Playful interaction with Teo, a Mobile Robot for Children with Neurodevelopmental Disorders

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ABSTRACT
Teo is a mobile robot designed for children with Neuro-Developmental Disorder (NDD). Teo's behavior can be remotely controlled by the caregiver or autonomously activated by effect of internal sensors or an external depth sensor. Teo has a soft body that can react to different types of touch (e.g., hugs, punches, or slaps); it can move freely on the floor and can manifest emotional reactions (through light, sound, and movement effects). Our robot can be used for therapy-driven game-based activities as well as free play. The latter involve spontaneous interaction with Teo and free exploration of its affordances, to facilitate children's familiarization with the robot and to promote socialization, positive emotions, and self-expression skills. The paper describes the design of Teo and examples of free play activities that can be performed with the robot. We also report the main results of the exploratory studies that have been performed at 2 therapeutic centers and have involved 11 children with NDD, highlighting the benefits of free play with Teo.

CCS Concepts

• **Human-centered computing** → Field studies; Empirical studies in collaborative and social computing; **Accessibility systems and tools**; Empirical studies in accessibility; •**Social and professional topics** → People with disabilities.

Keywords

Human-centered Design; Human-Robot Interaction; Accessibility; Autism; ASD; Robot Design.

1. INTRODUCTION
The Neurodevelopmental Disorders (NDD) are a group of conditions with onset in the developmental period. They are characterized by a range of developmental deficits that frequently co-occur and vary from very specific limitations of learning and control of executive functions to deficits in social skills and intelligence, producing sever impairments in personal, social, academic or occupational functioning.

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The use of robots has been proven successful in many cases of subjects with different NDD forms, e.g., ADHD (Attention Deficit - Hyperactivity Disorder) [26] [27], or ASD (Autistic Spectrum Disorder) [4][5][9][22] and in several researchers the activities with the robot are shaped as games, especially for children [41][6]. Still, given the wide range of NDD conditions and the specific characteristics of each single subject, there is space for new exploratory experiences involving robotic interaction to enlarge the set of success stories and to identify new forms of therapeutic and educational interventions for this target group.
The papers discuss a robot called Teo that has been designed as a play tool for children with NDD of different ages and with different forms of disability.

Teo enables a wide range of game-based experiences and supports some play dimensions that are largely unexplored with this target group, such as (joint) movements in space, physical manipulation, and robot personalization. Teo is mobile, holonomic, huggable, and emotional. It is free of moving on the floor in any direction at a speed similar to that of humans in indoor environments. Its "natural" mobility has the potential of making the robot more easily accepted by NDD subjects and enables them to explore spatial relationships during robotic interaction. Teo's a soft body includes a set of sensors that detect various forms of body manipulation, such as hugs, caresses, slaps, and punches, and is equipped with sound speakers that support verbal communication, and colored LEDs. LEDs are not used for representation purposes (e.g., to represent eyes or mouth), but to provide a stimulation channel where light intensity, color, and rhythm can be explored. Teo also wears large buttons on its hat that enable intentional touch interaction, analogously to what done by existing devices used with ASD subjects [29]. The emotional reactions of the robot (e.g., in response to different forms of manipulation) are expressed by means of sound, light effects, or body movements. The set of stimuli offered by Teo contribute to create fun, to build an emotional bond with the robotic companion and to develop the awareness of cause-effect phenomena. Stimuli can be either controlled by the therapist or triggered automatically by effect of interaction (to relieve the caregiver from an attentionally intensive control of the child). Teo can be integrated with an external depth sensor (such as Kinect) that senses both the human player and the robot itself, to support shared activities involving full-body interaction in the physical space. Teo can be used alone or in combination with virtual worlds or characters on external digital displays (e.g., TV screen or projector) [12], which enlarges the gamut of activities that can be played with the robot. On screen multimedia contents as well as robotic behaviors and sequence or intensity of the stimuli offered by Teo are customizable by therapists to address the needs and preferences of each specific child. Some physical characteristics, namely, the face expressions, can be personalized by the children themselves.

The rest of the paper presents Teo and its set of integrated and customizable capabilities, and describes how it can be used for free play, according to the spirit of the LUDI COST project [1] we are taking part of. We also report about the exploratory studies performed at two therapeutic centers to elicit Teo's potential for children with NDD, and discuss the measured benefits of free play with our robot.

2. RELATED WORK

In the last years, a large number of researchers have investigated the application of robots for NDD subjects, mostly focusing on ASD children (e.g., [7, 15, 4, 5, 6, 22, 18]), and have explored how robotic interaction can help these subjects to develop skills needed for independent living.

Children with NDD, as most children, are attracted by technological devices, even more if these can react to their actions. One important trigger for this attraction is the recognition of previous happenings, which, in principle, could be supported by robots programmed to consistently react to stimuli. However, repeatability strongly depends on the reliability of the sensors as well as on the level of detail of the stimulus as perceived by the subject as trigger for the expected behavior. For this reason and, often, on therapists' explicit request, most of the robots used in NDD therapies are remotely controlled [30]. This approach gives the complete control of the person-robot interaction to the caregiver. Still, it requires frequent shifts of attention from the cared person to the robot, to make it actually perform the expected (re)action. Often, an additional operator is needed to help the therapist and prevent her from losing the correct relationship and connection with the subject under treatment.

In most cases, the experiences with the robot focus on a single type of task, such as imitation [19], communication or question answering [18], and the interactions with the robot are framed in a specific protocol to achieve a specific therapeutic goal. Few of the robots developed for NDD subjects can sustain free play, which involves spontaneous, intrinsically motivated, unstructured activities [10] and has a fundamental role for the child's physical, cognitive and social development [3], [17], [24]. Even when the tasks with the robot include gamification features, the subjects are often expected to follow a pre-defined path of actions and to be exposed to a pre-planned sequence of stimuli.

Many different shapes have been explored for robots in NDD contexts, from abstract ones to cartoon-like, to simplified humanoids, to realistic human-like faces [15]. Taking into account Mori's conjecture about the uncanny valley [16], and the difficulty of NDD subjects to interpret the multiple signals expressed by realistic human faces and body, it might be preferable for this target group to provide abstract shapes rather than realistic representations, while it is certainly important that the subject could easily understand where the robot is facing and "looking at".

Very few of the robots used in NDD therapy can successfully exploit movements in space, since they are either static (e.g., Kaspar [20], Keepon [13]), manipulable (to a certain extent) but not mobile (e.g., Paro [14]). In some cases (e.g., Nao [23]) they have a slow and clumsy movement that they easily become unbelievable and boring, so children lose attention in movement-related tasks. Interesting exceptions are IROMEC [19] and Labo-1 [5], and QUEBall [21], which explore the possibility to define space-related activities with children with ASD. Both IROMEC and Labo-1 are differential drive robots, have a rigid shape and limited movement possibilities, and run at a speed not comparable with that of a child, so reducing the opportunities of playful interaction in the physical space. QUEBall has a simple spherical morphology of a relatively small dimension and rolls while moving. It provides a wide range of movement, visual, sound and touch interaction capabilities to encourage the child to learn and play. Still, to enable rolling the plastic surface of QUEBall offers limited tactile affordances and stimuli.

Few cases explore long term robotic interaction through many sessions and master the complexity of maintaining and supporting the relationship between the robot and the user while following the evolution of the subject, adapting the robot's behavior and affordances accordingly [8]. Finally, to our knowledge no existing robot used in the NDD arena can be personalized by caregivers and by the subjects with NDD themselves, limiting the range of interaction opportunities and personalized interventions that robotic interaction can potentially offer in this field.

3. THE DESIGN OF TEO

3.1 Requirements

Teo's body and behavior have been co-designed by a team of two designers, four engineers and 15 therapists (psychologists, neuro-psychiatrists, special educators) from two different rehabilitation centers who have long-term, everyday experience of NDD subjects (children and adults). The NDD specialists, none of whom acquainted with robotics, have collaborated with designers and engineers along the entire development process. They regarded the robot as a possibly useful tool to improve their interventions with children with NDD, and presented their wishful thinking while technical people worked to implement it. By analyzing together a sequence of progressive prototypes, we finally came to the current version, depicted in figure 1.

The salient requirements on Teo's body and behavior are discussed below. Some of them match existing guidelines in the current state of the art in robotic interaction for children with NDD (mainly ASD). Other requirements are novel, especially those concerning the partially unexplored dimensions of physical manipulation and joint exploration of the space; they are derived from the therapists' experience and their reflections on the progressively generated prototypes.

Teo should play different roles while interacting with children with NDD. Extending the taxonomies proposed in [38], we have classified Teo's roles as follows. As *Rewarding agent,* the robot provides feedback and positive reinforcements to the actions performed by the child. As *Facilitator,* it suggests what to do and when to do it. As *Prompt,* it elicits behaviors enhancing the game play. As *Emulator,* it promotes imitative skills. As *Mediator,* it *mediates* the social behavior between the child and his play companions (e.g., caregivers or peers). As *Restrictor,* it limits the child's range of possible choices or constrains the possibilities of movement in the space.

The interaction with Teo should be multimodal and include both physical manipulation and joint (child + robot) movements. According to embodied cognition theories [25], manipulation and tactile experiences play a fundamental role in the development of sensori-motor capabilities as well as cognitive skills. Joint movements promote and motivate children to exercise perception and awareness of the physical space.

In response to child's interaction, Teo should offer different types of stimuli, both one-by-one and in a multisensory combination.

Clear feedback should be provided by the robot to answer to users' communicative actions, both to create engagement and to support the development of cause effect understanding, and

Teo's behavior should be consistent with some positive experiences already done by the subjects, to reduce the distress caused by unknown phenomena that is typical of NDD subjects. In particular, the shape of the robot should remind familiar shapes, possibly something that the subject likes, such as cartoon characters.

The physical aspect, interaction modalities and behavior of the robot should be strongly customizable, to adapt the interactive experience to the specific profile and evolving needs of each child. In particular, it should be possible to add or remove physical elements reminding human face or body, since they might be disturbing for some subjects. Enabling the children themselves to do some customizing activities may help to improve the relationship and confidence with the robot, which comes to be perceived as a creature of the subject.

3.2 Teo's body

The whole structure of Teo is about 60 cm high, a size that makes subjects (from 3 years old up to adults) confident to control and manipulate it. The structures are composed by the base and the body (Figure 1).

Figure 1: Left: An initial version of Teo, smaller, with velcro-attached eyes. Right: the final version, with magnetic pad.

The base consists of a robust, triangular, holonomic (omnidirectional) base, only 10 cm high (diameter 40 cm), and contains motors, batteries, electronics, a colored LED strip, infrared and sonar distance sensors. The base can move at a speed of up to 1.2m/sec. This gives Teo the possibility to perform unconstrained movements on the floor, which resembles the movement capability of human beings who have no problems in moving laterally or changing direction. Teo's kinematics, widely adopted in many robotic applications (e.g., for robotic soccer Robocup [39] or service robots like Pepper [40]) overcomes the limitations in speed, dexterity, and robustness intrinsic in existing humanoids (such as Nao [23]) and differential drive robots that are often used in robotic research in the ASD arena (e.g., IROMEC [14]).

Attached on the base there is the body, made of a cloth sack, about 50 cm high. Differently from other therapeutic robots that have soft bodies (e.g., Paro), Teo is "fully soft": it does not have an internal skeleton and is filled with polystyrene micro balls only. This soft body can be manipulated in a way similar to what is done with plush toys to enable tactile experiences similar to others already known by the subjects. The color of the body is pastel yellow, which has been selected to be enough attractive, but at the same time not too strong to disturb sensible subjects. Being the body just a sack, it is relatively easy to build it in different colors, would this be needed to adapt Teo to specific visual needs of a child.

A set of 400 mm long, single-zone Force Sensing Resistors (FSR) optimized for use in human touch control is embedded in Teo's back skin, to enable it to distinguish different types of touch. A Bluetooth speaker is embedded in the body to enable Teo's sounds or vocal output.

Teo wears a changeable hat. The hat can have either a well recognizable shape (like a cylinder hat), which rises expectations about having a face on the body, or a more neutral hemispheric shape, leaving the subject free to interpret it either as a hat on to of a head, or just as a component of a neutral body. The hat holds a set of big push-buttons used as interaction affordances, to enable children to express choices, to answer questions, or simply to trigger Teo's behaviors. Buttons can be personalized by therapists by inserting the tags that are more meaningful for the current activity, either realistic images or PCSs (Picture Communication Symbols, commonly used in AAC Augmented Alternative Communication interventions [11]).

The final shape of the body is a kind of ovoid, so that Teo can be considered as "just a new object", or something that be recognized as familiar and resembles what children might have seen in popular cartoons such as Minions or Barbapapa.

Inspired to Mr.Face (a play tool commonly used in NDD therapy), Teo is equipped with a set of a detachable pieces like eyes, eyelids, or mouths that can be attached to the body (using Velcro in the initial prototypes and a magnetic pad in the final version – see Figure 1). This feature makes it easy for the child to create their own version of Teo's face and expressions, e.g., to make the robot more similar to cartoonlike characters.

3.3 Teo's interactive behavior

Teo supports three main forms of full-body interaction, hereinafter referred to as Robot Manipulation, Robot + Child Interaction at a Distance, and Virtual World Joint Interaction.

Robot Manipulation involves the tactile contact with Teo. Teo's sensorized body can distinguish among caresses, hugs, and two levels of violent punches or slaps. Depending on the intensity and dynamics of the body deformation induced by the physical contact, the manipulation produces stimuli (*emotional multimodal expressions* [36]) that are intended to represent Teo's emotional states. Teo becomes *Happy* when its body is softly caressed or touched and replies to this pleasurable manipulation by vibrating, rotating itself cheerfully, and moving around, while a green colored light LED strip slowly blinks. Teo becomes *Angry* when its body is hit with moderate force; to manifest this emotion, it moves sharply towards the child, turning on all LEDs to red light. Teo becomes *Scared* when its body is brutally hit; it reacts by slowly retreating itself while LEDs become yellowish and pulse slowly.

In *Robot + Child Interaction at a Distance*, the child and the robot move together in the space; the user's movements or position trigger Teo's emotional effects that are similar to the ones above mentioned, and depend on the mutual distance, or the speed and direction of relative movements. As the distance sensors that are placed in Teo's body provide poor information, most of the needed data come from an external depth sensor (Kinect) that detects the presence and movements of the child and the robot when they are in the sensor's field of view.

Virtual World Joint Interaction takes place when the robot and the child are near a digital display or projection showing multimedia contents such as stories or characters. The depth sensor can detect the robot's and the user's position and movements, or the child's gestures. The integrated system triggers the proper effects in the virtual world according to the movements and positions of the child and the robot and the logic of the ongoing activity.

The execution of Teo's behaviors is performed in three modalities: *remotely controlled*, *autonomously reactive*, and *programmed*.

In *remote control* mode, the caregiver triggers the desired stimuli on Teo's body and drives the robot movements, states, and behaviors using a remote controller, as it happens for most existing robots used in therapeutic contexts. The remote controller can be a joystick, a tablet, or a Bluetooth pen [37]. With a tablet, the caregivers can actuate an additional form of verbal interaction, by selecting an utterance to be expressed by the robot (e.g., "Bravo!", or "Ehi!") from a built-in set, or by editing a text on the fly which is translated using a text-to-speech synthesizer. Still, a tablet makes the caregiver's role of control more evident and the experience less magic. A blue-tooth pen does not provide this verbal capability, but it can be easily hidden in the hand, giving the impression that Teo behaves autonomously. The remote control mode makes it possible to set up a countless number of experiences where the robot can act as a social play companion, without any apparent direct involvement of the caregivers who maintain their role of adult/therapist. Still, remote control is demanding for the caregiver. He or she must pay a constant attention to the child and at the same time must operate on Teo to maintain the emotional and cognitive connection between the child and the robot, controlling Teo in a believable and timely way and giving the impression that the robot is moving by itself and behaves consistently with the current context. This burden can be alleviated by leaving the remote control of the robot in the hands of a third trained person.

Teo operates in *autonomously reactive mode* when a play activity is suspended or not yet started, the robot is a "social presence" state, either *Waiting* and *Invitation to Interact* [28], and reacts to the presence of distant users. In *Waiting* state, Teo detects whether nobody is close enough and manifests that it is waiting for someone to interact with. This is expressed by slowly turning left and right on place (as if it was looking around), while blue LEDs around the robot base are dynamically turned on and off to simulate an analogous light movement. In *Invitation to Interact* state, Teo detects that someone gets close, and rotates towards the subject, verbally inviting him to play.

As a *programmed* robot, Teo acts autonomously as a play companion in the context of goal oriented, structured activities and behaves according to its role as defined in the current game [35]. Depending on the activity logic, the activity state, and the movements and positions of both Teo and the child, an external system drives the robot to specific areas, or activates light, audio, or vibration effects on Teo's body. At any time, the caregiver can turn the remote control "off", to make Teo act as an autonomous reactive agent and to relief the burden of controlling it, or "on", to create the best combination of stimuli for a specific subject and play context, modulating the multi-sensory stimuli that the experience with Teo may create.

4. PLAYING WITH TEO

A therapeutic session with Teo typically exploits all the above mentioned behaviors and interaction modes, and alternates moments of free play with the execution of structured play activities, while the therapist provides support when needed, outlines Teo's affordances, and takes or releases the remote control of the robot depending on the current context of play.

In *Free play,* the child can freely act in a framework given by the specific setting. Teo is typically controlled remotely by the therapists, eventually with moments in which Teo acts as autonomous agent. Free play involves the spontaneous manipulation of Teo and the exploration of the robot's physical affordances and the body interaction capability, as well as joint exploration of the physical space.

Structured play focuses on the development of specific skills according to the therapeutic plan of each child. Structured play activities are goal oriented, follow a pre-defined flow of tasks and offer a pre-planned sequence of (multisensory) stimuli. During structured play, Teo typically acts as a programmed robot (switching to remote control mode when needed) and exploits its *Virtual World Joint Interaction* capability, in synch with the interactive behavior of the virtual elements and characters in the on-screen or projected digital space.

A detailed description of structured activities is reported in [2]. The rest of this section focuses on free play activities, framing them in a model of intervention for children with NDD (depicted in Fig. 2) that has been defined in cooperation with the therapists consistently with existing theories and their current practices.

Figure 2: Model of intervention

The basic assumption of the model is that the learning process for children with NDD unfolds along a set of mental and emotional states that involve relaxation [31], affection [32], and engagement [33] (and a number of intermediate states) before achieving a condition in which the development of skills in the communication, social, affective and cognitive spheres can be actuated [34]. Free play is mainly devoted to achieve relaxation and affection, and to autonomous skill development, while structured goal oriented activities focus on the development of specific skills, and both of them attempt to achieve a state of engagement.

Relaxation is an emotional state of low tension in which anger, anxiety, or fear are absent. The deficits induced by NDD create a persistent state of insecurity, uncertainty, and inadequacy. This in turn originates anxiety, psychological rigidity, and resistance to any change in routine. Relaxation is fundamental to help children unlock these states.

As the presence of Teo in the playground affected is potentially worrying, the child must be helped to learn that this "object" is predictable and safe, and become confident that it is good, harmless, and inoffensive. This can be achieved through forms of free play that help the children to familiarize with this new thing that is Teo. They mainly involve the exploration and manipulation of Teo's body using all senses, the actuation of few light and sound stimuli, and the experience of Teo's movements remotely controlled by the therapist. Children are expected to progressively relax, but this state may remain episodic, unless a state of affection is reached.

Affection denotes a strong positive feeling of affective bond towards an entity. Children need to establish affection towards Teo in order to use it for a prolonged time and in a functional, goal-oriented way. While developing affection, children learn to feel emotions. Affection is thought to be an emotional trigger that helps children to further release remaining tensions and to fully embrace the challenge of "getting involved", so moving to the engagement state. To achieve affection, therapists typically may stimulate and facilitate forms of free play with Teo that promotes trust in the robot and create controlled stimuli that increase Teo's attractiveness and the child's willingness to experience the various affordances of the robot. For example, caregivers may invite the child to hug Teo, to move it around, to talk with him, to follow it while it is moving in the room, while they trigger the appropriate stimuli using the remote controller. The interactive behavior of Teo enabled by the *Robot + Child Interaction at a Distance* mode (either remotely controlled or autonomous) supports also other forms of free play for affection purposes. The child freely explores the space and the possibilities of interacting with the robot at the distance, without any specific rule or direction, and enjoys Teo's emotional reactions or its "Waiting" and "Invitation to Interact" behaviors.

Engagement is a state of active, voluntary involvement in an activity and the willingness to act upon the associated objects maintained for a (relatively) prolonged time. In children with NDD, this state can be achieved through forms of free play, alone or in group that promote pleasure, fun, and sense of control and ownership (agency). With typically developed children, engagement is typically regarded as a learning facilitator whereas, with children with NDD, engagement is a form of learning per se, and a precondition for the execution of structured, goal oriented activities. To promote engagement, the form of free play most used by our therapists involves the use, by the child alone or with peers, of the components that enable to personalize Teo's face. This activity also helps to develop the capability of emotion representation, emotion recognition, and self-expression, which are underdeveloped in many NDD subjects. Children direct and lead Teo's personalization in any way they wish and create their own character, possibly matching the emotional expression they believe is appropriate for the current situation of play and social situation. This composition game is so open that often results into an amazing assembly of eyes, mouth and other components, without any realistic face composition.

5. EXPLORATORY STUDIES

We performed two exploratory studies at local therapeutic centers to investigate the potential of Teo as a tool to help children with NDD learn through free play. Overall, the study involved 11 NDD subjects and the 5 specialists who take care of these children during the regular treatments at the centers. All caregivers are experienced therapists (physiologists, special educators, or neuro-psychiatric doctors specialized in NDD) who have been working with the involved subjects for at least one year on a regular base.

The total number of sessions with Teo was 43, each one involving in average from 10 to 15 minutes of free play. A dedicated room was instrumented in each center for the purposes of our research. In each session, one therapist worked with the subject(s) while at least one member of the technical team was present to offer technical support when needed. In study 2, an additional therapist participated as observant and took notes during each session.

The first study took place at a rehabilitation center specialized in children and adults with ASD, involving 2 therapists and 3 low functioning autistic children aged 3. Each child attended 9 sessions with Teo, on a weekly basis, for a period of 2.5 months.

The second study took place at a rehabilitation center that serves children with NDD aged 1-16. The participants were 3 specialists and 8 children aged 6-10 with different functioning levels (4 low-functioning, 3 medium-functioning, 1 high-functioning) and various disorders (Down syndrome, intellectual disability, ASD, Prader-Willy syndrome and psychosis). Children were split in two groups: those with most severe cognitive deficits played alone while children whose socialization problems were more severe than cognitive impairments played with a peer. Each child attended two sessions with Teo in two subsequent weeks.

5.1 Main results of Study 1

The therapeutic team at the center involved in study 1 created the evaluation protocol and defined a reporting form according to a set of behavioral variables and associated behavioral signals that are relevant for the activities to be performed with Teo. Variables were scored (1) for "absent", (2) for "emerging" and (3) for "present". Variables and signals are derived from the current practice, therapeutic approach, assessment methods, and underlying theories that are adopted in this center. A subset of these variables (the corresponding signals are omitted for lack of space) is described in Table 3. The therapist of each child who also worked with him or her during all sessions filled the form after each session.

The plots in Figure 4, derived from the analysis of therapists' forms, report the evolution of outcomes (y-axis) along the 9 sessions (x-axis) for each child C1, C2, and C3 and for each behavioral variable.

Cat	Var	Description
Robot Interaction	V1a	Initial Interaction: The child looks and grabs the accessories
	V1b	Advanced Interaction: The child uses the accessories in an appropriate way
	V2a	Verbal social communication
	V2b	Non-verbal social communication
	V3	Ability of manual exploration
Self - Expression	V4	Interest for something new
	V5	Manifestation of positive emotions
	V6	Capability of externalize own needs (e.g., to ask for help)
	V7	Manifestation of negative emotions

Figure 3: Main behavioral variables explored in Study 1

The results are not homogeneous, and the signal's values have some ups and downs, as it often happens with children with NDD. The enormous diversity of each individual's condition, even for subjects with comparable diagnostic profile, introduces many confounding variables that are difficult to control. So all results must be interpreted in light of the characteristics of each single child and the contingent situation of each session.

Among the three subjects, C1 is the one with the highest IQ and general profile; she has some verbal capability (but difficulty in articulating sentences) and can socialized with the adults. Both C2 and C3 (who are siblings) have severe cognitive and communication deficits, low capability of understanding and expressing verbal messages, very limited attention skills, and very seldom manifest any interest towards the proposed activities. These symptoms are more severe in C2 than C3.

Considering the limited number of sessions (9) and the relative short duration of the study (2.5 months) the therapeutic team considers the general trend as positive for all children. In particular, the benefits of even a relatively short term free play experience with Teo are stronger for subjects with more severe impairments (C2 and

C3), but up to a given level: When a deficit is too severe, it demands for a longer treatment, more structured and more focused.

All variables denoting positive behaviors either progressively increases for all children or remained invariant. Invariant values occur when, since the first session, the subject is scored either good/very good in the corresponding variable, or very low. This happens in a number of cases: in C2, for variable V1b (Advanced Interaction); in C1 for the variables V1a (Initial Interaction), V2b (nonverbal social communication), V4 (interest for something new) and V5 (Manifestation of positive emotions); in C2 and C3, for the variable V2a (Verbal Social Communication). The last results were somehow expected. C2 and C3 have such a limited verbalization capability that any improvement in this sphere would require a more intensive and specific treatment.

The variable denoting negative emotions decreases in C2 and has an increment in one session only, for C1 and C3, which the therapists ascribe to a problematic health state of these children during these sessions.

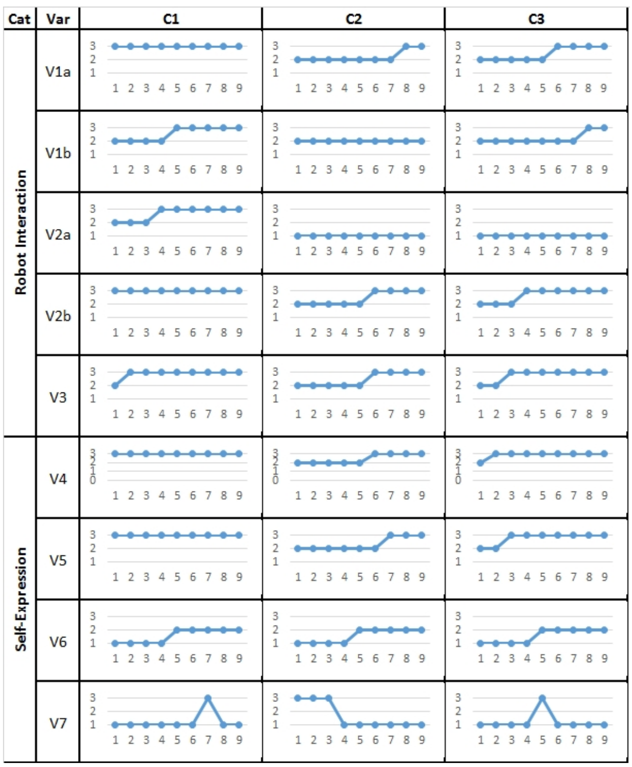

Figure 4: Key findings of Study 1

5.2 Main results of Study 2

In study 2, the results were elaborated from the analysis of video recordings of all sessions. The coding scheme for video analysis were defined by the team of all therapists at the center. Also in this case the coding schema (behavioral variables and corresponding signals) was based on the therapeutic approach, assessment methods and practice adopted at the center.

The variables are listed at the bottom of figure 5 (again, the corresponding signals are omitted for lack of space). The variables were also used also to structure the notes taken by the observed during the sessions. They differ from the variables considered in study 1, which is not surprising considering the enormous number of theories, methods, and practices that characterize NDD.

The video analysis was performed by an external independent rater (a psychologist specialized in NDD). The results were compared with the notes taken by the observer therapists. At the end, doubts or inconsistencies in the ratings were discussed with the therapeutic team, re-analyzing together the corresponding moments of the videos.

The diagrams in Figure 5 reports the final results and show the frequency of signals, calculated as the mean of the correspondent signals per minute. They allow us to compare the behavior of each child in the first and the second session, and the behaviors of those playing alone (C1, C2, C3, C4) against those playing in pairs (C5, C6, C7, C8).

As in study 1, and for the same reasons, the findings are not homogeneous. Still, also the therapeutic team at this second center judges these results as positive and promising. The specialists also pinpoint that the results have to be considered “as a whole” for each single child, highlighting how in some cases the negative values of some variables are balanced by the progresses of other ones.

Let us consider for example the two variables concerning Robot Interaction (RI): “Communication with Teo” (which is quantified on the basis of verbal or nonverbal communication signals directed to Teo, including sounds, words, sentences, or body movements such as pointing) and “Manipulation of Teo” (which considers the tactile experience with Teo’s body). “Communication with Teo” increases for most children regardless to the play modality. For C1, C3, C5 and C6 this variable has a steep increase from the first to the second session. It has slight decrease in C2 (playing alone) and a stronger decrease in C7 (playing with another child). “Manipulation of Teo” decreases in session 2 for all children except C1 and C5.

Overall, C1 and C5 had the highest increase of interactions with Teo in the second session, while C2 and C7 has the highest decrease.

C1 is a girl with severe Attention Deficit/Hyperactivity Disorder. She relaxed in few minutes after meeting Teo, and she was able to concentrate on it, performing different free play activities for 25 minutes, which was considered extremely positive by the therapists considering the nature of her disorder.

C2 is a girl with Down Syndrome who can speak but is usually not interested at all to the activities proposed in regular therapeutic sessions. Still, even if her verbal and tactile interaction with the robot decreased, in the second session C2 was the only child manifesting some form of creativity (meant as the ability to make new things with Teo that were not envisioned by the therapists and not explicit in Teo’s affordances). She created a new free game. She used the tie worn by Teo to pull the robot and move it around; eventually, she took another tie and waved it like a matador’s cape to induce Teo to catch her; at the end of the session, she showed to the next child how it was possible to play with Teo. As this behavior was unexpected, and unique, it was not comprised among the signals of Robotic Interaction variables, and was classified as “Creativity” (C).

C7 had a health problem in the second session, which may explain his decreases interaction with Teo. This state did not prevent him to feel happier, to manifest much more positive emotions, and to engage more in social play (S) than in the first session, as discussed later in this section.

Concerning Self-Expression (SE), one of the lacking capabilities in NDD, all variables - “Externalization of Needs”, “Positive

Emotions", and "Negative Emotions", show a positive trend in session 2 for both groups of children. In particular, all children manifested higher positive emotion, with peaks for C7 and C8 in the second group. In single play sessions, C3 and C4 externalized much more needs, i.e., requests of help from the caregiver. This is a positive phenomenon since it denotes an increased willingness to communicate with the adult and trust her. In session 2, Stereotypes (S) decrease in all children who manifested stereotyped behaviors also in session 1.

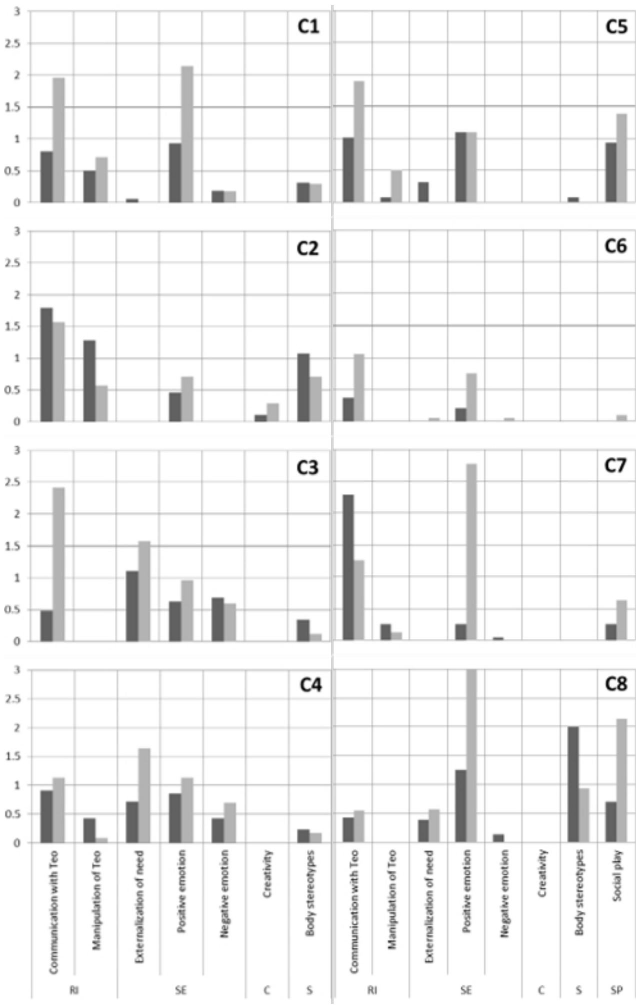

Figure 5: Main results of Study 2; Left - Children who played alone; Right - Children who played in pairs

Finally, we measured improvements also in the social sphere: Social Play (SP), which refers to playing with a peer and was obviously measured in the second group only, improved. Some examples of social behavior that emerged in the second session are the following. An autistic child (C7) called a mate to play with Teo: it was the first time he *explicitly* expressed the willingness to play in social mode. The "Mr. Face" activity performed in session 2 triggered an impressive pre-verbal communication process (depicted in Figure 6) between two medium functioning children with ASD (C5 and C6) who did not speak with peers nor look at each other during regular sessions. Initially, they stuck expressions on different sides of the robot, working in parallel, but ignoring each other. Eventually, C5 pushed down Teo. At this point C6 decided to stick an angry face on Teo and showed it to C5. Therapists unanimously stated that this kind of pre-verbal communication is an extraordinary step ahead for these children.

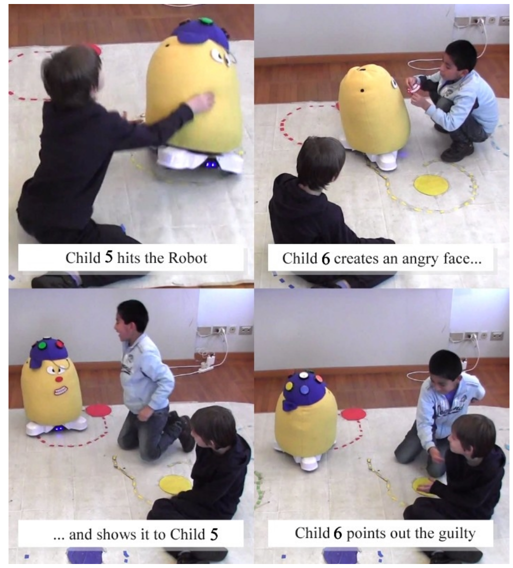

Figure 6: Pre-verbal communication between 2 autistic children

6. DISCUSSION AND CONCLUSION

In this paper we have presented Teo, a robot that can freely move in space and reacts to children's manipulations. Teo was co-designed by a team made of engineers, designers, and therapists in a highly interactive and iterative development process. We have discussed some free play activities that can be performed with Teo and described two exploratory studies aimed at evaluating the potential benefits of this robot.

The empirical results are preliminary and circumscribed, and should at present taken with caution for several reasons. As in most empirical research involving subjects with severe and multiple disabilities, causality relationships are hard to measure, and it is almost impossible to isolate all the potentially confounding variables that may influence the improvements process. Some positive effects are not present in all children. There is some variability in the way the technology was used in the contexts and sessions and with the different groups. We can only compare within session behaviors, and we don't know the degree to which what we measured during the activities with Teo can be translated to other contexts and moments of the participants' life.

In spite of the above limitations. all therapists involved in our study agree that free play with Teo has elicited operational behaviors, social interaction, and emotional responses that normally do not occur using other methods, or that require a much longer time to be achieved. They are quite convinced that the integration of robotic and full-body interaction in the space, with Teo's capability to freely move, to be manipulated in a natural way and to have multisensory reactions, paves the ground towards new forms of free play for children with NDD, and more generally opens new directions in the treatment of these subjects.

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