Puffy - an Inflatable Mobile Interactive Companion for Children with Neurodevelopmental Disorders

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Abstract
The paper describes the design of Puffy, a robotic companion for children with Neurodevelopmental Disorders that has been developed in cooperation with a team of therapists and special educators. Puffy has a combination of features which makes it unique with respect to existing robots for this target group. Puffy is mobile and its egg-shaped body is inflatable and soft. Puffy can interpret children's gestures and movements, facial expressions and emotions. It communicates using voice, lights, movements in space, as well as inside-out projections in its body.

Author Keywords
Neurodevelopmental Disorder; Children; Robot; Learning; Play, Disability

Introduction
Neurodevelopmental disorders (NDD) are disabilities associated primarily with the functioning of the neurological system and brain [2]. According to DSM-5 (The Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition [3]) NDD are "a group of conditions with onset in the developmental period. The disorders typically manifest early in development, often before the child enters grade school, and are

Figure 1. The inflatable body of Puffy

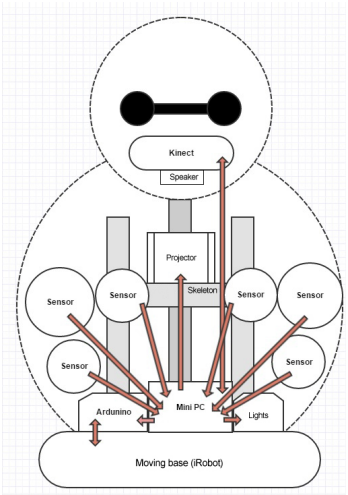


Figure 2. Puffy: Technology

characterized by often co-occurring developmental deficits that produce impairments of personal, social, academic, or occupational functioning. The range of developmental deficits varies from very specific limitations of learning or control of executive functions to global impairments of social skills or intelligence". Example of NDD in children include attention-deficit/hyperactivity disorder (ADHD, autism spectrum disorder (ASD), and intellectual disability (ID). Some studies highlight the growing percentage of NDD children, which has been substantially increasing over the last four decades [23][24].

NDD children are attracted by technological devices [5] and a vast body of research explores the use of interactive technology for this target group. Particularly, there are several studies on the use of robots for NDD interventions. Most of them focus on autistic children and investigate how robotic interaction can help these subjects to develop social, motor, cognitive skills [7][9][10][11][15][17]. This paper presents Puffy, a robotic companion that we have designed in cooperation with NDD specialists (Figure 1). Puffy is meant to support educational and therapeutic interventions for children with NDD, particularly those with perceptual and sensory processing impairments and deficits in the cognitive, social and behavioral spheres. The design of the physical and interaction characteristics of Puffy is informed by: i) general design guidelines reported in the current literature on socially assistive robots for autistic children [6][13][22]; ii) lessons learned from our own previous experience on robots for children with NDD [5][26]; iii) feedbacks and suggestions on the progressive prototypes of Puffy offered by a team of 15 therapists (psychologists, neuro-psychiatrists, and special educators) from two different rehabilitation centers who have long-term, everyday experience of NDD subjects (children and adults) and have been collaborating with our research in the last 5 years.

The Design of Puffy

The visual appearance of the robot, its affordances, multisensory stimuli, and behavior, are fundamental to attract attention, to promote trust, affection and engagement, to convey meaning, and to foster cause-effect understanding [9]. Puffy has a *combination* of features which makes it unique with respect to existing robots for this target group. It is *mobile* and its *egg-shaped big body* is *inflatable* and *soft*. Puffy can *interpret children's gestures and movements, facial expressions and emotions*. It communicates using *voice*, *music*, *movements* in space, as well as *lights* and *projections embedded in its body,* offering multiple stimuli for the different senses. Children's interactions associated to the stimuli and behaviors of Puffy are stored as time-stamped structured data which can be later analyzed by therapists. They offer a broad amount of automatically gathered information which otherwise would have been collected manually, and allow the caregiver to monitor and assess the children's behavior and progresses over the time. All the above features are enabled by the integration of various technological components embedded in the body of Puffy and attached to its rigid internal skeleton: an Arduino Uno, a mini PC, a Philips Hue Go smart light, a projector, a Kinect, several touch and pressure sensors, and an iRobot base (Figure 2).

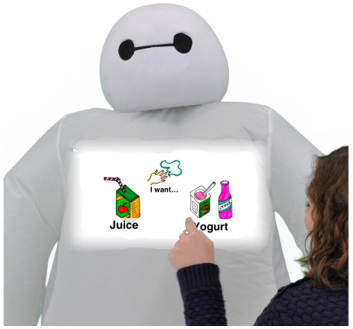
Body Shape and Fabric

Considering Mori's conjecture about the uncanny valley [48], and the difficulty of many subjects with NDD to

Figure 3.

Hugging Puffy

Touching Puffy (below)



interpret the complexity of the signals expressed by the human face and body, *abstract minimalistic "harmonic"* shapes are thought to be preferable to realistic human-like representations [20][21]. Some facial components would be included, particularly eyes, to facilitate the child's understanding of what the robot is "looking at" [15]. In addition, by practicing eye contact with the robot, children (e.g. with autism) who are uncomfortable in making eye contact with humans would be helped to generalize this behavior in human-human relationships. To facilitate eye contact with the robot [15], the most appropriate *height* for the robot should be approximately the average size of the target group. Considering the deficits in sensory integration and discrimination that affect our target group [19] the robot should *avoid* visual *overstimulation*, as the one created by the aggregation of (moving) components of different shapes [31] and multiple colors. Finally, the visual appearance of the robot should evoke a *familiar* element, possibly something that the subject likes such as cartoon characters, to mitigate the potential distress that the unknown often generated in subjects with NDD.

Taking these requirements into account, the body of Puffy has the familiar appearance of Baymax, the robotic protagonist of the popular cartoon "Big Hero 6". Puffy has a compact uniform structure, curved shape, and a wide round belly (Figure 1), which confer to Puffy a fluffy and warm appearance making it a reassuring figure that can be easily hugged and touched (Figure 2). Puffy wants to tower over the children with its 130 cm of height, playing the part of the gentle "big brother" as shown in Figure 3.

The body of Puffy is monochromatic. We have chosen the white color as it is neutral and, according to therapists, well accepted by all children with NDD. The plastic fabric of the body is very light, semi-transparent, and opaque. Lightness is a prerequisite for the most distinctive and innovative trait of Puffy, i.e., its being *inflatable,* while opaqueness and semi-transparency are needed to support light and projection effects.

Inflatable structure

According to Bicchi's analysis [4] the physical structure of robots is evolving from traditional rigid, heavy industrial machines into soft bodies exhibiting new levels of versatility, adaptability, safety, elasticity, dynamism and energy efficiency [5]. Inflatable robots have been recently adopted in some critical environments such as disaster relief and field exploration [32]. Still, their use among children, particularly those with disability, is unexplored, and Puffy is an innovation in the field.

Inflatable robots meet the requirements for robustness and safety that are needed for children with NDD. The soft lightweight inflatable body works as a sort of shock absorber in a case of an accidental strong collision or fall, and is less likely to cause harm during interaction with humans as well as it protects itself from a damage of devices equipped inside its body. In addition, the deformable structure offers manipulatory experiences that can be particularly engaging.

The body of Puffy is blown up by a fan located on the back (which also has a cooling purpose) and makes the robot soft to the touch and particularly suitable for being hugged and touched. The fan is also used to create controllable breathing effects by compressing or expanding the air inside, which can be used to convey the emotions of the robot, as described in the next section.

Mobility

Puffy has a fluent holonomic mobility, and is able to wander around, chase the child, and/or get closer, thanks to its 4-wheel base (the iRobot embedded in the body). Mobility is important not only to trigger engagement but also to develop spatial awareness skills, i.e., the appropriate perception of one's own body in the physical space and of the spatial relationships with other entities. It is worth noting that most assistive robots used in NDD therapy (e.g. Kaspar [12], Keepon [16], Paro [13], and SAM [26]) can be manipulated (to a certain extent) but are static, i.e., cannot move in the space. Two exceptions are Nao [33] and Teo [5]. While Teo has similar mobility features as Puffy, which were shown effective for spatial learning purposes among children with NDD, Nao has slow and clumsy movements, which may easily bore the child and reduce attention and curiosity towards movement-related tasks.

Visual Stimuli

Thanks to its embedded smart light, Puffy provides luminous stimuli visible through its white opaque body. Smart light can be digitally controlled to achieve a variety of luminous effects in terms of intensity, color and dynamics (e.g. blinking) (Figure 6). Light has the role of attracting children's attention and acts as a communication medium: to increase the perception of movement, to simulate a rhythm of heartbeat, and to convey the emotions and feelings of Puffy, as discussed in the next section. Puffy's body is used to display *visual digital contents* (images, videos, or animations) that are functional to task-oriented interactions (e.g., to provide instructions or feedbacks on task performance) or are used improve engagement and to convey emotional expressions (e.g., smiles). For similar purposes, rigid social assistive robots use a tablet, a PC screen, or a smartphone placed *on* the body [27], which could not be used in the soft deformable structure of Puffy. Our robot includes a compact projector embedded *inside* that projects the contents on its belly (Figure 3). The white opaque light weighted plastic material and the shape of the inflatable body result into curve-rounded projections with ambiguous borders, which create a pleasant aesthetic effect and a sense of magic. This is exploited in particular engaging during storytelling activities, described later in the paper.

Aural Stimuli

Through its speakers, Puffy offer two types of aural stimuli: voice and music. Voice is used to ask questions, provide verbalized instruction during a task, attract the child's attention, express attention to the talking child through backchanneling (e.g., Uh-huh, "Hmm", "Really?", "Wow"! [27], and tell stories (as discussed in the next sections). Music is played when Puffy detects a child's state of distress, to promote relaxation. Music is renowned to influence pulsation, accelerating or slowing it down, and to affect human mood. Puffy exploits a precise sort of music, played at the frequency of 432 Hz, the benefits of which have been proved by several studies [1]. According to Richard Huisken, a Dutch researcher who founded the "Back to 432 Hz" committee, "music tuned to 432 Hz is softer and brighter, giving greater clarity and softness. Many people experience more meditative and relaxing states of body and mind when listening to such music."

Interaction

Puffy supports *multimodal* interaction with the children. Thanks to the pressure sensors set in specific points of the body, Puffy perceives every physical contact and its entity,

and reacts accordingly. Embodied cognition theories [25] posit that manipulation and tactile experiences play a fundamental role in the development of sensory-motor capabilities as well as cognitive skills. Puffy can distinguish an affectionate, mild hug from a strong hit, and can react consequently, e.g., to communicate its gratitude or discomfort. For example, in response to a caress, the internal light becomes green (a color which is associated to pleasure), while the speakers emit pleasure sounds. When an inappropriate behavior is sensed, Puffy changes its "attitude", enlightening in red (a color which is associated to embarrassment and hurt) and complaining verbally. Thanks to the dynamic inflatable structure of Puffy, emotional clues can be expressed also through other body effects, to help children interpret the emotional states of the robot. For instance, Puffy inflates when it feels happy or confident, and shrinks when feeling depressed or scared.

Through the sensors embedded in the Kinect, Puffy can see the child and hear what the child says. Processing the child's position and movements in the physical space, her facial expressions, and her speech, Puffy identifies her mood and relational intentions, and reacts consistently through movement as well aural and visual stimuli.

In collaboration with the team of NDD specialists, we have sketched a model of *proxemics interaction* [30] which exploits spatial relationships (Figure 4) and is used by the robot to recognize the child's relational attitude towards the robot. The distance between Puffy and the child and their mutual positions are interpreted as predisposition ((or lack thereof) to interact. For example, if the child is facing Puffy from a distance of about 50 cm, the robot detects that the user is within a "personal" zone, where Puffy can easily reach her and start interacting (e.g., asking a question). If the robot locates the child in the "social zone", it emits sounds and lights to attract her attention.

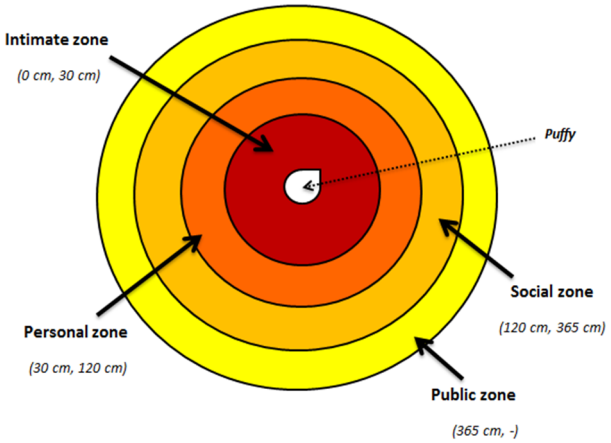


Figure 3. Model of spatial relationship

Learning through Play with Puffy

Puffy has been designed to support both free-play and task-oriented activities. Free-play consists of spontaneous interactions in which the children, individually or in group, explore Puffy, its affordances, and its reactions. Free play is constrained only by the physical affordances and action-feedback capability of the robot. According to our previous experience with Teo [28], free-play with a robot helps children with NDD to familiarize with the new object and to trust it, and promotes creativity and social skills. Task-oriented activities are more structured game-based learning experiences that aim at promoting specific skills. They are designed as flows of interactions, i.e., combinations of prompts (by the robot), actions (by the children), and stimuli (by the robot). Examples of task-oriented

Figure 4. Puffy narrating a tale

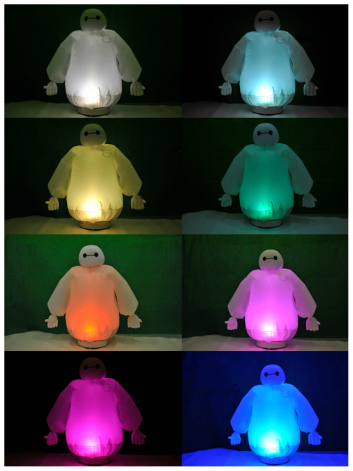


Figure 5. Puffy enlightened in different colors

activities with Puffy are "Make Your Choice" and "Storytelling", which mainly exploit aural and visual stimuli, and "Tag", which exploits the mobility capability of Puffy. Their design is inspired by some activities that are performed in the regular therapeutic practices at the centers we are collaborating with us, and, as it happens there, can be performed individually or in group, with the caregivers' supervision.

Make Your Choice

Puffy proposes to the children tasks that aim at promoting cognitive skills at different levels. These tasks have a similar interaction mechanism: Puffy asks a question, the possible options are visually shown through body projections, and a child makes her choice by touching the body of Puffy on the corresponding visual area. Some tasks are very simple and help the child with severe intellectual impairments to learn to make choices, to develop a sense of agency [29], or to practice with simple concepts, e.g., recognizing colors, shapes, or number. More complex ones which involve higher level skills such as memory or understanding abstract concepts.

Storytelling

There is abundant evidence, from the psychological and pedagogical literature, that listening, telling, and reflecting on stories promote the development of a wide spectrum of competences: expression, communication, recognition, recall, interpretation, analysis and synthesis [17]. Storytelling plays an important role also in educational practices for children with NDD [18], both as an individual and a group activity. It is regarded as a means to develop attention skills, to promote curiosity, to enhance generalization and to develop appropriate behavior. As many socially interactive robots [8], Puffy is a *storyteller*. While it tells a story aurally, relevant images are projected on its belly (Figure 5). To maintain engagement and attention, Puffy often takes a break and asks questions to its listeners about facts, characters, places, or objects appeared beforehand during the story. Two images for two different answers appear on its belly: a right and wrong one. A child should select the one hold to be true by touching the body on the corresponding image. The correct answer triggers a rewarding effect by Puffy ("Bravo!"), who then continues with the storytelling. A wrong choice results into an verbal invitation to try again.

Tag

In this activity, Puffy invites the children to play with it and start chasing one of them (randomly selected). This simple exergame aimed at fostering movement capability and developing spatial awareness.

Conclusion

Puffy is a robotic companion for children with neurodevelopment disorders (NDD) which provides a multi-sensory, engaging experience thanks to a unique combination of qualities: it is inflatable and mobile; it embeds lights and projections; it supports multiple forms of interaction, which exploit the robot capability of sensing and processing user touch, manipulation, speech, movement, and position and reacting with aural and visual stimuli. The design of Puffy has been informed by the requirements identified by a set of specialists in NDD and is grounded on our previous experiences with socially assistive robots [5] [28] as well as on results reported in the existing literature.

Still, the potential impact of integrating Puffy in regular interventions for children with NDD has yet to be proved. The strength and weakness of this robot for learning purposes among this target group will be tested in an empirical study at a center we are collaborating with, involving children with ASD, ID, and ADHD.

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