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Interactive Robots as Facilitators of Children's Social Development

Hideki Kozima and Cocoro Nakagawa
National Institute of Information and Communications Technology
Japan

1. Introduction

Early communication between a child and a caregiver is mainly embodied through touch and eye-contact, which convey various kinds of emotional information (Kaye, 1982; Trevarthen, 2001). This communication of emotion develops into joint attention (Butterworth & Jarrett, 1991), where both alternate between looking at the same object or event and looking at each other. By mutually monitoring emotions and attention in this way, the child and the caregiver share awareness of a topical target as well as emotional attitudes towards it. Thus, the child can learn the meaning and value of various objects and events in the world, which leads him or her to the acquisition of language and culture (Tomasello, 1993, 1999).

With inspiration from the psychological study of social development, we have developed a child-like robot, Infanoid (Kozima, 2002), and a creature-like robot, Keepon (Kozima et al., 2004), as research platforms for testing and elaborating on psychological models of human social intelligence and its development in real-world settings. We are currently implementing on these robots software modules required for embodied interaction with people, especially with children. In addition, we are observing and analyzing social development in children when they interact with these robots. These two complementary research activities will help us to model social communication and its development during the first years of life.

This paper describes design principles of interactive robots for the cognitive study of human social intelligence and for the development of pedagogical and therapeutic services for children's social development. After reviewing recent psychological findings on children's social development and recent advances in robotics facilitating social interaction with children, we discuss design principles that make robots capable of embodied interaction with children. We introduce our robotic platforms, Infanoid and Keepon, as examples of implementation of these design principles. We then describe how typically-developing children interact with Infanoid and Keepon, from which we model how social interaction dynamically unfolds as time passes and how such interactions qualitatively change with age. We have conducted longitudinal field observations of a group of children with developmental disorders and a group of typically-developing preschool children interacting with Keepon. We learned from these observations that an appropriately designed robot could facilitate not only dyadic interaction between a child and the robot, but also triadic interaction among children and carers, where the robot functions as a pivot of the interpersonal interactions. Finally, we discuss the possible use of interactive robots in pedagogical and therapeutic services for typically-developing children and for those with developmental disorders, especially autistic spectrum disorders.

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2. Background

2.1 Social Development in Childhood

Children, especially those in the first year of life, develop the capability for social communication through physical and social interactions with their caregivers (e.g., mothers) and artefacts such as toys (Kaye, 1982; Trevarthen, 2001). Even neonates have various innate competencies to respond to and act on the environment, such as those for detecting and tracking human faces (Fantz, 1961; Morton & Johnson, 1991), mimicking orofacial actions, i.e., neonatal imitation (Meltzoff & Moore, 1977; Nadel & Butterworth, 1999), and recognizing the prosodic features of their mothers' voices (DeCasper & Fifer, 1980; Fernald, 1991). These competencies are, of course, the driving force for them to interact with the environment; however, to be socially meaningful, a child's acts have to be responded to, guided, and given social functions by adults (especially, caregivers).

Let us briefly look at how social development is initiated and maintained in a supportive environment during the first year of life.

- **Under three months of age:**
  The child establishes eye-contact with the caregiver along with exchanges of voice and/or facial expressions in the form of rhythmic turn-taking. The temporal structure mainly originates from the caregiver's reading of the child's response pattern. (Fig.1, left.)
- **Three to nine months of age:**
  The caregiver interprets and actively reponds to the child's mental states, such as desire and pleasure or displeasure. Although it is still asymmetric, their interaction seems socially meaningful. The child gradually learns to predict the caregiver's behavior, which makes the interaction more symmetric. (Fig.1, middle.)
- **Over nine months of age:**
  Joint attention, i.e. an activity in which two people look at the same target (Butterworth & Jarrett, 1991), emerges in the child-caregiver interactions (Tomasello, 1999; Trevarthen, 2001). With the help of gaze and/or pointing, they share perception of the target and refer to each other's actions directed at the target (including vocalization and facial expressions), thus sharing the emotional meaning or value of the target (Dautenhahn, 1997; Zlatev, 2001). (Fig.1, right.)

The development of child-caregiver interaction during the first year of life establishes the basis of an empathetic understanding of each other's mental states (Trevarthen, 2001). With this foundation, the child starts learning various social skills like language use, tool use, and cultural conventions (Tomasello, 1999; Zlatev, 2001; Kozima & Ito, 2003).

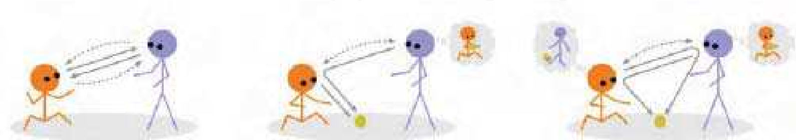

Fig. 1. Three stages of social development in the first year of life: eye-contact and exchange of emotions (left), proto-social interaction by the caregiver's interpretation (middle), and joint attention and sharing actions regarding the target (right).

2.2 Eye-contact and Joint Attention

Eye-contact and joint attention are fundamental activities that maintain child-caregiver interactions. A child and a caregiver spatially and temporally correlate their attention and emotions, in which they refer to each other's subjective feelings of pleasure, surprise, and frustration (Dautenhahn, 1997; Zlatev 2001). We believe all communication emerges from this mutual reference.

Eye-contact is the joint action of two individuals looking into each other's face, especially the eyes (Fig. 2, left). It serves not only to monitor each other's gaze and facial expressions, but also to synchronize interactions and to establish mutual acknowledgment (Kozima et al., 2004), such as "My partner is aware of me" and "My partner is aware that I am aware of her."

Joint attention is the joint action of two individuals looking at the same target by means of gaze and/or pointing (Butterworth & Jarrett, 1991) (Fig. 2, right). First, the caregiver actively follows and guides the child's attention so that the child can easily capture the target; then the child gradually becomes able to follow and guide the partner's attention. Joint attention not only provides the interactants with shared perceptual information, but also with a spatial focus for their interaction, thus creating mutual acknowledgment (Kozima et al., 2004), such as "I and my partner are aware of the same target" and "Both of our actions (such as vocalization and facial expressions) are about the target."

Fig. 2. Exchange of emotions and attention through eye-contact and joint attention: exchange of emotions through eye-contact (left), and empathetic understanding through joint attention (right).

2.3 Interactive Robots for Children

There has been a growing amount of interest in designing interactive robots that can engage in social interaction with children. This is motivated not only by pedagogical, therapeutic, and entertaining applications of interactive robots, but also by the assumption that the underlying mechanism for children's embodied interaction and its development is the fundamental substratum for human social interaction in general.

Motivated by this assumption, a number of research projects in the field of embodied interaction have developed interactive robots explicitly for interaction with children. For example, Kismet (Breazeal & Scassellati, 2000) is one of the pioneering examples of "sociable robots"; Kismet emphasized the elicitation of caretaking behaviour from adults, facilitating the robot's learning to communicate with people, but the robot was also effective at facilitating peer interaction with children. Another pioneer is the AuRoRa project (Dautenhahn, 1999), which reported that even simple mobile robots gave autistic children a relatively repetitive and predictable environment that encouraged spontaneous interactions, such as chasing games, with the robots. Billard developed a doll-like robot, Robota (Billard, 2002), for mutual imitation play with autistic children; Robins intensively analyzed two children playing together with Robota and observed mutual monitoring and cooperative behavior to derive desirable responses from it (Robins et al., 2004). Scassellati is building and using social robots (Scassellati, 2005) for the study of social development, especially that of children with autistic spectrum disorders. Michaud devised a number of mobile and interactive robots, including Roball and Tito, and observed interaction with autistic children in order to explore the design space of child-robot interactions that fosters children's self-esteem (Michaud & Théberge-Turmel, 2002). Goan used a creature-like robot, Muu (developed by Okada) to observe child-robot interactions mediated by the shared activity of arranging building blocks (Goan et al., 2005).

2.4 Autistic Spectrum Disorders

It is notable that several of the studies previously discussed have dealt with autism, or autistic spectrum disorders, which is a neurophysiological disorder caused by a specific and mainly hereditary brain dysfunction (Frith, 1989). People with autism generally have the following major difficulties.

- **Social (non-verbal) interaction:**
  They have difficulty in understanding others' intentions and emotions from gaze, facial expressions and gestures, and in sharing interests and activities with others.
- **Linguistic (verbal) interaction:**
  They have difficulty in verbal communications, especially in pragmatic use of language. They also have delayed language development or a lack of it, and stereotyped or repetitive speech.
- **Imagination:**
  They have difficulty in maintaining the diversity of behaviour and have stereotyped and restricted interests and actions. They also have difficulty in coping with novel situations.

These difficulties limit the ability of autistic people to establish and maintain social relationships with others. Researchers in social robotics therefore have a particular interest in autism to better understand the underlying mechanisms responsible for social interaction and its development.

3. Robotic Platforms

We are presently developing interactive robots for modeling the development of embodied social interaction and for investigating the cognitive mechanisms of human social development. We describe two robots we have built: Infanoid, an upper-torso child-like humanoid, and Keepon, a simple creature-like robot.

3.1 Infanoid: A Child-like Humanoid

Infanoid (Fig. 3, right), our primary research platform, is an upper-torso humanoid robot that is 480 mm tall, the approximate size of a 4-year-old human child. The latest version of Infanoid has 29 actuators (mostly DC motors with digital encoders and torque-sensing devices) and a number of sensors arranged in its relatively small body. It has two hands, each of which has four fingers and a thumb, capable of grasping small objects, pointing, and making a variety of other hand gestures.

The head of Infanoid has two eyes, each of which contains two different colour CCD cameras for peripheral (120°, horizontally) and foveal (25°, horizontally) views; the eyes can perform saccadic eye movements and smooth pursuit of a visual target. The video images taken with the cameras are fed into a PC for real-time detection of human faces (by skin-colour filtering and template matching) and physical objects such as toys (by colour and motion segmentation). The distance to faces and objects can be computed from the disparity between the images from the left and right eyes.

Infanoid has lips and eyebrows to produce various expressions (Fig. 3, left). The lips also move in synchronisation with the sound produced by a speech synthesizer. By changing the inclination of the lips and the gap between them, the robot can express a variety of emotional states.

Fig. 3. Infanoid, the child-like humanoid (right) with an expressive face (left).

Infanoid hears human voices from microphones positioned at each of its two "ears" and it analyses the sound into a sequence of phonemes; it does not have any *a priori* knowledge of language (such as lexicon or grammar). It also recognises salient changes in the fundamental frequency to extract emotional contours of human speech. By feeding the output of speech analysis into a speech synthesizer, it carries out vocal imitations while sharing attention with the interlocutor, which we consider to be a precursor to the primordial phase of language acquisition.

3.2 Keepon: A Creature-like Robot

The creature-like robot, Keepon (Fig. 4, left), was designed to engage in emotional and attentional exchanges with people, especially babies and toddlers, in the simplest and most comprehensive ways. Keepon has a yellow snowman-like body, 120mm tall, made of soft silicone rubber. The upper part (the "head") has two eyes, both of which are colour CCD cameras with wide-angle lenses (120°, horizontally), and a nose, which is actually a microphone. The lower part (the "belly") contains small gimbals and four wires with which the body is manipulated like a marionette using four DC motors and circuit boards in the black cylinder (Fig. 4, middle, right). Since the body is made of silicone rubber and its interior is relatively hollow, Keepon's head and belly deform whenever it changes posture or someone touches it.

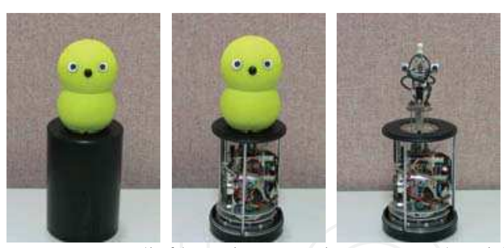

Fig. 4. Keepon's simple appearance (left) and internal structure (middle/right).

The simple body has four degrees of freedom: nodding (tilting) ±40°, shaking (panning) ±180°, rocking (side-leaning) ±25°, and bobbing (shrinking) with a 15-mm stroke. These four degrees of freedom produce two qualitatively different types of actions:

- **Attentive action:** (Fig. 5, left)
  Keepon orients towards a certain target in the environment by directing the head up/down and left/right. It appears to perceive the target. This action includes eye-contact and joint attention.
- **Emotive action:** (Fig. 5, right)
  Keepon rocks and/or bobs its body keeping its attention fixed on a certain target. It gives the impression of expressing emotions, such as pleasure and excitement, about the target of its attention.

Note that Keepon can express "what" it perceives and "how" it evaluates the target with these two actions. These communicative functions of Keepon's actions can easily be understood by human interactants, even babies and toddlers.

Fig. 5. Two types of actions: attentive (left) and emotive (right).

3.3 Modes of Operation

Infanoid and Keepon are operated in either "automatic" or "manual" modes. In the automatic mode, a set of software modules detects the locations of a human face, toys with predetermined colour, and moving objects. These locations, together with their likelihood of presence, are represented in an "attention map", or a map of saliency or attractiveness. A habituation mechanism shifts its attention after being locked onto a strong stimulus for a long time. The robots orient their bodies to the most salient target on the attention map; the robots' emotional expressions are determined by the type (face/toy/motion) and the saliency value of the target. Infanoid and Keepon automatically alternate eye-contact and joint attention with people in the automatic mode, forming an action loop situated in the environment (Figs. 6 & 7).

Fig. 6. Infanoid engaging in eye-contact (left) and joint attention (right).

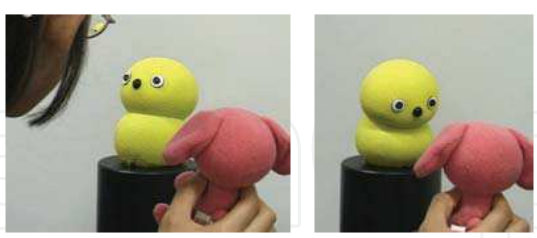

Fig. 7. Keepon engaging in eye-contact (left) and joint attention (right).

In the manual mode, a human operator (or a "wizard", usually at a remote PC) controls the robots' postural orientations, facial/bodily expressions, and vocalizations. The operator watches video from the on-board cameras and listens to sound from the on-board microphone. To perform interactive actions on the robots, the operator uses a mouse to select points of interest on the attention map and uses key-strokes that are associated with different emotive actions.

4. Child-robot Interaction

We have observed a number of live interactions between Infanoid or Keepon and typically-developing children. The children had no prior experience or instructions with the robots.

4.1 Interaction with Infanoid

To date, we have observed 15 typically-developing children (from six months to nine years of age) interacting with Infanoid (Fig. 8). In these observations, Infanoid ran in the automatic mode, in which it alternated between eye-contact and joint attention with pointing. If necessary, the operator adjusted the robot's attention, e.g., the orientation of the eyes, the head, the arms, and/or the body. First, each child was seated alone in front of the robot. About three to four minutes later, the child's caregiver came in and sat next to the child. Interaction continued until the child became tired or bored; on average, each child interacted for about 30 minutes.

Fig. 8. Unfolding interaction between Infanoid and a four-year-old boy: neophobia (left), exploration (middle), and interaction phases (right).

From the series of observations, we found that most of the children, especially those from three to seven years of age, demonstrated the following changes in their interaction.

- **Neophobia phase:** (Fig. 8, left)
  When the child interacted with the robot alone, for the first three to four minutes, he or she looked seriously into the robot's eyes. Even when the robot produced a mutual or an aversive gaze, the child's eyes were locked onto the robot's eyes. The children showed embarrassment and uncertainty about what to do.
- **Exploration phase:** (Fig. 8, middle)
  Using his or her caregiver as a secure base, the child next started exploring how the robot changed its attention and expressions in response to various interventions, such as showing it toys or poking it. When the child elicited an interesting response from the robot, he or she often looked referentially at or made commments to the mother. Through this exploration, the child discovered that the robot is an autonomous agent that shows attention and emotion.
- **Interaction phase:** (Fig 8, right)
  The chlid gradually entered into social interactions, where he or she pointed to toys or gave them to the robot by putting them in its hand. Verbal interaction also started by the child asking questions (e.g., "Which one do you want?", showing two toys).

We assumed that these different phases in the interaction would reflect changes in the children's ontological understanding of Infanoid: first as an unknown, ambiguous "moving thing", then as an "autonomous system" that had attention and emotions, and finally as a "social agent" that deserved to be involved in social interactions, including verbal ones. In most cases, these dramatic changes occurred within the first 10 to 15 minutes.

4.2 Interaction with Keepon

We have also observed 25 typically-developing infants in three different age groups, i.e., those under one, one-year-olds, and those over two, interacting with Keepon with their caregivers (Fig. 9). The robot ran in the manual mode, where a remote operator controlled the robot's attentive and emotive expressions manually with the help of video captured by the on-board and off-board cameras. The robot usually alternated between eye-contact with the infant or the caregiver and joint attention to toys in the environment. When the infant demonstrated any meaningful response, such as touching and pointing, the robot made eye-contact and showed positive emotions by rocking or bobbing its body. Interaction continued until the infants became tired or bored; on average, each infant's dealings lasted about 10 to 15 minutes.

Fig. 9. Unfolding interaction between Keepon and a 27-month-old girl: approach (left), exploration (middle), and interaction phases (right). Note that those under one stayed in the approach phase, one-year-olds reached the exploration phase through the approach phase, and those over two reached the interaction phase through the first two phases.

We found from these observations that infants in each age group showed different styles of interaction.

- **Under one year:** (Fig. 9, left)
  Interaction was dominated by tactile exploration using the hands and/or mouth. The infants did not pay much attention to the attentive expressions of the robot, but they exhibited positive responses, such as laughing or bobbing their bodies, to its emotive expressions.
- **One year old:** (Fig. 9, middle)
  The infants demonstrated not only tactile exploration, but also awareness of the robot's attentive state, sometimes following its attention. Some of the infants mimicked its emotive expressions by rocking and bobbing their own bodies.
- **Over two years:** (Fig 9, right)
  The infants first carefully observed the robot's behaviour and how caregivers interacted with it. Soon the infants started social exploration by showing it toys, soothing (by stroking its head), or verbal interactions (such as asking questions).

The differences between the interactions of each age group reflects differences in their ontological understanding of Keepon. The infants first recognised the robot as a "moving thing" that induced tactile exploration; then, after observing the robot's responses to various environmental disturbances, they recognised that it was an "autonomous system" that possesses attention and emotion as an initiator of its own expressive actions. Next, they found that the robot's responses, in terms of attention and emotion, had a spatiotemporal relationship with what they had done to it; finally, they recognised it as a "social agent" with which they could play by exchanging and coordinating their attention and emotions.

5. Therapeutic and Pedagogical Practices

Our research fields include a day-care centre for children with developmental disorders, especially those with autistic spectrum disorders, and a preschool mainly for typically-developing children. At the therapeutic day-care centre, children (mostly two to four years old), their parents (usually mothers), and therapists interact with one another, sometimes in an unconstrained manner (i.e., individually or within a nuclear relationship of child/mother/therapist), and sometimes in rather organised group activities (e.g., rhythmic play and storytelling). In these dynamically and diversely unfolding interactive activities, the children's actions are watched, responded to, and gradually situated in the social context of everyday life. At the preschool, a larger number of children (three to four years old) interact with one another around Keepon with minimum intervention from their teachers. Here, we especially observe how various actions and their meanings to Keepon are expressed, exchanged, and shared among the children.

5.1 Keepon in the Playrooms

A wireless version of Keepon was placed in the two playrooms just like one of the toys on the floor. At the therapeutic day-care centre, seven to eight combinations of child/mother/therapist engaged in the therapeutic sessions (three hours each) in the playroom, during which they sporadically interacted with Keepon. During free play (i.e., the first hour), children could play with Keepon at any time. During group activities (i.e., the following two hours), Keepon was moved to the corner of the playroom so that it did not interfere with the activities; however, if a child became bored or stressed by the group activities, he or she would be allowed to play with Keepon.

At the preschool, about 25 children and 3 teachers shared the playroom and sporadically played with Keepon in the morning (three hours). Children could play with Keepon at any time during free play (i.e., the first 90 minutes). During group activities (i.e., the following 90 minutes), Keepon was moved to an appropriate position (e.g., on the shelf or on the piano) by teachers so that it did not interfere with their activities.

In the playrooms, Keepon was operated in the manual mode. An operator in another room controlled the robot by (1) alternating its gaze between a child's face, the carer's face, and sometimes a nearby toy, and by (2) producing a positive emotional response (e.g., bobbing its body several times with a "pop, pop, pop" sound) in response to any meaningful action (e.g., eye-contact, touch, or vocalisation) performed by the child. We manually controlled Keepon because (1) Keepon should wait for a child's spontaneous actions, and (2) when the child directs an action, Keepon should respond with appropriate timing and manner.

Throughout the observations, we recorded live interactions between Keepon and the children from Keepon's perspective (Fig. 10). In other words, we recorded all the information from the subjective viewpoint of Keepon as the first person of the interaction. Strictly speaking, this subjectivity belongs to the operator; however, the interaction is mediated by the simple actions that Keepon performs, and every action Keepon performs can be reproduced from the log data. Therefore, we may say that Keepon is both subjective (i.e., interacting directly with children) and objective media (through which anyone can re-experience the interactions), enabling human social communications to be studied.

Fig. 10. A child seen from Keepon's subjective viewpoint.

5.2 Case Studies with Autistic Children

At the day-care centre, for the past three years (over 95 sessions, or totally 700 child-sessions), we have been longitudinally observing a group of children with autism, PDD (pervasive developmental disorder), Asperger's syndrome, Down's syndrome, and other developmental disorders (Fig. 11). We observed over 30 children in total; some of the children moved in and out of the centre during this period. We describe below three typical cases.

Fig. 11. Keepon in the playroom at the remedial day-care centre.

Case 1: M — A three-year-old girl with autism

The first case is a three-year-old girl M with autism. At CA 1:11 (chronological age 1 year and 11 months), her MA (mental age) was estimated at 0:10. At CA 3:5, she was diagnosed as autism with moderate mental retardation. Here, we describe how the interaction between M and Keepon unfolded in 15 sessions over five months (CA 3:9 to 4:1), during which she did not exhibit any apparent production of language.

- From Session 1 (hereafter referred to as S1), M exhibited a strong interest in Keepon, but did not get close to it. Through S1 to S7, M avoided being looked at directly by Keepon (i.e., gaze aversion); however, M gradually approached it from the side and looked at it in profile.
- In S5, after watching a boy put a paper cylinder on Keepon's head, M went to her therapist and pulled her by the arm to Keepon, non-verbally asking her to do the same thing. When the therapist completed her request, M left Keepon with a look of satisfaction in her face. Through S5 to S10, her distance to Keepon gradually decreased to less than 50cm.
- In the free play of S11, M touched Keepon's head using a xylophone stick. During the group activity, M reached out with her arm to Keepon but did not actually touch it. In the intermission of the group activity, M sat in front of Keepon and touched its belly with her left hand, as if examining its texture or temperature.
- After this first touch in S11, M began acting exploratively with Keepon, such as looking into its eyes, waving her hand at it, and listening to its sound. From S12, M

vocalised non-words to Keepon, as if she expected some vocal response from it. In S13, M put a knitted cap on its head, and then asked her mother to do the same thing. In S14, M actually kissed the robot.

We can see here the emergence of both spontaneous dyadic interactions (Baron-Cohen, 1995; Tomasello, 1999), such as touching Keepon with a xylophone stick (Fig. 12, left), and interpersonally triggered dyadic interaction, such as putting a paper cylinder on its head (Fig. 12, right). The latter especially suggests that M was a good observer of others' behavior, although she seldom imitated others even when instructed. Because the boy's action was mediated by Keepon and an object (e.g., the paper cylinder) that were of interest to M, it would be relatively easy for her to emulate (Tomasello, 1999) the same action and result.

Fig. 12. Emergence of dyadic interactions: exploratory actions directed to Keepon (left) and interpersonally triggered/copied actions (right).

Case 2: N — Another three-year-old girl with autism

The second case is a three-year-old girl N with autism and moderate mental retardation (MA 1:7 at CA 3:1; no apparent language). We observed her interactions with Keepon for 39 sessions, which lasted for about 18 months (CA 3:4 to 4:8).

- In S1, N gazed at Keepon for a long time. After observing another child playing with Keepon using a toy, N was encouraged to do the same, but did not show any interest in doing that.
- Through S2 to S14, N did not pay attention to Keepon, even when she sat next to it. However, N often glanced at the robot, when she heard sounds coming from it.
- In S15, after observing another child place a cap on Keepon's head, N touched Keepon with her finger.
- In S16 (after a three-month interval from S15), N came close to Keepon and observed its movements. During snack time, N came up to Keepon again and poked its nose, to which Keepon responded by bobbing, and N showed surprise and a smile; the mothers and therapists in the playroom burst into laughter. During this play, N often looked referentially and smiled at her mother and therapist.
- From S17, N often sat in front of Keepon with her mother; sometimes she touched Keepon to derive a response. From S20, N started exploring Keepon's abilities by walking around it to see if it could follow her.
- During snack time in S33, N came up to Keepon and started an "imitation game". When N performed a movement (bobbing, rocking, or bowing), soon Keepon mimicked her; then N made another, and Keepon mimicked her again. Through S33 to S39, N often played this "imitation game" with Keepon, during which she often looked referentially at her mother and therapist.

We can see especially in S16 and in S33 the emergence of triadic interactions (Baron-Cohen, 1995; Tomasello, 1999), where Keepon or its action functioned as a pivot (or a shared topic) for interpersonal interactions between N and her mother or therapist (Fig. 13). In those triadic interactions, which were spontaneously performed in a playful and relaxed mood, it seemed that

N wanted to share with the adults the "wonder" she had experienced with Keepon. Within this context, the "wonder" was something that induced smiles, laughter, or other emotive responses in herself and her interaction partner. It is also notable that the "imitation play" first observed in S33 was unidirectional, in which Keepon was the imitator and N was the model and probably the referee; however, this involved reciprocal turn-taking, which is one of the important components of social communication.

Fig. 13. Emergence of triadic interaction: the child discovers "wonder" in Keepon (left), then looks at the partner to share this "wonder" (right).

Case 3: A three-year-old boy with Asperger's syndrome

The third case is a boy S with Asperger's syndrome with mild mental retardation (MA/cognition 3:2 and MA/language 4:3 at CA 4:6). Here, we describe the first 15 sessions, which lasted for about nine months (CA 3:10 to 4:6).

- In the first encounter, S violently kicked Keepon and turned it over; then, he showed embarrassment, not knowing how to deal with the novel object.
- From S2, S became gentle with Keepon. Often S scrambled with another child for Keepon (S3 and S6), suggesting his desire to possess the robot. In S5, S showed his drawing of the both of them to Keepon, saying "This is Pingpong [Keepon]; this is S."
- In S8, S asked Keepon, "Is this scary?", showing bizarre facial expressions to the robot. When an adult stranger approached Keepon, S tried to hide it from her, as if he were protecting Keepon.
- In S11 and S16, when another child behaved violently with Keepon, S often hit or pretended to hit the child, as if he were protecting Keepon.
- During snack time in S14, S was seated next to Keepon. S asked the robot and another child if the snacks were "Yummy?".
- In S15, Keepon wore a flu mask. S came up to Keepon and asked "Do you have a cough?" a couple of times. When his therapist came in, S informed her of the presence of the mask, saying "Here's something".

In the early stages of interaction, we saw a drastic change in S's attitude toward Keepon. S exhibited exceptionally violent behavior towards Keepon in the first encounter. But after S2, S demonstrated exceptionally gentle behavior towards Keepon, trying to monopolize and sometimes to protect it. His therapist suggested that S usually expressed violent behavior towards strangers to whom he did not know how to relate, but he would behave socially after getting used towards them. It is noteworthy that S seemed to regard Keepon as a human-like agent that not only perceived the environment and evaluated its emotional content, but also understood language, regardless of his relatively good cognitive and linguistic capabilities.

5.3 A Case study with typically-developing children

Finally, we discuss how a group of 25 typically-developing children in a class of three-year-olds (average CA 4:0 throughout the year-long observation) interacted with Keepon in the playroom of their preschool (Fig. 14). At around 8:30 a.m., one of the teachers brought

Keepon to the playroom and put it on the floor with other toys. In the first 90 minutes, the children arrived at the preschool, gradually formed clusters, and played freely with each other and with Keepon. In the next 90 minutes, under the guidance of three teachers, the children engaged in various group activities, such as singing songs, playing musical instruments, and doing paper crafts. Keepon was moved as necessary by the teachers so that it did not interfere with the activities; sometimes it sat beside the teacher who was telling a story, or sat on the piano watching the children who were singing or dancing.

Fig. 14. Keepon in the playroom with typically-developing three-year-olds at a preschool. (Coutesy of *Kyoto Shimbun*).

Throughout the year-long observations (25 sessions of three hours each, over 600 child-sessions), we experienced various interactions between the children and Keepon that were qualitatively and quantitatively different from what we observed at the remedial day-care centre. Here are some anecdotes about what Keepon experienced with the children at the preschool:

- When Keepon lost its miniature cap crafted for it, a boy TK noticed this and asked Keepon "Did you loose your cap?". Keepon nodded, and TK responded with "Endure being without your cap", stroking Keepon's head with an empathetic voice and facial expression.
- During reading time, a boy TM and a girl NK came up to Keepon and showed it picture books one by one. Note that they opened the books in the appropriate direction for Keepon to "see" them.
- Two boys, FS and TA, strongly beat Keepon's head several times, as if demonstrating their braveness to each other. Two girls, KT and YT, observing this, approached Keepon and checked if it had been damaged; then YT said "Boys are all alike. They all hit Keepon", while gently stroking Keepon's head.
- A girl YT tried to teach Keepon some words. Showing it the cap, she said, "Say, *Bo-shi*"; then she switched to Keepon's knitted cap and said, "This is a *Nitto Bo-shi*, that you can wear in winter". Note that Keepon could only respond to her by bobbing its body with the "pop, pop, pop" sound.

Especially during free play time (the first 90 minutes), the children showed a wide range of spontaneous actions, not only dyadic between a particular child and Keepon, but also *n*-adic, in which Keepon functioned as a pivot of interpersonal play with peers and sometimes with teachers. Since the children were generally typically-developing, they often spoke to Keepon, as if they believed that it had a "mind". They interpreted Keepon's responses, although they were merely simple gestures and sounds, as having communicative meaning within the interpersonal context. We have never observed this with the autistic children, who rarely interacted with peers. Compared with the experimental setting (Section 4), where children became bored after 15-minute interactions, it is interesting that children in the preschool never lost interest even after 20 sessions.

6. Discussion

6.1 Children's Understanding of the Robots

We saw in Section 4 that children changed their ontological understanding of Infanoid as the interaction unfolded and of Keepon as they grew older: first as a "moving thing", then as an "autonomous system" to explore, and finally as a "social agent" to play with. Interestingly, children generally showed a great deal of anxiety and embarrassment towards Infanoid at first; however, with Keepon, they spontaneously approached it and started "tasting" its texture and motion, and gradually entered into an explorative and social interaction with the robot. What created this difference between Infanoid and Keepon?

We assume that the children first recognize the motions of the arms, hands, eyes, etc., separately. Each part of the robotic body emits rich information in its motion; however, it is difficult for children to recognize the gestalt of the entirety of these moving parts. The gestalt would be "autonomy", "life", or the sense that the robot perceives and acts in the world as we do. In case of Infanoid, the children had a difficulty in comprehending the gestalt, which requires (1) effortful analysis of the meanings of each moving part and (2) an effortful integration of the meaning into a coherent "unity" that all autonomous life would have. Meanwhile, Keepon is completely different from humans in terms of its appearance (form), but the simplicity of being able to express only attention and simple emotions, combined with the life-like softness of the body, would enable the children and infants to intuitively understand the gestalt (Fig. 15).

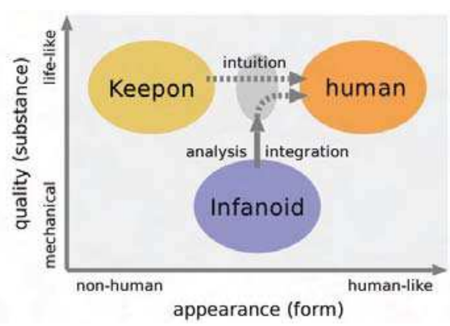

Fig. 15. The different ways that children take to understand the human-like gestalt (autonomy or life) in Infanoid and Keepon.

Understanding of the gestalt, namely, the sense that the robot perceives and acts as we do, worked as the motivating basis for children to explore and communicate with it. This would be a fundamental prerequisite for any kind of human-robot communication, not only for children, but also for people in general.

6.2 Complexity and Predictability

Children's ontological understanding of a robot depends also on the complexity of its behaviour. What a robot can perceive and how the robot responds to it would change the children's "stance" (Dennett, 1987) in interaction with the robot. For example, a robot may exhibit periodic actions just like a clockwork toy, reflexive actions in response to some specific stimuli, an action situated in the physical environment (e.g., positions of the child or toys), or coordinated actions situated within the social environment (e.g., attention and/or emotions of the child). This spectrum of complexity represents the predictability of the robot's action, or the action's dependence on internal and external information (Fig. 16).

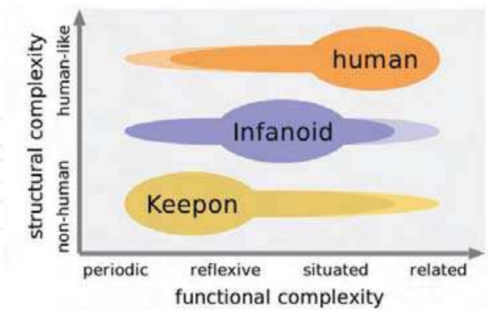

Fig. 16. A design space for interactive robots: the functional and structural complexity determines the predictability of the robots' behaviour.

Although it would be difficult to control their structural complexity, the functional or behavioural complexity of robots can easily be manipulated by gradually increasing (or freeing) their degrees of freedom and by gradually introducing a dependence on the physical and social situations to their behaviour. Manipulating the structural and, especially, the functional complexity, we can tune the predictability of a robot's behaviour to each child's cognitive style and developmental stage, providing a "zone of proximal development" (Vygotsky, 1934/1962). When a child encounters a robot whose behaviour has an appropriate predictability for that particular child, he or she should approach the robot in a relaxed mood and spontaneously start explorative interactions in a playful mood. From this, the child might subsequently learn to predict and control the robot's behaviour in terms of its dependence on physical and social situations.

6.3 Facilitating Social Interactions

When the complexity of a robot is appropriate for a particular child, the robot's behaviour attracts his or her attention and elicits various actions from the child (Fig 17, left). As we saw from the case studies (Section 5), the children enjoyed the dyadic interaction with the robot with a sense of security and curiosity, in which they gradually learned the meanings of the robot's responses. The way this dyadic interaction unfolds varies from one child to another, but it is noteworthy that every individual child, either spontaneously or with minimum intervention by a therapist or mother, builds a relationship with the robot.

The robot also attracts a child's attention to another child who is interacting with it. As we witnessed in the case with the girl M, each child curiously observed how others were acting on the robot and what responses they induced from it. For the child observer, the interactions between the robot and the other child were comprehensive, because of its structural simplicity and functional predictability. Especially when the other child induced a novel, interesting response from the robot, the observers would also feel pleasure and excitement (Fig. 17, middle).

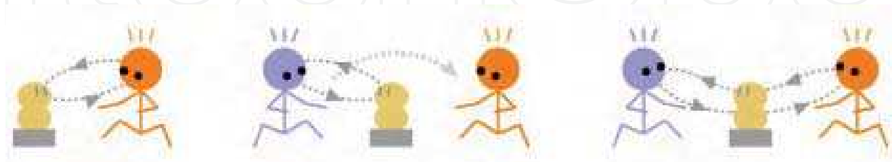

Fig. 17. Facilitating children's interpersonal interaction: a child finds a "wow" in the interaction with the robot (left), observes another child's "wow" (middle), and relates the self's "wow" and other's "wow" using the robot as the pivot.

A child is surprised at the robot's interesting response and observes others also being surprised at the same or similar response from the robot. These two "wows" are qualitatively equivalent, since both come from a simple robot with moderate predictability. Here, we can see that an interactive robot has the potential to serve as a pivot for relating the child's own "wow" with others' "wow" (Fig. 17, right). As we saw in the case studies, when the girl N induced a surprising response from Keepon, probably with the help of the therapists, who exaggeratedly reacted to her discovery by bursting into laughter, N checked with her mother for the same "wow" as if she were saying "Mom, it's interesting! Did you see that?".

7. Conclusion

We have presented in this paper design principles of interactive robots for inducing in children various spontaneous interactions based on their ontological understanding of the robots. We have built an upper-torso humanoid, Infanoid, and a creature-like robot, Keepon. Both can engage in eye-contact and joint attention with human interactants, though which the robots and humans can exchange emotional and attentive states. In our psychological experiments on child-robot interaction, we found that children regarded Infanoid as a "moving thing", an "autonomous system", and a "social agent" as the interaction unfolded during the course of 30 minutes sessions. With Keepon, children deepened their interaction as with Infanoid; those under one, one-year-olds, those over two reached the understanding of the robot as a "moving thing", an "autonomous system", and a "social agent", respectively.

We then carried out field studies at a remedial day-care centre and at a preschool, where we longitudinally observed interactions between children and Keepon in rather unconstrained everyday situations. These field studies suggest the following:

- Children, even those with difficulty in interpersonal communication (e.g., those with autism), were able to approach Keepon with a sense of curiosity and security. This was probably because the robot seemed to be neither a complex human nor a simple toy.
- Most typically-developing children and some with developmental disorders extended their dyadic interactions with Keepon into triadic interpersonal ones, where they tried to share the pleasure and surprise they found in Keepon with others, such as their caregivers.
- Each child exhibited a different style of interaction that changed over time, which would tell us a "story" about his or her personality and developmental profile. These unique tendencies cannot be thoroughly explained by a diagnostic label such as "autism" or a broad psychological term such as "introverted".

The "story" of each child has been accumulated as video data, which is being utilized by therapists, psychiatrists, and paediatricians at the day-care centre for planning their therapeutic intervention, and by teachers at the preschool for improving their educational services. We also provided the video data to parents with the hope that it may positively influence their own child-care.

Although we conducted our field studies using the manual mode, where a human operator tele-operated the robots, our observations demonstrate that interactive robots with appropriate structural and functional complexity can facilitate children's social interactions with robots, peers, and carers. In creating robots that can autonomously socially interact with people, we are still missing a wide range of robotic and AI technologies; however, for children, especially those with developmental disorders, current technology for interactive robots, even when tele-operated, can certainly be applied to facilitating their social interaction and its development.

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