.B	G	G	G		P	G&P	P	P
T.M	G		G		P	G&P	G&P	
B.S	G	G	G	G&P	P	P	G&P	G&P

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