Int J Soc Robot (2009) 1: 3–18
DOI 10.1007/s12369-008-0009-8

ORIGINAL PAPER

Keepon

A Playful Robot for Research, Therapy, and Entertainment

Hideki Kozima · Marek P. Michalowski · Cocoro Nakagawa

Accepted: 28 October 2008 / Published online: 19 November 2008

Abstract Keepon is a small creature-like robot designed for simple, natural, nonverbal interaction with children. The minimal design of Keepon's appearance and behavior is meant to intuitively and comfortably convey the robot's expressions of attention and emotion. For the past few years, we have been observing interactions between Keepon and children at various levels of physical, mental, and social development. With typically developing children, we have observed varying styles of play that suggest a progression in ontological understanding of the robot. With children suffering from developmental disorders such as autism, we have observed interactive behaviors that suggest Keepon's design is effective in eliciting a motivation to share mental states. Finally, in developing technology for interpersonal coordination and interactional synchrony, we have observed an important role of rhythm in establishing engagement between people and robots. This paper presents a comprehensive survey of work done with Keepon to date.

Some portions of this paper are modified from content appearing in [28–32, 34, 35].

H. Kozima · C. Nakagawa
National Institute of Information and Communications Technology, Hikaridai 3-5, Seika, Soraku, Kyoto 619-0289, Japan

Present address:
H. Kozima (✉)
School of Project Design, Miyagi University, Gakuen 1, Taiwa, Kurokawa, Miyagi 981-3298, Japan
e-mail: xkozima@myu.ac.jp

M.P. Michalowski
Robotics Institute, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15217, USA
e-mail: michalowski@cmu.edu

Keywords Human-robot interaction · Robot design · Social development · Autism therapy · Rhythmic synchrony · Interpersonal coordination

1 Introduction

When designing robots capable of natural social interaction with people—whether we build such robots for scientific, utilitarian, or aesthetic ends—it is instructive to study how social intelligence unfolds during the early stages of human life. For the past several years, we have been developing *Keepon*, a social robot that is designed to conduct nonverbal interactions with children, to help us study, test, and elaborate on psychological models of the development of social intelligence.

This paper discusses the design, development, research, and applied fieldwork conducted with Keepon. After reviewing psychological findings on children's social development and recent advances in robots for facilitating social interaction, we discuss design principles for embodied interaction with children and introduce Keepon as an implementation of these principles. In addition to a dynamic and robust hardware platform, we have developed a body of perceptual and behavioral software modules that may be autonomous or teleoperated for different types of research. We have conducted longitudinal field observations of typically-developing preschool children and children with developmental disorders, particularly autistic spectrum disorders, interacting with Keepon. Our approach is to conduct ethnographic observations of our designed social robot interacting with children in a comfortable, natural context, with results intended to simultaneously inform robot design, cognitive theory, psychological experimental design, and therapeutic and pedagogical practice.

From our observations, we can model how social interaction unfolds dynamically and how such interactions change qualitatively with age. We have learned that an appropriately designed robot can facilitate not only dyadic interaction between a child and the robot, but also triadic interaction among children and caregivers, with the robot functioning as an interpersonal "pivot." Qualitative and quantitative analysis of these interactions suggests that autistic children possess the motivation to share mental states with others, which is contrary to the commonly held assumption that this motivation is impaired in autism. We believe that the minimal design of Keepon's appearance and behavior helps children understand socially meaningful information and stimulates their intact motivation to share interests and feelings with another. We discuss the possible use of such interactive robots in pedagogical and therapeutic services for facilitating social development in typically-developing children as well as those with developmental disorders. Finally, we discuss ongoing research on the nonverbal aspects of interpersonal coordination, particularly rhythmic interactional synchrony, in establishing engagement between people and robots.

2 Designing Child-Robot Interaction

There has been a growing interest in designing interactive robots with which human children can naturally and intuitively interact. This research trend is motivated not only by the potential pedagogical, therapeutic, and entertaining applications of interactive robots, but also by an assumption that the development and underlying mechanisms of children's embodied interaction form a fundamental substratum for human social interaction in general. In this section, we review recent engineering and psychological work, describe our design principles for interactive robots for children, and introduce Keepon as an implementation of these design principles.

2.1 Interactive Robots for Children

A number of research projects in the field of embodied interaction have developed robots explicitly for interaction with children. For example, *Kismet* [6] is a pioneering example of a "sociable robot." Kismet engaged people in natural and intuitive face-to-face interaction by exchanging a variety of social cues, such as gaze direction, facial expression, and vocalization. Kismet's elicitation of caretaking behavior from people (including children) enabled a form of socially situated learning with its human caregivers.

Another pioneer is the *AuRoRa* project [18], which reported that even simple mobile robots provided autistic children with a relatively repetitive and predictable environment that encouraged spontaneous and relaxed interactions (e.g. chasing games). Billard [5] developed a doll-like anthropomorphic robot, *Robota*, for mutual imitative play with autistic children; Robins [40] analyzed two children playing with Robota and observed mutual monitoring and cooperative behavior to draw desirable responses from it.

Scassellati [41], who has been building and using social robots for the study of children's social development, observed autistic children interacting with a robot with an expressive face and found that they showed positive proto-social behaviors (e.g. touching, vocalizing, and smiling at the robot) that were generally rare in their everyday life. Michaud [36] has devised a number of mobile and interactive robots, including *Roball* and *Tito*, and has observed interaction with autistic children in order to explore the design space of child-robot interaction for fostering children's self-esteem. Okada [39] developed a creature-like robot, *Muu*, to observe how autistic children spontaneously collaborate with the robot in shared activities such as arranging colored blocks.

Keepon's appearance design falls somewhere between the minimalism of robots such as Roball or Muu and the anthropomorphism of robots such as Kismet or Robota. We believe that some basic traits common to people and animals (e.g. lateral symmetry and two eyes) are important cues to the potential for social agency. At the same time, keeping the appearance simple—so that it is aligned with the robot's behavioral capabilities—is important for helping people understand and feel comfortable with the robot's behavior. Our work with Keepon also differs from the aforementioned robots in the length of our longitudinal studies: over the past four years, we have conducted and recorded approximately 400 hours of interaction between Keepon and hundreds of children.

2.2 Human Social Development

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 artifacts such as toys [25, 45]. Even neonates have various innate competencies to respond to and act on the environment, such as those for detecting and tracking human faces [21, 37], mimicking orofacial actions (i.e., neonatal imitation) [33, 38], and recognizing the prosodic features of their mothers' voices [19, 22]. 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 look briefly at how social development is initiated and maintained in a supportive environment during the first year of life (Fig. 1):

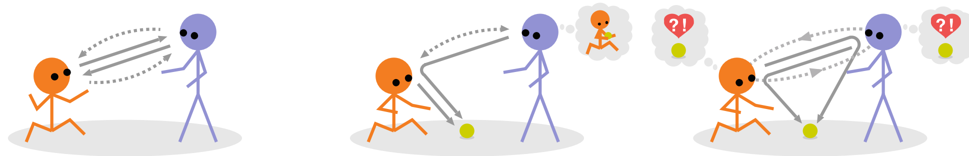

Fig. 1 Three stages of social development in the first year of life: eye-contact and exchange of emotions (*left*), proto-social interaction by the caregiver's interpretation (*middle*), and empathetic understanding, joint attention, and shared actions regarding a target (*right*)

– Under three months of age—The child establishes eye-contact (the joint action of two individuals looking into each other's faces) with the caregiver and exchanges vocal and/or facial expressions in the form of rhythmic turn-taking (Fig. 1, left). The temporal structure mainly originates from the caregiver's reading of the child's response pattern.[1]
– Three to nine months of age—The caregiver interprets and actively responds to the child's mental states, such as desire, pleasure, or displeasure (Fig. 1, middle). 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.
– Over nine months of age—Joint attention (the activity in which two people look at the same target or point at it by means of gaze and/or deictic gesture [8]) emerges in the child-caregiver interactions [43, 45] (Fig. 1, right). They share awareness and perception of a target and refer to each other's actions towards it (including vocalization and facial expressions), thus sharing the emotional meaning or value of the target [17, 49].[2]

Touch, eye contact, and joint attention are fundamental behaviors that maintain child-caregiver interactions and establish a basis for empathetic understanding of each other's mental states [25, 45]. A child and a caregiver spatially and temporally correlate their attention and emotions, referring to each other's subjective feelings of pleasure, surprise, or frustration [17, 29, 49]. We believe that all communication emerges from this mutual reference. With this foundation, the child starts learning various social skills such as language use, tool use, and cultural conventions [29, 43, 49].

2.3 Keepon's Development

With inspiration from the psychological study of social development and its deficiency in autism (discussed in Sect. 4), we first developed the upper-torso humanoid robot *Infanoid* [28], which is 480 mm tall, the approximate size of a four-year-old human child. With 29 actuators (mostly DC motors with digital encoders and torque-sensing devices) and a number of sensors, it can express attention (by directing its eyes, face, and hands), facial expressions (by moving its eyebrows and lips), and other hand and body gestures. Infanoid was able (1) to detect a human face and direct its gaze to the face (eye contact), and (2) to estimate the direction of attention from the face and search the attention line for any salient object (joint attention). In preliminary studies, we observed that children generally enjoyed social interactions when they were able to read the robot's attention and emotions. However, we also found that Infanoid conveyed an overwhelming amount of information to some children, especially those under three years of age, who at first exhibited embarrassment or anxiety around Infanoid. We attribute this to Infanoid's anthropomorphic but highly mechanistic appearance—children's attention was often attracted by moving parts, especially the hands, fingers, eyes, and eyebrows—and effort was required to integrate the qualitatively different movements into a holistic recognition of a social agent.

Having learned from this difficulty, we began to develop a creature-like robot, *Keepon*, which was to have a minimal

[1]Eye contact serves not only to monitor each other's state of attention (e.g. gaze direction) and emotion (e.g. facial expressions), but also to temporally synchronize interactions and to establish mutual acknowledgment [30], such as "My partner is aware of me" and "My partner is aware that I am aware of her". It has been widely assumed that autistic children generally show indifference to others' gaze; however, a brain imaging study [16] revealed that children with autism sometimes emotionally over-react (as evidenced by high activation in the amygdala) to direct gaze from a non-threatening face. This suggests that autistic children are perhaps overwhelmed by eye contact with others and therefore avert their gaze.

[2]In the first stage of joint attention the caregiver actively follows and guides the child's attention so that the child can easily capture the target. Next, the child gradually becomes able to follow and guide the partner's attention. Finally, the child and caregiver coordinate their initiations and responses, forming spatio-temporal patterns of attention exchange. In the first stage, children are only capable of coordinating attention with others in relation to a visible object or event; in later stages, invisible psychological entities such as emotions and concepts will be incorporated into the targets of attention. Joint attention not only provides interactants with shared perceptual information but also with a spatial focus for their interaction, thus creating mutual acknowledgment [30], such as "My partner and I are aware of the same target" and "Both of our actions (such as vocalization and facial expressions) relate to the target". Again, it is widely recognized that autistic children rarely engage in joint attention with others; however, when instructed by an experimenter, they are often capable of identifying the targets of others' attention.

design for facilitating the exchange of attention and emotion with people—especially babies and toddlers—in simple and comprehensible ways. The simplest robot for our purposes would be one that could display its attention (what the robot is looking at), as exemplified in Fig. 2 (left). The presence of active attention would suggest that the robot can perceive the world as we see and hear it. The next step would be a robot that displays not only attentive but also emotive expressions. Emotional actions would suggest that the robot has a "mind" to evaluate what it perceives. However, adding a few degrees of freedom to the robot's facial expressions would risk a flood of information that could so overwhelm the children (as Infanoid did) that it would be difficult for them to grasp the gestalt of the robot's behavior. Therefore, we decided to use the robot's bodily movement to express emotions such as pleasure (by rocking the body from side to side), excitement (by bobbing up and down), and fear (by vibrating), as shown in Fig. 2 (middle). In the final design stage, we made a neck/waist line, as shown in Fig. 2 (right). This line provides a clear distinction between the head and the belly, giving a slightly anthropomorphic (but not overwhelming) impression to children, and allows for life-like deformation of the body as the robot changes its posture.[3]

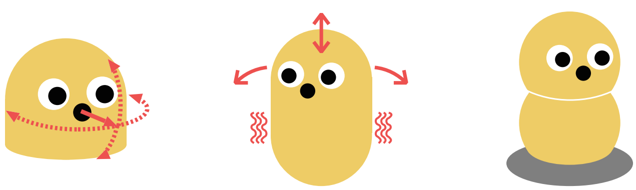

Fig. 2 Designing Keepon's appearance for the interactive functions of expressing attention (*left*) and emotion (*middle*), and the final sketch (*right*)

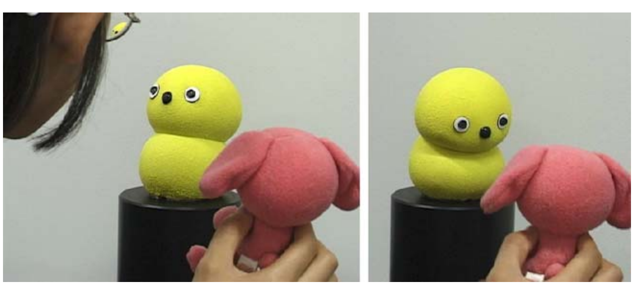

Fig. 3 Keepon, the interactive robot, engaging in eye contact (*left*) and joint attention (*right*) with a human interactant

As an implementation of these design principles, Keepon has a yellow snowman-like body that is 120 mm tall (Fig. 3). The upper part (the "head") has two eyes, both of which are color 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 wires with which the body is manipulated like a marionette using four DC motors and circuit boards that are encased in the black cylinder (Fig. 4, left). 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, right).

The simple body has four degrees of freedom (Fig. 5): nodding (tilting forward and back) ±40°, turning (panning left and right) ±180°, rocking (leaning side-to-side) ±25°, and bobbing (compressing vertically) with a 15 mm stroke. These four degrees of freedom produce two qualitatively different types of actions:

– **Attentive action:** Keepon orients towards a certain target in the environment by directing its head (i.e. gaze) up/down and left/right. This action enables eye contact and joint attention.
– **Emotive action:** Keepon rocks from left to right and/or bobs its body up and down while keeping its attention fixed on a target. This gives the impression of expressing Keepon's internal rather than perceptual state. These behaviors suggest emotions such as pleasure and excitement about the target of Keepon's attention. These behaviors

[3]The name "Keepon" comes from the Japanese word for yellow ("kee") and onomatopoeia for the robot's bobbing behavior ("pon").

Fig. 4 Keepon's structure: its simple appearance and marionette-like mechanism (*left*), which drives the deformable body (*right*)

are accentuated by short "popping" sounds appropriate to the movement from a speaker below the robot's body.

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

Keepon can be operated in "automatic" mode, in which a set of software modules detects the locations of human faces, colorful toys, and moving objects. These locations, together with their likelihood of presence, are represented in an "attention map" of salience or attractiveness. A habituation mechanism shifts this attention after being locked onto a strong stimulus for a long time. The robot orients its body to the most salient target on the attention map, while the robot's emotional expressions are determined by the type of object and its relative salience. Keepon can thus automatically alternate between eye-contact and joint attention with people, forming an action loop situated in the environment. However, as we shall discuss, we have normally conducted our research and therapeutic practice in a "manual" or teleoperated mode.

3 Studying Social Development

Our studies of Keepon interacting with typically developing children have been conducted in a laboratory setting as well as in the naturalistic environment of a preschool playroom. Our goals were (1) to verify the effectiveness of our minimal design on attentive and emotive exchange with younger children, and (2) to observe how the nature of these interactions differed across age, experience with the robot, and group dynamics.

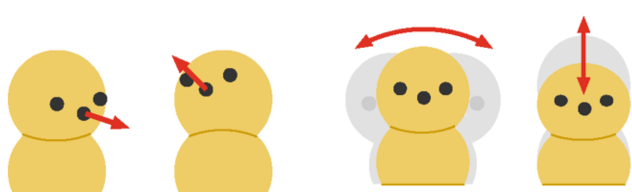

Fig. 5 Keepon's functions: expressing attention by orienting its head (*left*) and expressing emotions by rocking and/or bobbing its body (*right*)

3.1 Method

While Keepon can be operated in "automatic" mode as described, we intentionally used a "manual" mode for most of our interaction studies. The self-contained robot base is equipped with batteries and bi-directional wireless communication hardware (Fig. 6) to transmit video, sound, and control data to a human operator (or "wizard," usually at a remote PC). The operator controls the robot's postural orientations, bodily expressions, and sounds while watching video from the on-board cameras (Fig. 7) and listening to sound from the on-board microphone. The operator also watches video from an off-board camera to get a side view of the interaction, which gives him or her greater situational awareness—especially when the on-board cameras are covered by a child's hand or face.

To make the robot act, the operator uses a mouse to select points of interest on the camera monitor and uses keystrokes that are associated with different emotive actions. The robot can thus (1) alternate its gaze between a child's face, a caregiver's face, and nearby toys, and (2) produce positive emotional responses (e.g. bobbing its body with a "pop, pop, pop" sound) in response to any meaningful actions (e.g. eye contact, touch, or vocalization) performed by the child. We used this form of manual control so that Keepon can appropriately respond to children's spontaneous actions.

3.2 Unfolding Interaction with Keepon

In the lab, we observed interactions between Keepon and 25 typically developing children in three different age groups: under 1 year ($N = 8$, average 9.0 months old), 1–2 years old ($N = 8$, average 16.5 months old), and over 2 years old ($N = 9$, average 37.3 months old). Each child, together with a caregiver, was seated in front of Keepon on the floor; there were no particular instructions provided. The robot ran in the manual mode described above. The robot was

Fig. 6 A self-contained version of Keepon, equipped with a battery and wireless connections

usually made to alternate between eye-contact with the infant or the caregiver and joint attention to toys in the environment. When an infant demonstrated any meaningful response, such as touching or pointing, the robot made eye-contact and showed positive emotions by rocking or bobbing its body. Interaction continued until children became tired or bored; on average, each child's interaction lasted about 10 to 15 minutes. We found from these observations that children in each age group showed different styles of interaction [31]:

- **0–1-year-olds:** Interaction was dominated by tactile exploration using the hands and/or mouth. The children 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.
- **1–2-year-olds:** The children demonstrated not only tactile exploration but also awareness of the robot's attentive state, sometimes following its attention. Some mimicked its emotive expressions by rocking and bobbing their own bodies.
- **2+-year-olds:** These children first carefully observed the robot's behavior and how caregivers interacted with it. Soon they initiated social exploration by showing it toys, soothing it (by stroking its head), or verbally interacting with it (such as asking questions).

Fig. 7 A child seen from the subjective viewpoint of Keepon as the first person of the interaction

The differences between the interactions of each age group reflect differences in their ontological understanding of Keepon. The 0-year-olds recognized the robot as a *moving thing* that induced tactile exploration. The 1–2-year-olds first encountered a moving thing, but after observing the robot's responses to various environmental disturbances, they recognized that it was an *autonomous system* that possesses attention and emotion as the initiator of its own expressive actions. The 2+-year-olds, through the recognition of a "thing" and then a "system", recognized that Keepon's responses, in terms of attention and emotion, had a spatiotemporal relationship with their own actions; they thus recognized it as a *social agent* with whom they could play by exchanging and coordinating their attention and emotions.

3.3 Naturalistic Playroom Observation

At the preschool, we introduced the previously described wireless, manually-controlled Keepon into the playroom just like the other toys on the floor. We were interested in how these interactions would differ from the laboratory sessions, as a result of the both the natural setting and group

Fig. 8 Interaction between Keepon and typically developing children: a 2-year-old showing a toy and soothing the robot (*upper*), a 6-month-old touching (*lower left*), and a 5-year-old challenging the robot (*lower right*)

dynamics. We especially observed how various actions and their meanings to Keepon were expressed, exchanged, and shared among the children [31].

Throughout the observations, we recorded the live interactions from the subjective viewpoint of Keepon's first-person perspective. Strictly speaking, this subjectivity belongs to the operator; however, the interaction is mediated by the simple actions that Keepon performs, and every action can be reproduced from logged data. Therefore, we may say that Keepon is both a subjective medium (enabling indirect interaction with children) and an objective medium (through which anyone, including caregivers and professionals, can re-experience the interactions), enabling human social communication to be studied in a novel way.

A group of 27 children in a class of 3–4-year-olds interacted with Keepon in the playroom of their preschool. In each session, at around 8:30 a.m., one of the teachers brought Keepon to the playroom and put it on the floor with the 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 as she told a story, or it sat on the piano to watch the children sing or dance. The children showed various spontaneous interactions with Keepon, individually and in a group, and the style of these interactions changed over time. In Session 1 (hereafter S1), the children demonstrated shyness and embarrassment around Keepon, not knowing what it was and how they should interact with it. After S2, they gradually initiated a variety of behaviors toward Keepon—from hitting it to feeding it. Following are examples of various styles of play that Keepon experienced in the playroom:

- **Violent vs. protective behavior:** In S3, a boy TM (hereafter TM/m) beat Keepon several times, and a girl SR (hereafter SR/f) stopped him, "No! No!" In S9, when NR/m hit Keepon's head several times, HN/f stopped him by saying, "It hurts! It hurts!" In S13, FS/m and TA/m strongly hit Keepon's head a couple of times, as if demonstrating their braveness to each other. YT/f and IR/f, observing this, approached Keepon and checked if it had been injured, then YT/f said to Keepon and IR/f, "Boys are all alike. They all hit Keepon," stroking its head gently.
- **Caregiving behavior:** In S4, IZ/m pretended to feed toy food to Keepon. In S5, NK/f put a cap on Keepon. When the cap was gone, a YT/m put his own cap on Keepon. In S7, when it was lost again, TK/m and NK/f soothed Keepon, saying, "Did you loose your cap?" and "Try to get by without your cap." In S16, being away for a couple of sessions, NK/f came to Keepon and said, "We haven't seen each other for a while," as if easing Keepon's loneliness. In S17, after two girls hugged Keepon tightly, other girls found a scar on its head. NK/f pretended to give medicine to Keepon with a spoon, saying, "Good boy, you'll be all right." In S19, after playing with Keepon for a while, IZ/m asked other children nearby, "Please take care of Keepon." IZ/m managed to get an OK from KT/f, then left. In S21, when playing house, IZ/m introduced Keepon to TK/m, saying, "This is my child." When TK/m pretended to feed toy food, IZ stopped him, saying, "My boy doesn't like it." In S23, NZ/m noticed Keepon had a flu mask and asked Keepon, "Caught a cold?" NK/f then put a woolen scarf around Keepon's neck, and NR/m and YS/f asked NK/f, "Is he ill?" and "Does he have a cold?"
- **Demonstrative behavior:** In S6, KT/f played with Keepon in the outdoor playground; a boy in the 4-year-old class approached Keepon and said to KT/f (referring to Keepon), "This is a camera. This is a machine," but KT/f insisted, "No, these are Keepon's eyes!" In S8, pointing to an insect cage, SR/f guided Keepon's attention to it. During reading time in S11, NK/f and TM/m approached and showed their picture books to Keepon. In S17, YT/f taught Keepon some words—showing it the cap, she said, "say, *Bo-shi*," then switched to Keepon's knitted cap and said, "This is a knit *Bo-shi*, that you wear in winter" (to which Keepon could only respond by bobbing). In S25, NK/f gave a toy sled to Keepon. Keepon showed a preference to another toy NK/f was holding. After some negotiation, NK/f brought over another sled and persuaded Keepon, "Now you have the same thing as me."
- **Self-conscious behavior:** In S22, after all the children practiced a song with the teachers, several of them ran to Keepon and asked one by one, "Was it good?", to which Keepon responded by nodding and bobbing to give praise. In S24, NZ/m sang a song quietly for a while; when he noticed Keepon beside him, he became surprised and ashamed.

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 for interpersonal play with peers and sometimes with teachers. Since the children were generally typically developing, they often spoke to Keepon as if they believed it had a "mind." They interpreted Keepon's responses, although merely simple gestures and sounds, as having communicative meanings in an interpersonal context. We have never observed this with the autistic children (described below), who rarely interacted with their peers. Compared with the experimental setting (Sect. 3.2), where children became bored after 15-minute interactions, it is interesting that children in the preschool never lost interest even after 20 sessions.

4 Practicing Therapeutic Care

4.1 Autism Spectrum Disorders

It is notable that several of the research projects discussed in Sect. 2.1 have directly or indirectly worked with autism, a developmental, behavioral, and neurophysiological disorder caused by specific and mainly hereditary brain dysfunctions [24]. According to the major diagnostic criteria (e.g. DSM-IV [1] and ICD-10 [48]), people with autism generally have the following major impairments:

- **Social (non-verbal) impairment:** Difficulty in understanding, as well as indifference to, others' mental states, such as intentions and emotions exhibited by gaze direction, facial expressions, and gestures; difficulty in reciprocal exchange and sharing of interests and activities with others.
- **Linguistic (verbal) impairment:** Difficulty in linguistic communications, especially in pragmatic use of language; delayed or no language development; stereotyped or repetitive speech (echolalia), odd or monotonous prosody, and pronoun reversal.
- **Imaginative impairment:** Difficulty in maintaining a diversity of interest and behavior; stereotyped actions and routines; difficulty in coping with novel situations; absorption in meaningless details while having difficulty with holistic understanding.

"Childhood autism" is a subtype of broader "pervasive developmental disorders (PDD)." PDD is also referred to as "autism spectrum disorders (ASD)." Roughly speaking, a child will be diagnosed as "autistic" if he or she exhibits all three impairments before the age of three. Another major subtype is "Asperger's syndrome," marked by relatively good language skills (especially syntactic and semantic ones) but poor social interaction or imagination. When a child exhibits at least one of the three impairments, but does not meet the criteria for a specific subtypes of PDD (such as childhood autism or Asperger's syndrome) or other mental disorders, he or she will be diagnosed as having PDD. According to recent statistics [2], the prevalence of PDD is estimated to be 116.1 in 10,000, with autism accounting for 38.9 of that figure.

The impairments associated with autism or PDD limit the ability to exchange and share mental states with others. This makes it difficult for children to establish and maintain the social relationships necessary for learning language and other social conventions. Researchers in social robotics therefore often have a dual interest in autism: (1) the hope of better understanding the underlying mechanisms responsible for social interaction and its development, and (2) the recent promising evidence (discussed in Sect. 2.1) that robots can be effective in eliciting social behaviors in children with autism.

4.2 Keepon in a Therapeutic Setting

Our field site was a day-care center for children with developmental disorders, especially those with PDD (including childhood autism and Asperger's syndrome). In the playroom at the day-care center, 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 group of child, mother, and therapist), and sometimes in more organized group activities (e.g. rhythmic play and storytelling). In these dynamically and diversely unfolding interactive activities, the children's actions are observed, responded to, and gradually situated in the social context of everyday life.

As in the preschool setting, the wireless version of Keepon was introduced with the other toys on the floor. In their daily therapeutic sessions (three hours each), seven to eight combinations of child, mother, and therapist played in the room, where they sporadically interacted with Keepon. The initial position of Keepon varied in each session according to how other toys were arranged. 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.

For the past three years (over 100 sessions, or 700 child-sessions in total), we have observed over 30 children; some of the children enrolled in or left the center during this period. We describe here three representative cases [32], each of which best demonstrates the emergence of dyadic, triadic, and empathetic interactions.

4.2.1 Case 1—Emergence of Dyadic Interaction

The first case is a three-year-old girl, M, with autism. At CA 1:11 (chronological age of 1 year and 11 months), her MA (mental age) was estimated at 0:10 by the Kyoto Scale of Psychological Development. 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 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

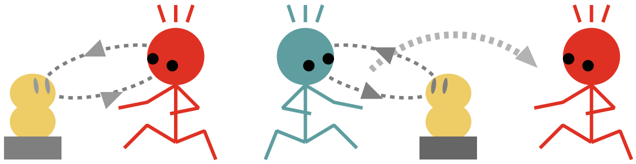

Fig. 9 Emergence of dyadic interactions: exploratory actions directed to Keepon (*left*) and interpersonally triggered/copied actions (*right*)

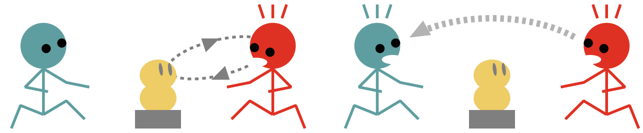

Fig. 10 Emergence of triadic interactions: the child discovers "wonder" in Keepon (*left*) and then looks at the partner to share this "wonder" (*right*)

same thing. When the therapist complied, M left Keepon with a look of satisfaction on her face. Through S5 to S10, her distance to Keepon gradually decreased to less than 50 cm.

– 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 vocalized 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 that M's persistent curiosity gradually reduced her fear of Keepon. We also see here the emergence of both spontaneous dyadic interactions (Fig. 9) [3, 43], such as touching Keepon with a xylophone stick, and interpersonally triggered dyadic interaction, such as putting a paper cylinder on its head. 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 [43] the same action and result.

4.2.2 Case 2—Emergence of Triadic Interaction

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 17 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 so.
– Through S2 to S14, N did not pay much attention to Keepon, even when she sat next to it. However, N often glanced at the robot when she heard sounds coming from it. The first touch was in S10.
– 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.

For the first five months (15 sessions), N did not appear curious about Keepon; even when N was held in her carer's arms in front of Keepon, she simply saw Keepon but did not act on it. After a three-month break, especially in S16 and S33, we witnessed the emergence of triadic interactions (Fig. 10) [43, 45], where Keepon or its action functioned as a pivot (or a shared topic) for interpersonal interactions between N and her mother or therapist. 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, where Keepon was the imitator and N was the model and probably the referee; however, this involved reciprocal turn-taking, which is an important component of social interaction.

4.2.3 Case 3—Emergence of Empathetic Interaction

The third case is a boy, S, with Asperger's syndrome with mild mental retardation (MA/cognition 3:2 and MA/langu-

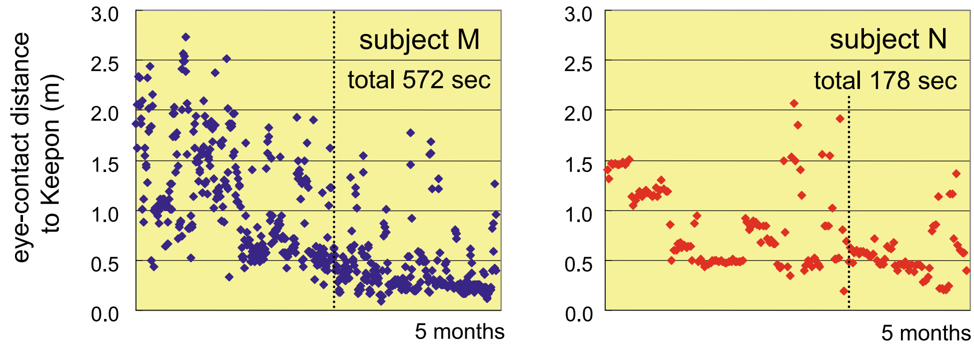

Fig. 11 Gradual decrease in eye contact distance between two children and Keepon plotted for the first five months of interactions (with total eye-contact time listed). The distance was geometrically estimated from (1) the distance between eyes, (2) the size of a face, or (3) the body height. The *dotted lines* represent when "first touch" occurred

age 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 knocked 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 a possessive attitude towards 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 good by saying, "Yummy?"
– In S15, Keepon wore a flu mask. S came up to Keepon and asked "Do you have a cough?" a few 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 to 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 S's relatively good cognitive and linguistic capabilities.

4.2.4 Discussion

Through our field practice, we learned that any therapeutic intervention presupposes that even autistic children possess the motivation for sharing and exchanging mental states with others, and that the challenge for therapists and parents is to elicit this motivation. The immediate goal of much therapeutic practice, therefore, is to improve not only the quality of the children's social (objective) lives, but also their personal (subjective) lives such that they can enjoy such social interaction with others. Although it is widely believed that this motivation is impaired in autism [44], we have observed in a number of cases that autistic children established social relationships with the simple robot, which was carefully designed to express its mental states comprehensibly. The children spontaneously engaged in dyadic exchange of attention and emotion with it, which then extended to interpersonal interaction with caregivers to exchange the pleasure and surprise they found in the dyadic interactions. They often showed vivid facial expressions that even their parents had rarely seen; sometimes they showed caretaking behavior such as putting a cap on the robot and feeding it toy food. This suggests that the "missing motivation" is *not* missing in autism.

For example, in Case 1, the autistic girl M at first avoided Keepon's gaze. As suggested by a brain imaging study [16], autistic children can emotionally over-react to someone's direct gaze even when the facial expression is non-threatening. According to her mother and therapist, however, M had never over-reacted to direct gaze from any person or animal, and she was rather indifferent to others' gazes and presence. However, in the first several sessions, M selectively over-reacted to Keepon's direct gaze. Meanwhile, however, M showed strong curiosity about Keepon, and this curiosity competed with her fear of direct gaze. As illustrated in Fig. 11 (left), M slowly but steadily got closer to Keepon, exploring what Keepon was and how it would respond to various behaviors, using her therapist as a secure base. As exemplified in Cases 2 and 3, some of the children then extended such interaction to triadic interaction, where Keepon functioned as a pivot for exchanging the pleasure and surprise they found in the dyadic interactions.

We assume that Keepon's simple appearance and actions helped autistic children perceive social contingency, or the presence of a "mind," in its attentive and emotive

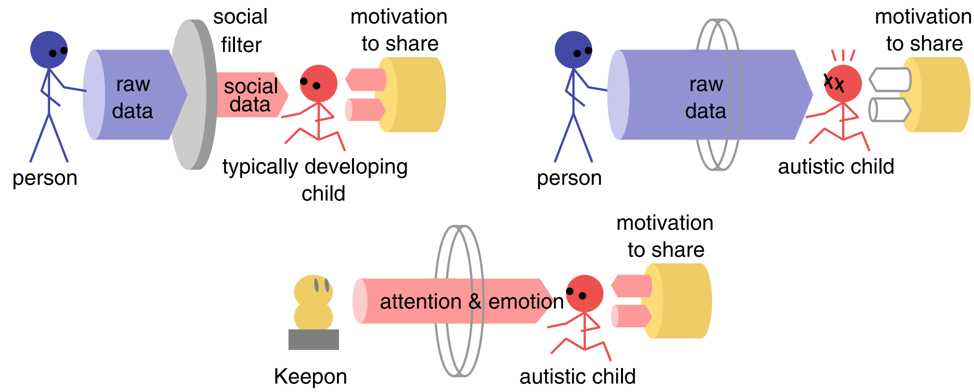

Fig. 12 The social filter in typically developing children (*left*), its possible dysfunction in autistic children (*right*), and the bypass channel produced by Keepon (*bottom*)

actions. We can intuitively consider a "mind" to be an internal process that selects a particular target from the environment ("attention") and displays a particular response ("emotion"). We propose that people normally have a *social filter* that extracts this basic information about attention and emotion from the flood of perceptual information produced by another person's behavior. We can look at autism as a failure of this filter, resulting in an overwhelming information overload. As discussed in Sect. 2, Keepon is only capable of expressing attention and emotion. This simplicity and comprehensibility might open a *bypass channel* (Fig. 12) through which children can directly perceive Keepon's attention, emotions, and therefore "mind" without being overwhelmed perceptually. The motivation for relating to others may be intact but difficult to activate due to a failure in sifting out meaningful information, whereas Keepon successfully activates the motivation by exhibiting only this meaningful information.

While we have presented three cases that are representative of the successful elicitation of social behavior from children with autism, it should be noted that these results are not to be considered "generalizable." Rather, they are meant to illustrate the potential for an appropriately designed robot to evoke rare but positive responses. In fact, given the vast spectrum covered by the term "autism," it is difficult to separate the efficacy of any therapeutic intervention from the variability and natural growth of individual children, or to expect similar behaviors or responses from any two children. Each child showed a different style of interaction that changed over time in a different way, which told us a "story" of his or her personality and developmental profile. We have been providing the therapists and parents with video feedback, which is a story about each child narrated from the first-person perspective of the robot, in order to establish a reference point for sharing and exchanging the caregivers' understanding of the children. The robot thus serves as a tool *during* the therapeutic sessions by enabling therapists to conduct a novel form of mediated interaction with the children as well as *after* the sessions by providing a recorded body of data that can be used by parents, therapists, and researchers in studying autism and in evaluating or tailoring individual children's therapeutic treatments.

5 Creating Rhythmic Interpersonal Coordination

In all of the described observations of interactions between Keepon and children, a common theme (in both the preschool and the therapeutic day-care center) is the use, and natural emergence, of rhythmic play. Sometimes this takes the form of structured music and dance sessions, and other times it is a property of repetitive or turn-taking behavior. Recently, we have been working to add a layer of *rhythmic intelligence* to Keepon's behavior, both in order to better participate in these forms of play (for educational, therapeutic, or entertainment purposes), and to add an additional channel (beyond attention and emotion) for nonverbal communication and establishing engagement between child and robot.

5.1 Interactional Synchrony

Interactional synchrony is the temporal coordination of communicative behaviors between interactors (often without awareness or volition) in order to achieve a sort of "goodness of fit" between them [7]. Along with intrapersonal, or self-synchrony (between a speaker's own behaviors and vocalizations), interactional synchrony was originally conceptualized as congruence between changes in a speaker's vocal stream with those of a listener's movements. This synchrony was discovered through video analysis consisting of frame-by-frame labeling of change points in the direction of bodily movements and segmented speech [10–12]. The definition of interactional synchrony has been organized and expanded into the following three components [4]:

– **Interaction rhythm:** Social interaction is rhythmically organized. These rhythms are the expression of the oscillatory neurobiological language of the central nervous system through learned cultural patterns of interaction [9]. Two or more people coordinate their rhythms,

achieving synchrony, through a process known as *entrainment* [10, 27], whereby multiple different rhythms converge on, or capture, each other. These rhythms that govern our interactive behavior are a fundamental precursor to our communicative development; human neonates move in precise and sustained synchronous organizations of change of movement with the articulated structure of adult speech as early as the first day of life [13, 14].
- **Simultaneous movement:** In addition to a correspondence between the frequency, speed, and tempo of interaction rhythms, interactional synchrony is characterized by the co-occurrence of movements, gestures, vocalizations, or body positions between two or more interactors [7]. This is often observed as simultaneous change in direction of movement in different body parts or segmentation points in a vocal stream [11]. In other words, while two rhythms may be synchronized in frequency, simultaneous movement furthermore implies that interaction rhythms are synchronized in phase. A purely reactive system cannot, theoretically, be synchronous in this way, due to delays in sensing, processing, and acting. It may be argued that one of the reasons for the rhythmic organization of social behavior is that it enables synchrony and simultaneous movement through *anticipation* on this short time scale.
- **Smooth meshing:** Meshing refers to the coordination of two or more interactors' behavioral patterns into a single, unified, meaningful "whole" [4]. The adaptation of an interactor's behaviors and patterns is seen to relate to the other's actions; for example, a listener nods and uses other backchanneling cues at appropriate times during a speaker's utterance [7]. The way in which synchrony varies in an interaction is related to the individuals' roles in the interaction. One's responses to the tempo of another individual's movement and speech may indicate engagement, disengagement, acknowledgment, or the assumption of the role of speaker. These joint changes in the nature of interactional synchrony have the important function of achieving "the delicate coordination of expectancies among participants, so essential to the smooth running of an encounter" [26]. On a longer time scale (e.g., of conversational turn-taking), this principle enables anticipation of changes in the interaction and the ability to guide these changes.

Given the important role of rhythmicity and synchrony in human interaction, it is clear that difficulties in establishing interactional synchrony can make face-to-face interpersonal communication and interaction difficult, if not impossible; in fact, certain social and developmental disorders have been linked (either as causal to or symptomatic of) a person's difficulties in establishing rhythmic interaction. Such disorders are frequently treated by therapeutic methods that specifically address these rhythmic difficulties. Music, dance, and rhythmic play, in addition to being widely used in standard educational practice from infancy to adulthood, are also well-established methods in treatment and therapy for a wide range of ailments, including autism/PDD and other physical, psychiatric, behavioral, and emotional disorders [15, 23]. Trevarthen and Malloch [46] speak of music as a communication of motives and experience, pointing out an inherent musicality in infant-parent vocal interaction. They discuss the use and impact of musical therapy in social development, arguing that music is therapeutic because it "attunes to the essential efforts that the mind makes to regulate the body, both in its inner neurochemical, hormonal and metabolic processes, and in its purposeful engagements… with other people."

5.2 Technology for Rhythmic Intelligence

The development of robust social intelligence requires new methods of perceiving, modeling, and behaving according to environmental and interaction rhythms. We are developing computational models of rhythmic interaction that accommodate multiple sensory modalities (such as audio, video, motion, and force) and allow a robot such as Keepon to behave (in terms of movement and sound) in synchrony with perceived rhythms. In line with the three components of interactional synchrony, rhythmic intelligence should enable robots to rapidly and effectively adapt to the rhythms of their interacting partners, to anticipate and follow changes in interaction rhythms, and to lead or guide interactions using changes in their own rhythms. We have implemented a system on Keepon that can perceive rhythms in a variety of modalities and can synchronize periodic dance-like movement to these rhythms. In initial observations, we have found that qualities of the robot's rhythmic behavior have effects on the behaviors of children.

In order to perceive rhythms in multiple modalities, we have begun to develop methods of extracting rhythmic information from movement and sound. For audio, we have used simple amplitude peak detection to identify clear beats such as the hitting of a drum. By measuring the time intervals between the most recent consistently spaced beats, we can track changes in the tempo of clear environmental beats. For isolating rhythms in music, we have integrated a more sophisticated beat detection algorithm [42] that uses band-pass filtering. For improving reliability in experimental scenarios, where consistency is important, we have also hand-labeled the beats in songs used as environmental rhythmic stimuli. For visual movement, we have used simple methods of detecting periodic movement through intensity variation and optical flow. We identify frames of interest by looking for peaks in average pixel intensity or changes in the average direction of movement. By treating these events as "beats" and identifying consistent spacing, as with audio, we can

Fig. 13 Keepon dancing with a child using visual movement detection (*left*). Keepon and the two toys used with the accelerometer (*center*): a stuffed rabbit (169 g, 290 mm long) and a soft paddle (137 g, 320 mm long). Keepon dancing with a child holding the paddle (*right*)

identify the frequency of periodic movement in the environment.

To overcome the difficulties of sensing human movement through vision, we have developed an additional system for detecting rhythmic movement through the use of a battery-powered three-axis accelerometer with wireless data transfer implanted in a toy (Fig. 13). Such a toy, in addition to providing cleaner data about physical movement, also gives children affordances for engaging in more physical, exaggerated, and rhythmic play. The accelerometer provides force data for three axes of movement. The magnitude of the overall acceleration is the Euclidian norm of the vector defined by these three values. We detect rhythmic movements of the toy by finding peaks in this magnitude. Since the sensor data is rather noisy, these peaks, or direction change points, are found from zero-crossings in lowpass-filtered data. We can then treat these direction change points as "beats" in the same way as musical beats or visual movement direction changes were described above.

5.3 Observations of Child-Robot Dance Interaction

We conducted a pilot study of Keepon's rhythmic interaction with over 200 children during an open house at our lab [34]. The robot was set up to synchronize its rhythmic movement to environmental movement as visually perceived using optical flow. Under these circumstances, due to imperfect perception (and great variability in children's movement), the robot was at times synchronized to the music and at times unsynchronized. We analyzed the effects of the robot's synchrony to music on children's interactive behavior (Fig. 13, left). We observed a wide range of modes of play stimulated by the dancing robot and used two methods of coding video from these interactions. The first method of applying per-child codes looked at (among other things) whether the robot was initially synchronized to music in the beginning of an interaction and whether, as a result, the child performed explicit rhythmic behaviors during the interaction. We found a significant positive effect of the robot's synchrony on the occurrence of rhythmically interactive play. Using an additional fine-grained time-based coding scheme in Noldus Observer, we found supporting trends in the durations of labeled activity. Such analysis is sensitive to our design of coding schema (which we are improving) and will, in the future, benefit from alignment with recorded system data (sensory input and control commands). These preliminary results indicate that rhythmic intelligence is both feasible and important for socially interactive robots.

More recently, we have been working to develop more experimental methods for evaluating the effects of rhythmic synchrony on engagement in an interaction [35]. Specifically, we are interested in the different ways that a robot might take an "active" or "passive" role in leading or following the rhythms of an interaction. In order to improve the perception of human movement, we used the accelerometer-instrumented toy as described, and prepared Keepon to synchronize its movements either to those of the toy or to the tempo of a number of prepared songs. A teleoperator followed a strict script regarding what to attend to (i.e., toy or faces) and when to switch between synchronizing the robot to the toy or to the music. Although we created a controlled scenario in which children experienced the same context for interaction, we found that the robot's novelty, the children's ages, and individual variance in attitudes made it difficult to consistently elicit the desired rhythmic behaviors. We believe that the holistic nature of social interaction requires that we allow each child's interaction to unfold naturally, with appropriate scaffolding from caregivers, if we want to control for a particular variable. In other words, we cannot entirely remove the bias of prior exposure to the robot due to the necessity for a period of introduction, as in the naturalistic settings of the preschool and therapeutic day-care center. These difficulties must be overcome in experimentally and quantitatively evaluating this technology.

Our work with rhythmic interaction has also resulted in a rather unique and significant kind of interaction between Keepon and people, mediated by the Internet. Videos of Keepon demonstrating its rhythmic movement became "virally" popular on video streaming sites and technology blogs during mid-2007. These videos have attracted millions of views, thousands of comments, and dozens of response videos that reveal a powerful resonance between Keepon's dynamic rhythmic movement and a general audience. Keepon's popularity as a character, and not just as a robot, suggests that our design principles for a robot to promote comfort and comprehensibility among children (even those with social difficulties) are equally effective, if not more so, in establishing engagement with adults.

6 Discussion and Conclusion

In Sect. 2, we described the design principles upon which Keepon's appearance and behavior are based. We believe that a robot's functional and structural complexity determine the predictability of its behavior. Although it can be difficult to control structural complexity, the functional or behavioral complexity of robots can easily be manipulated by gradually increasing (or freeing) degrees of freedom and by gradually introducing a dependence on physical and social situations to their behavior. By manipulating the structural and, especially, the functional complexity, we can tune the predictability of a robot's behavior to each child's cognitive style and developmental stage, providing a "zone of proximal development" [47]. When a child encounters a robot whose behavior has appropriate predictability for that particular child, he or she can approach the robot in a relaxed and playful mood and spontaneously start explorative interactions. The child might subsequently learn to predict and control the robot's behavior in terms of its dependence on physical and social situations.

In Sect. 3 we saw that typically developing children exhibit qualitative changes in their behavior with (and probably ontological understanding of) Keepon over the course of their development as well as their experience with the robot. They saw Keepon first as a "moving thing," then as an "autonomous system" to explore, and finally as a "social agent" to play with. Children's ontological understanding of a robot also depends on the complexity of its behavior. What a robot can perceive, and how the robot responds, changes the children's interactive "stance" [20] towards the robot. For example, a robot may exhibit periodic actions just like a clockwork toy, reflexive actions in response to some specific stimuli situated in the physical environment (e.g., movement of the child or other toys), or coordinated actions situated in the social environment (e.g., attention, emotion, and changing roles). This spectrum of complexity represents the predictability of the robot's action, or the action's dependence on internal and external information. It is necessary to conduct further research, perhaps in the realm of interactional synchrony, comparing responses to different levels of the robot's rhythmic contingency to environmental and social stimuli.

Interestingly, children had generally showed a great deal of anxiety and embarrassment towards Infanoid; however, with Keepon, they spontaneously approached it and started "tasting" its texture and motion, gradually entering into an explorative and social interaction with the robot. What caused this difference between Infanoid and Keepon? In the case of Infanoid, we assume that children first recognized individual motions of the arms, hands, eyes, etc., separately. Children had difficulty comprehending the gestalt, which requires not just effortful analysis of the information from each moving part, but an additional effortful integration of these meanings into a coherent "unity" characteristic of autonomous life. Keepon, meanwhile, is completely different from humans in terms of its appearance or form, but the simplicity of expressing only attention and simple emotions, combined with the life-like softness of the body, enables children and infants to intuitively understand the gestalt. The sense that the robot perceives and acts as we do serves to motivate children to explore and communicate with it. This is a prerequisite not just for child-robot communication but for any kind of human-robot communication.

In Sect. 4 we described our longitudinal observation of autistic children interacting with Keepon, where we learned the following:

- Autistic children, who generally have difficulty in interpersonal communication, were able to approach Keepon and gradually establish physical and social contact. Since the robot exhibited its attention and emotions in simple and comprehensible ways, children could understand the social meaning of the robot's actions without becoming bored or overwhelmed. When the complexity of the robot's behavior is appropriate for a particular child (somewhere between simple toy and complex human), it attracts his or her attention and elicits various social actions from the child. Children enjoyed this dyadic interaction 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 caregiver, built a relationship with the robot.
- Some children extended their dyadic communication with Keepon into triadic interpersonal interaction, in which the robot functioned as a pivot for sharing and exchanging their pleasure and surprise with caregivers. The robot could also attract a child's attention to another child who was interacting with it. As we witnessed in the case of M, each child curiously observed how others were acting on the robot and what responses they induced from it. For the child observers, the interactions between Keepon and other children were comprehensible because of their structural simplicity and functional predictability. Especially when another child induced a novel, interesting response from the robot, the observers would also feel pleasure and excitement.

Based on these empirical findings, which are somewhat contrary to common assumptions about autism, our major claims are that (1) simple robots with minimal and comprehensible expressiveness can facilitate a spontaneous exchange of mental states in autistic children; (2) autistic children therefore possess the motivation for this mental exchange; and (3) the major social difficulties that autistic children generally suffer from stem not so much from a lack of this motivation but rather from the difficulty in sifting out socially meaningful information (e.g. attention and emotion) from the vast incoming perceptual information. These hypotheses have to be investigated in further research.

In the therapeutic field, therapists and parents generally agree that autistic children possess the motivation for sharing and exchanging mental states. We observed that each of the children spontaneously enjoyed such interactions in a different style that changed over time, which told us a "story" about his or her individual developmental profile. These unique tendencies cannot be thoroughly explained by a diagnostic label such as "autism" or "Asperger's syndrome." The "story" has been accumulated as video data, which is being utilized by therapists, psychiatrists, and pediatricians at the day-care center to help tailor their therapeutic activities. We also provide the video data to parents in the hope that it may positively influence their own childcare.

Finally, our recent work in developing technology for rhythmic intelligence, described in Sect. 5, aims to situate a robot like Keepon more deeply in its physical and social environment by making it responsive to the subtle but fundamental flow of time in all of our behaviors. Robust, natural communication includes non-verbal aspects such as gestures and body posture. While some research has investigated these aspects of communication in human-robot systems, very little has been done to investigate the rhythmic patterns of synchronization that underlie much of our face-to-face interaction. We are developing a computational model of rhythmic synchrony that will enable a robot like Keepon to generate rhythmic patterns and to detect such patterns in people, so as to maintain engagement and to intelligently guide interactions. Movement and dance are also known to have therapeutic effects, and rhythm is an important component of many treatment programs for autism. One aim of our work in rhythmic intelligence is to use and evaluate interactional synchrony in the context of the therapeutic settings in which we have been working.

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 and 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 teleoperated) can certainly be applied to facilitating their social interaction and development.

Acknowledgements The authors are grateful to the therapists, children, and caregivers at Omihachiman-City Day-Care Centre for Children with Special Needs, especially to Yuriko Yasuda and Motoaki Kataoka (Kyoto Women's University). We are also indebted to Ikuko Hasegawa and the teachers, children, and caregivers at Hachioji Preschool at Omihachiman. We are thankful to Hiroyuki Yano (NICT), Daisuke Kosugi (Shizuoka Institute of Science and Technology), Chizuko Murai (Tamagawa University), Nobuyuki Kawai (Nagoya University), Yoshio Yano (Kyoto University of Education), Kazuhide Hashiya, Hiromi Kobayashi, Saori Tanaka, and Kentaro Yamamoto (Kyushu University), who collaborated with us in facilitating and studying child-robot interactions. Selma Sabanovic (Stanford), Robyn Cruz (Lesley University), Reid Simmons, Jodi Forlizzi, and Illah Nourbakhsh (Carnegie Mellon University) have provided valuable advice. This work was supported by JSPS grant #18330144 and a NSF Graduate Research Fellowship.

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