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Does the social robot Nao facilitate cooperation in high functioning children with ASD?

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Abstract

We designed a coordination-cooperation game dedicated to teaching the Theory of Mind (ToM) to children with autism spectrum disorder (ASD). Children interacted with either a robot or a human. They had to coordinate their gestures with the beats of a ditty sung by their partner (coordination), who then implicitly asked them for help (cooperation). Before and after this cooperation-coordination task, the children performed a helping task that assessed their ToM skills: the ability to infer social partners' intentions. Despite the regularity and predictability of the robot, children made the most progress in the helping task after interacting with a human. Motor coupling was more stable in child-human than in child-robot dyads. The ability of the social partner to

actively maintain a stable social coupling seems to be a primary factor inciting the child to learn and transfer the just-practiced social skills.

Keywords: autism, interpersonal coordination, relative phase, theory of mind

1 Introduction

Autism spectrum disorder (ASD) is a pervasive neurodevelopmental condition diagnosed based on two behavioral markers: impairments in social communication and interaction, and restricted/repetitive patterns of behavior and interests [1]. The disruption of social skills was recently ascribed to a lower reward value of social stimuli [2]. According to the social motivation theory of autism, because the brain's reward system is only weakly activated by social reinforcement, persons with ASD prefer to interact with objects rather than humans [3], gaze at non-social rather than social patterns [4], and receive non-social rather than social rewards [5].

Another possibility is that the social impairments in ASD originate from abnormal sensory processing [6]. Perception in ASD is disturbed by enhanced attention to details [7], reduced ability to capture relationships [8], painful sensory overload [9], and weak tolerance of high-variance sensory data [10] [11]. Humans constituting the most complex, varying, and unpredictable type of sensory input, firsthand accounts of persons with ASD often ascribe their social disturbances to the challenges entailed by the perceptual processing of human stimuli [12] [13]: *Ian [a person] was a jigsaw of bits that my mind was in no state to make sense of as a whole.* [14]).

Because of the above-mentioned motivational and perceptual particularities of ASD, it is often thought that robots might help children with ASD [15] [16]. The appearance of robots is simple, their behavior regular and predictable, and their motivational value potentially enhanced, making them promising avatars of human partners, capable of reducing the barriers to social relations in ASD [17] [18] [19]. To assess the advantage of these features, we compared here a robot-delivered to a human-delivered educational intervention, where children with ASD engaged in a motor game dedicated to facilitating the subsequent practice of social skills. To complete this endeavor, we borrowed tools from social robotics [20], perception-action framework [21], and complex system theories [22].

1.1 Social Robots and ASD

Since the pioneering studies by Emanuel and Weir [23] and Dautenhahn [24], nearly 40 social robots have been used to assist persons diagnosed with ASD, including Robota [25], Keepon [26], Kaspar [27], IROMEC [28], Flobi [29], Nao [30], Probo [31], Kibo [32], QTrobot [33], Leka [34], and Daisy [24] (see [34], for a list). Observations showed that children with ASD readily interact with

these machines, and indeed turn more frequently to robots than to humans (e.g., [35] [34]). This is important: capturing the child's attention is an essential and often exhausting task for the educator.

Until recently, however, data supporting the efficacy of social robots did not fully convince the end-users. The key problem is that supportive evidence mostly came from technical reports, marred with methodological flaws (see [35] [36] [37][38] [39] [40] [41] [42]) disagreeing with the methodological standards of health services [43] [44]. Hence, today's challenge in social robotics is to reach a consensus on research priorities, methodological gold standards, and practical constraints stemming from various disciplines striving to develop robots-assisted interventions for ASD [41]. Aware of the enormity of the challenge, and the immaturity of our attempt, we designed a pilot study testing whether the humanoid robot *Nao* can facilitate the learning and transfer of a key social skill: inferring a social partner's mental state.

1.2 Theory of Mind

In psychology, the ability to infer others' mental states is referred to as the theory of mind (ToM)[45]. For a long time, a ToM impairment was viewed as the primary deficit in ASD [39]. In young children, the ability to infer others' intentions may be experimentally assessed with a *helping task* [46] [47], a method recently used with children with ASD [48]. The child witnesses a scene where an adult apparently struggles to achieve a goal (e.g., he/she accidentally drops a marker on the floor and unsuccessfully reaches for it). Typically developing (non-ASD) children aged 18 months spontaneously help the adult by handing him/her the object [47]. This behavior is interpreted as manifesting the ability to infer the adult's intention. In this study, the typical helping task was administered by a human both before and after the educational intervention, following the prepost experimental paradigm.

In ASD, ToM acquisition seems to be delayed [49] [47], calling for educational interventions. To improve ToM skills involved in the helping task, we designed an educational intervention dedicated to practicing the inference of others' intentions. During a practice trial, the partner (robot or human) implicitly asked the child to find an object (*Is my book over there? I can't find it*). The child was expected to infer the partner's intention and to bring him/her the required object. If the child did not cooperate, the implicit request changed to an explicit one (*Is my book over there? Help me, please*). In any case, if the child brought the required object, the partner rewarded him/her with praise, in line with the principles of applied behavior analysis, ABA [50]. ABA advises dividing learning into discrete training trials and providing a reinforcer immediately after the desired behavior. It also emphasizes the effectiveness of rewards and cautions against keeping the learner in a prolonged state of failure. Below, this teaching method is referred to as a *cooperation task*.

Due to the perceptual simplicity and motivational appeal of robots, they can serve as effective social mediators, facilitating children's understanding of other humans. Specifically, children with ASD are expected to show greater

progress in inferring the intentions of their human partners when the educational intervention is led by the robot Nao, as opposed to a human. Therefore, we anticipate that *the improvement in the helping task, administered by a human, will be larger after participating in a cooperation task led by Nao compared to one led by a human.* (Hypothesis 1). All hypotheses are listed in Table 1.

1.3 Perception-Action Underpinnings of ToM

To help children to progress in the helping task, we examined the mechanisms of ToM through the lens of perception-action theories. In this framework, the premise is that people do not have direct access to others' intentions, and thus must infer them from the observation of others' gestures [51] [52] [53] [54] [55] [56], as evidenced by a bulk of experimental data on non-ASD individuals [57] [58] [59] [60] [61] [62] [63]. Non-ASD infants poorly infer the intended result of observed actions that they cannot yet perform on their own (ex: [55]).

More specifically, the inference of others' intentions relies on the perceptual-motor *coupling* between observed and practiced gestures [64]. This coupling is thought to take place in the mirror neuron cortical system, which fires when a typical individual performs, observes, or anticipates goal-directed gestures [65] [66] [67] [68]. This mechanism is especially involved in interpersonal coordination tasks, where two perceptually coupled persons act in coordination: they walk, sing, dance, or clap hands together (see Figure 1, left panel) [69] [70]. When the coupling is stable, social behaviors are enhanced (see [71] for review). Synchronous coordination pattern generating the most stable coupling of all [72] [73] [69] [70], typical (non-ASD) children who had just coordinated in synchrony were more inclined to help their partner than children who had

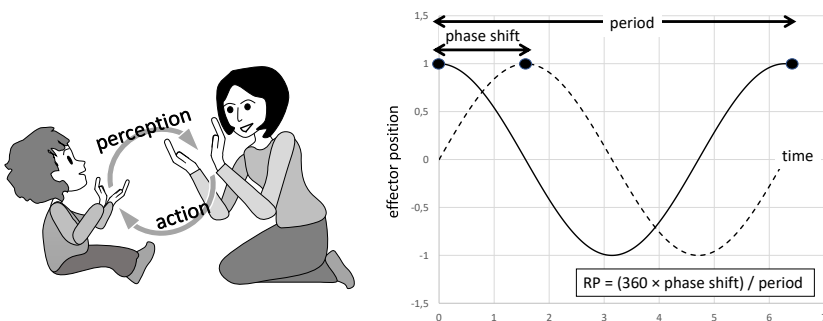


Fig. 1 Perception action coupling (left panel) and computing of relative phase (right panel). See the text for further explanations.

Just before the cooperation task, we involved the children with ASD in a *coordination task* where they had to synchronize a simple gesture, namely a

button press, with the actions of their non-ASD partners. We expected *there should be a relationship between the pre-learning coordination skills of these children, and the effect of our educative intervention, assessed by the progress in helping task* (Hypothesis 2).

1.4 Coordination-cooperation paradigm

In ASD, the perceptual-motor coupling is flawed: persons with ASD, known for their motor anomalies [78] [79] [80] [81] [82] [83] [84] [85] [86], produce less stable coordination patterns than their typical counterparts [87] [88] [89] [90] [91]. We aimed to enhance interpersonal coupling stability by increasing the regularity of partner's motion. Making itself regular and predictable is a powerful strategy to enhance coordination in any task [92] [93] [94]. Our key hypothesis is that *robots, being regular and noiseless like a metronome, would encourage coupling stability in interpersonal coordination task* (Hypothesis 3) and thereby facilitate the learning of ToM skills in subsequent cooperation task.

During our educational intervention, we administered a new coordination-cooperation paradigm, involving a coordination task immediately followed by a cooperation task in each trial. The coordination task was dedicated to forge the child-partner coupling and the cooperation task to practice and learn cooperation skills. During the cooperation task, children with ASD were given an opportunity to produce a simple, well-known gesture in synchrony with a social partner. The partner sang a ditty, where s/he complained about losing an object (*I am always looking for what was in there*). The child was instructed to beat the rhythm of the melody. The melody was paced by a signal, regular in the Nao group, where it was produced by the robot, and variable in the human group, where it was produced by intrinsically varying human. In both conditions, the melody started by ten regular pacing signals providing a baseline for coordination skill.

1.5 Coordination Assessment

The quality of coordination is a feature invisible to naked eye. Kelso's group showed that coordination is reliably measured by the *relative phase* (RP; [95] [96], an index quantifying how much one partner lags behind the other in each movement cycle, and expressed in degrees (see Figure 1, panel B). In dyadic coordination, when the co-actors are in synchrony RP is close to zero. If coordination is stable, only small moment-to-moment variations in RP are noted during a trial. If it is accurate, there is little divergence between the required RP and actual RP [97] [98] [99].

A closer look at coordination can also inform us about the leader-follower strategy adopted by the partners [100] [101]. Previous studies among typical individuals had shown that socially skilled persons display the follower strategy [102], as following a partner allows for greater monitoring of the other's actions, and thence greater self-other integration [103]. We expected that *children with*

ASD who displayed the best social skills adopt the follower strategy (Hypothesis 4).

To sum up, we proposed here a preliminary study attempting to compare a robot-led to a human-led educative intervention. We expected children interacting with Nao would produce more stable and accurate RPs and would make more progress in helping task than children from the control group (Hypothesis 1 and 3). We also made hypotheses about the relationship between motor and social skills in ASD. First, children who initially displayed the best motor skills would progress furthest in the helping task, second, children who initially displayed the best social skills would adopt the follower strategy during coordination (Hypothesis 2 and 4). We finally expected that *children who involved themselves in the coordination task (i.e., who produced the required number of coordination patterns) would display the most progress in the helping task* (Hypothesis 5).

Table 1 Hypotheses and experimental results

Hypothesis	Experimental evidence
1. Children with ASD make more progress in helping tasks in Nao rather than in control condition.	On the contrary, children progressed in control condition only.
2. There is a relationship between progress in helping task and motor skills in ASD.	Yes, there was a positive correlation between progress on the helping task and scores on the DCDQ evaluating motor skills.
3. Robots, being regular and noiseless like a metronome, encourage coupling stability and accuracy in interpersonal coordination tasks.	Stability of coordination was higher but its accuracy lower when the child interacted with the human rather than with the robot.
4. Children with ASD who displayed the best social skills to adopt the follower strategy.	Yes, children with the best autonomy skills tended to follow rather than lead coordination.
5. Children who involved themselves in the coordination task would display the most progress in the helping task.	Yes, children who produced more coordination patterns performed better on the posttest helping task.

2 Method

2.1 Participants

The study sample comprised 23 children with a mean age of 60.52 months (SD = 16.19). All participants had been diagnosed with ASD based on the Autism

Diagnostic Interview-Revised [104] and Autism Diagnostic Observation Schedule (ADOS [105]) criteria, and on expert clinical judgment in accordance with DSM-5 guidelines (American Psychiatric Association, 2013).

They were recruited at a private diagnostic center. They were randomly assigned to either the experimental group (N = 13 interacting with Nao) or the control group (N = 10 interacting with a human). After the exclusion of two children from the Nao group, one because of low age (38 months) and one because of low motor skills (25 in DCDQ), the two groups were homogeneous in terms of age, IQ, and social, motor, attentional and learning-related skills (see Table 2). The Nao group included thus N = 11 and the control group N = 10 individuals, falling in the range of sample sizes of robot studies (ex: [106][107][40]). The male female ratio was 3.6:1, mirroring the male-female ratio in autism (4:1 or 3:1; [107]).

All participants had IQs in the typically developing range (ie. higher than 70, see Table 2). They were native French speakers, had normal or corrected-to-normal eyesight, normal hearing, and no history of birth complications, and were not receiving any medical treatment. All the children underwent a medical examination to exclude neurological and psychiatric diseases and attention deficit hyperactivity disorder (ADHD).

The experimenters were five psychology students, all females, in their final year of postgraduate studies dedicated to ASD. They were specially trained to administer the coordination cooperation learning paradigm and accompanied by a clinical psychologist specializing in ASD. The experimenter who sang Nao's song in the control condition was a musician.

The study was approved by the research ethics committees in Toulouse (CERNI-2016-003). The families of all the children received a letter explaining the goals, the experimental procedure and the rights of parents and children, and provided their written informed consent in accordance with the Declaration of Helsinki. A declaration of collection and storage of data was also made to the French Data Protection Authority (CNIL; ref.: 7e42415863j). Written informed consent was obtained from the individual(s) or the individuals' legal guardian/next of kin for the publication of any potentially identifiable images or data included in this article.

2.2 Material

2.2.1 Psychometric tests

To capture the characteristics of the children with ASD, we administered seven psychometric tests (see Table 2). Indications of perceptual and verbal reasoning were yielded by a *progressive matrices reasoning test* and a *similarities test*, both drawn from the *Wechsler Intelligence Scale for Children IV* [108]. Social and communication skills were captured by the *Social Communication Questionnaire* (SCQ; [109]) adapted to French by Kruck et al. ([110]). Reciprocal social interaction was evaluated by two tasks drawn from ADOS2

Table 2 Psychometric Tests. Psychometric tests, their interpretation, mean and SD for each group, together with the results from t-test. The expression 'score <70: delay' or 'score >70: disorder' means that a score lower or higher than 70, respectively, should be interpreted as a sign of delay. The difference between human and Nao group of children gave no significant results (ns), as documented by the p-values, all above 0.05

Test	Assessed skill	Score interpretation	Human		Nao		t	DF	p-value
			Mean	SD	Mean	SD			
Age			64.636	18.554	56.300	10.945	1.237	19	0.231
WISC.Similitudes	Verbal reasoning	score <70: delay	9.182	5.382	8.200	4.590	0.447	19	0.660
WISC.Matrices	Perceptual reasoning	score <70: delay	8.273	4.650	8.500	3.100	0.130	19	0.898
ADOS:Interaction	Reciprocal social interaction	score >8: disorder	6.000	3.578	4.400	4.061	0.960	19	0.349
SCQ	Autism score	score >15: disorder	15.273	3.636	15.600	4.3	0.189	19	0.852
Helping task	Understanding of partner's intentions	higher: better	11.864	3.675	11.080	2.417	0.571	19	0.575
VABS VRP	Interrelationships	higher: better	13.636	2.908	12.900	3.604	0.518	19	0.611
VABS VPL	Play and leisure	higher: better	14.364	3.957	13.000	5.077	0.690	19	0.498
VABS VA	Adaptive skills	higher: better	10.545	4.059	11.900	3.957	0.773	19	0.449
VABS VP	Autonomy	higher: better	11.909	4.230	11.200	4.849	0.358	19	0.724
Conners C1	Behav. difficulties	score >70: disorder	48.909	9.300	49.600	12.997	0.141	19	0.889
Conners C2	Academic difficulties	score >70: disorder	80.455	26.901	76.100	31.737	0.340	19	0.737
Conners C3	Physical symptoms	score >70: disorder	62.182	23.237	57.500	17.977	0.512	19	0.614
Conners C4	Impulsiveness	score >70: disorder	60.273	7.115	52.100	8.386	2.416	19	0.026
Conners C5	Anxiety	score >70: disorder	55.182	11.250	48.100	8.425	1.619	19	0.122
Conners C6	Hyperactivity	score >70: disorder	66.545	11.986	57.000	10.392	1.940	19	0.067
DCDQ	Motor skills	score <55: disorder	41.636	9.277	50.000	13.630	1.658	19	0.114

([105]): we refer to them thereafter as to ADOS-Interaction. Social adaptability was assessed through the *Vineland Adaptive Behavior Scales* (VABS) Second Edition Vineland-II [111], using the subscales evaluating interpersonal relationships, play and leisure time, autonomy, and adaptive skills. In addition, *Conners' Parent Rating Scale* [112], a diagnostic tool for attention deficit hyperactivity disorder (ADHD) was used to check for behavioral and academic difficulties, physical symptoms, impulsiveness, anxiety, and hyperactivity symptoms. Finally, an indication of motor functioning in everyday life was provided by the *Developmental Coordination Disorder Questionnaire* (DCDQ'07; [113]). All psychometric tests are listed in Table 2, which indicates the skill being assessed (second column) and the interpretation of the score (third column).

2.2.2 Helping task

Eleven objects were used for the helping task: paper ball and trash can, remote-controlled car, bookshelf and book, magnet, picture and pen, pencil case, and jacket and scarf.

2.2.3 Robot and pushbutton

Nao is a programmable humanoid robot developed by Aldebaran Robotics, a French robotics company. Weighing 5.4 kg and measuring 574 mm high, it can speak through two loudspeakers and produce gestures, with its 25 motors controlling 25 degrees of freedom (DOF): 11 DOF for the lower part, including the legs and pelvis, and 14 DOF for the upper part, including the trunk, arms and head. Nao is equipped with two cameras, four microphones, joint position sensors, and an inertial board with fall manager. Its main CPU is an Intel ATOM 1.6 GHz CPU running a Linux kernel. In this study, each robot action was programmed in Choregraphe 2.1.4 and Python 2.7, under the Windows 7 operating system.

To record the children's motor responses, the computer was connected to a 10-cm diameter Arcade pushbutton whose on/off state was recorded through a SparkFun Redboard. The acquisition board sent a 9 600 bps digital signal to a Hewlett Packard computer (Windows 7, Intel Core i5, 3.3 GHz), which stored the data for further analysis. All the experimental events and robot actions were controlled by the same computer, and a Python script synchronized their timestamp in microseconds using the system clock.

2.2.4 Nao's song and objects to be found

Nao's song was composed of a refrain and eight verses, sung a cappella to the tune of *Twinkle, twinkle little star* (see Figure 2), a ditty with very simple musical properties: two symmetrical phrases, two-part rhythm, tonal music with all notes between the tonic (C) and submediant (A) of the major scale. The refrain was paced with 16 clearly audible beats, delivered every 1400 ms (see Fig. 2, top line).

In the refrain, Nao complained that he was looking for an object:

I am always looking for what was in there

I am always looking, it is not fun at all!

In following verse, sung without the pacing signal, one of the objects to be found was identified, and the robot implicitly asked the child to help him:

Is my pen over there? I can't find it!

Moi, je cher-che tout le temps, ce qui é-tait là de-dans
ah, vrai-ment c'est pas mar-rant

Mon cray-yon est il par-la? Je ne le re-trou-ve pas

Fig. 2 Score and lyrics of Nao's song for the refrain (top) and one of the verses (bottom). Black arrows depict the pacing signal.

Each of the eight verses referred to one of the objects to be found. The request could come in three forms: implicit sung (*I can't find it*), implicit spoken (*I can't find it*), or explicit spoken (*Help me, please*). Nine objects were scattered on a gray carpet: eight to-be-found items (pencil, ball, doll, spoon, cube, hat, book, overcoat) and a distractor (bread roll).

2.2.5 Nao program

We developed seven program modules: a greeting module where Nao introduced himself (*Hello, my name is Nao. And you? What's your name?*), an instruction module where the robot explained the task to the child (*Let's play together. I'm gonna sing to the beat. And you, you're gonna press the button to the beat.*), a coordination module delivering 10 beats every 1400 ms and then the refrain, paced by the same auditory signal, a cooperation module where the experimenter could pick up each verse, a congratulation module with various congratulations and encouragements (e.g., *Well done! You're on the right track!*), a question module asking the child simple questions (e.g., *Do you want a break?*), and finally an acknowledgments module (*Thank you. I'm proud to have played with you! It made me happy! ... Good bye!*). During the refrain, Nao was programmed to dance by swinging his hips in the frontal plane to the beat of the Nao song. Given that Nao cannot speak, the song and all the sentences were recorded using the voice of a 9-year-old boy before the experiment. The audio recording was processed using the Audacity program to enhance the quality of the soundtrack.

2.2.6 Control condition

For the control condition, an analogous program was developed on Processing.org and implemented on another 2.1 GHz computer for the coordination and cooperation modules only. At the beginning of each coordination trial, the computer automatically delivered 10 beats, one every 1400 ms. Immediately afterwards, the lyrics of the Nao song were displayed on the screen, and the experimenter started singing. To help the adult to sing at the required pace, 16 red circles were displayed under the lyrics, with one appearing every 1400 ms. After the last circle had appeared, the screen went blank until the next verse began and the sequence of red circles reappeared. The song ended when the experimenter pressed the return key. Each time the experimenter pressed the press bar during the song, s\he delivered a beat. The computer, which was connected to the Arcade pushbutton and received a digital signal at a rate of 9600 bps, recorded the on/off pushbutton state and the final press of the return key.

2.3 Procedure

Before the experiment, we spent two months on pilot attempts, intended to scope and remove any bugs in our programs. The pilot attempts were conducted with different participants from those recruited for the study. We also trained the experimenters to test the children with ASD, interact with their parents, and carry out the experimental procedure. Parents were asked to speak to their child about the experimental intervention, presenting it as a game with Nao or with a human partner. The experiment took place in a quiet room at the psychologist's office where the children usually received care.

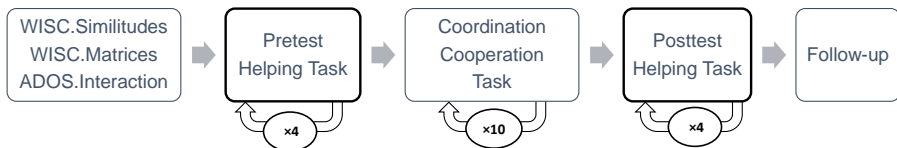


Fig. 3 Experimental procedure. The numbers inside the circles indicate the number of trials.

First, the children underwent three psychometric tests: similarities test, progressive matrices reasoning test, and ADOS (Interaction part). Then, the experiment started, following a pre post design. Four trials of the helping task were administered at the pretest, and four trials at the posttest. Between the pretest and the posttest, the coordination cooperation task was administered. These tests and the coordination cooperation task were administered by two different experimenters in different places in the room, separated by a screen.

2.4 Pretest helping task

Prior to the coordination cooperation task, we administered four distinct versions of the helping task to the children (Figure 4, left). These versions were drawn, randomly and without replacement, from the following set: the experimenter (1) throws a paper ball into a trash can, but the ball lands on the floor; (2) plays with a remote-controlled car, but the car crashes into a wall; (3) walks past a bookshelf and knocks a book to the floor; (4) uses a magnet to hang a picture, but the picture falls down; (5) opens the doors of a cabinet while carrying lots of books; (6) tries to color in a picture, but the felt-tip is dry and all the other felt-tips are out of reach; (7) puts felt-tip pens in a pencil case, but the zip does not close; and, (8) puts on a jacket and scarf, but the scarf falls to the ground. Each task began with the experimenter engaging in some action with an object and then being involved in an incident that prevented the task from being completed. If the child helped the experimenter to complete the action, s/he received 4 points. If not, the task could be repeated up to four times in a row. If the child responded successfully at the second, third or fourth attempt, s/he received 3, 2, or 1 points.

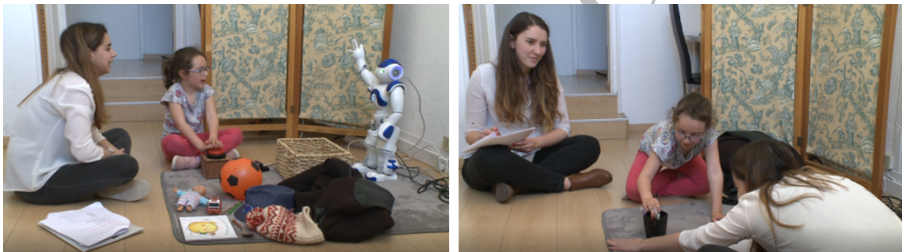


Fig. 4 Coordination cooperation trial with Nao partner (left panel) and helping task (right panel). Pictures extracted from our video recording of the robot-assisted experimental conditions, filmed by B. Bastard and M. Albert from UT2J-DICE, available at youtu.be/eWwccVz17ME

2.5 Coordination cooperation task

After the pretest helping task, participants were familiarized with the coordination task: the experimenter invited the child to listen to the pacing signal and then taught him/her to press the pushbutton in time with the pacing signal. Next, the adult explained that he/she would sing to the rhythm of the beats and asked the child to listen to the words of the song whilst performing the coordination task. The child was then told that if he/she thought there was something to do, he/she could do it.

After the explanation, the coordination cooperation task began (Figure 4, right). Each coordination trial started with 10 automatically generated beats at 1400 Hz. Immediately afterwards, the experimenter/robot produced the pacing signal by singing the refrain to this rhythm. When the refrain stopped,

the pacing signal and the pushbutton were removed, and cooperation task began. The experimenter/robot sang the refrain and a verse, drawn randomly and without replacement from the set of eight items, and waited 10 seconds to see whether the child would look for the required object and give it to him/her. If the implicit sung request failed to elicit a response, the verse was verbalized, and the experimenter again waited 10 s. If nothing happened, the request was verbalized in its explicit form. During the coordination task, the experimenter had to refrain from engaging in non-verbal behaviors that could have assisted the children in the coordination task. During the waiting period, the experimenter remained calm, and avoided gazing, pointing to or reaching for the object. If the child helped by bringing the required object, he/she was warmly congratulated. Ten coordination cooperation trials were administered in a row, each featuring a different object. In each trial, if the child brought the object, he/she was awarded 3 points (implicit sung request), 2 points (implicit spoken request), or 1 point (explicit request). No points were awarded in the case of a nonresponse.

2.6 Posttest helping task

After the coordination task, four new trials of the helping task were administered, following the same procedure as explained above. The whole experimental procedure is illustrated in Figure 3. A video (in French) displaying the robot-assisted experimental conditions, filmed by B. Bastard and M. Albert from UT2J-DICE, is available at youtu.be/eWwccVz17ME

2.7 Intervention set-up and durations

To avoid bugs, experimenters launched and tested the program just before each experimental session. Starting the robot and its program for the Nao condition took about 30 min. During the robot-led intervention, two experimenters had to be present: one launched each robot action by clicking on the corresponding program module, and the other assisted the child and evaluated his/her performance on the helping task. The set-up in human-led intervention took no more than 10 minutes and only one experimenter was present. In both experimental conditions, a coordination-cooperation trial lasted about one minute, and the whole experimental session between 1h and 1h30.

3 Results

3.1 Data Reduction and Statistical Analysis

3.1.1 Psychological measures

We calculated each child's scores on the cooperation task, the pre- and posttest helping tasks, and the psychometric tests (see Table 3). To evaluate their progress on the helping task, we calculated the difference between the posttest

and pretest scores. Before starting the data analysis, we compared the characteristics of the children in the control (human) and experimental (Nao) groups (see Table 2) using an independent samples t-test. In order to ensure that the two groups were equivalent, we excluded the data of two children in the Nao group from all the analyses involving human-robot comparisons. Intergroup comparisons were therefore run on the data of 21 participants only ($N = 11$ for the Nao and $N = 10$ for the human group). As one of the children in the Nao group was unable to press the button, the human-robot comparisons of coordination were run on the data of only 20 participants ($N = 10$ for the Nao and $N = 10$ for the human group). Correlation analyses involved the whole sample.

3.1.2 Coordination measures

In each trial, we used RP to assess coordination between the beats and the button presses [114]. As illustrated in Fig. 1 (right panel), we identified the onset of the button press, denoted below as $P_t + m$ (where $t < m < t+1$), for each time interval between two beats at T_{t+1} and T_t . We then calculated the difference between the beginning of the interval (T_t) and the timing of button press ($T_t - P_{t+m}$), and this difference was divided by the interval and multiplied by 360:

$$RP_j = \frac{T_i - P_{t+m}}{T_{t+1} - T_t} \times 360 \quad (1)$$

Given that the individual distributions of RPs were bimodal, simply averaging them did not seem an appropriate means of expressing the accuracy of coordination. We, therefore, computed five statistical indices from the RPs collected in each trial, using circular statistics methods cite[115]. First, we computed the circular distances between each actual RP and the required 0° RP value: the smaller the mean distance, the greater the accuracy. This measure is referred to hereafter as *absolute error* AE. Second, to express the stability of coordination, we computed the circular *stability index* R: the more stable the coordination, the smaller the RP variation, and the higher the R index. Third, we calculated the *entropy* of RP values: stable coordination was manifested by sharp distribution and thus low RP entropy. Formulas for R and entropy are provided in Appendix A. Fourth, we computed the *number of RPs* produced in each condition in order to express the extent of the child's involvement in the coordination task: the closer the value was to 160 (16 beats \times 10 trials), the greater the involvement. Fifth, to provide some insight into the coordination strategies adopted by the children, we calculated the ratio between the number of negative RPs (within the -180° 0° range), and the number of positive RPs (within the 0° 180° range), referred to hereafter as *NegPos*. A NegPos value above 1 was a hallmark of leader strategy, and a value below 1 a hallmark of follower strategy. All these indices (absolute error, stability, entropy, number of RPs, NegPos) were computed separately for each child and each experimental condition. They are listed, together with their interpretations, in Table 3.

Table 3 Coordination Measures and Their Interpretation

Measure	Interpretation
1. RP absolute error	Lower: more accurate condition only
2. RP stability	Higher: more stable
3. RP entropy	Lower: more stable
4. RP number	Close to 160: involved in the task
5. RP NegPos	Below 1: follower strategy

3.1.3 Statistical analysis

Assumptions lying behind the statistical parametric tests were checked using Levene's test for equality of variances and the Shapiro-Wilk test for normality. Our distributions did not diverged from normality ($p > 0.05$), and if their variances differed, Greenhouse Geisser corrections were applied. Given that our repeated-measures factor (Pre-post: pretest vs. posttest) had two levels, the assumption of sphericity of variances was always met.

After ensuring us that there were no baseline differences between the characteristics of the children from child-Nao and child-human group (see Table 2), we analyzed whether the robot assistance enhanced the impact of the coordination cooperation task on the inference of others' intentions (Hypothesis 1). To this end, we compared pretest versus posttest performances on the helping task in the experimental and control groups, using a 2 (Partner: Nao vs. human) \times 2 (Pre-post: pretest vs. posttest) analysis of variance on helping task scores (ANOVA). To check whether initial motor skills modulated the impact of the coordination cooperation task (Hypothesis 2), we analyzed the correlation between the DCDQ test and progress in the helping task. Progress was expressed by calculating the difference between performances on the helping task at pretest versus posttest.

We then assessed the quality of coordination to test whether coordination was more accurate and stable in the child-robot dyad than in the child-human dyad (Hypothesis 3). In so doing, we also checked the eventual effect of dividing attention between the refrain and the beats during the coordination period, by comparing the phase where only the beats were delivered (single-task condition), with the phase that featured both the beats and the refrain (dual-task condition). The effects of Partner (Nao vs. human) and Attention (single task vs. dual task) on absolute error and the stability index were assessed with a 2 (Partner) \times 2 (Attention) ANOVA, with repeated measures on Partner. Moreover, we examined whether the children were more involved during the interaction with Nao than with the human, by computing a 2 (Partner) \times 2 (Attention: single-task vs. dual task) \times 2 (NegPos: negative RP vs positive

RP) ANOVA on the number of RPs produced (cf. Hypothesis 5). For significant interactions, we ran post hoc analyses using t-tests with Benjamini Hochberg's α -correction for multiple tests.

Next, to provide further insight into the possible relationship between social skills and quality of coordination (Hypotheses 2), we performed Spearman correlations between measures yielded by the psychological tests and the coordination cooperation task. Social skills were captured by measures from the social (SCQ, ADOS, VABS: VRP, VPL, VA, VP) and attentional (Conners: C1 to C6) tests, as well as the scores from the cooperation task, the helping task administered before (HT1) and after the coordination cooperation task (HT2), and the measure of progress in the helping task (HTP). Given that coordination indices were strongly correlated ($r \geq 0.85$), to avoid redundancy we decided to focus this analysis on the measures reflecting the children's involvement in the task and stability of coordination. Children's involvement was manifested by the number of RPs produced in the beat and refrain conditions, and in the two conditions taken together (NRP). RP stability was represented by the entropy of RP distribution in the beat (ET) and refrain (ER) conditions. In order to carry out this analysis, we calculated a correlation matrix with corresponding p values. These p values were then adjusted using the Benjamini Hochberg adjustment for multiple comparisons. Significant relationships were illustrated using a graph layout based on the Fruchterman-Reingold algorithm from the qgraph R package.

The analysis ended with an examination of the leader-follower strategies adopted by the children (Hypothesis 4). We computed correlations between NegPos values and the measures of social skills (ADOS, SCQ, VABS), expecting to find a positive relationship between them.

For all analyses reported here, only effects significant at $p < 0.05$ are reported, along with the corresponding effect size estimates for the ANOVAs (generalized η^2). Data reduction and analysis was performed using JASP and R[®] statistical software, applying circular and qgraph R[®] packages.

3.1.4 data availability statement

Data will be made available at personal request.

4 Results

4.1 Helping Task

Figure 5 depicts the results of the helping task. A 2 (Partner) \times 2 (Pre-post) ANOVA on performance on the helping task revealed a main effect of Pre-post, $F(1, 19) = 4.771$, $p = 0.042$, $\eta^2 = 0.043$, and an interaction effect, $F(1, 19) = 6.277$, $p = 0.021$, $\eta^2 = 0.056$. Performance on the helping task was better at posttest than at pretest. Post hoc t-tests with Benjamini Hochberg correction only revealed a difference between pretest and posttest in the control condition ($t = -3.143$, $p = 0.031$, $\eta^2 = 0.67$): after interacting with the human,

the helping task score rose (see Figure 5, Panel A). Contrary to Hypothesis 1 (see Table 1), children made more progress in control rather than in human condition. In line with Hypothesis 2, there was a positive correlation between progress on the helping task and scores on the DCDQ evaluating motor skills ($r = 0.395$, $p = 0.035$; see Figure 5, Panel B).

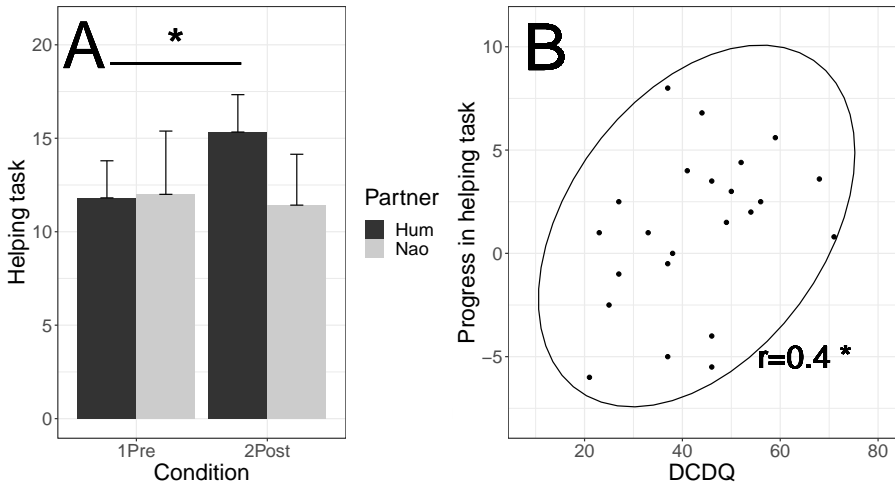


Fig. 5 Helping task : Helping task scores as a function of Pre-post and Partner factors (Panel A), and progress in the helping task as a function of DCDQ score (Panel B).

4.2 Coordination accuracy and stability

As illustrated in Figure 6 (panel A), A 2 (Partner) \times 2 (Attention) ANOVA carried out on RP stability revealed a main effect of Partner, $F(1, 18) = 6.491$, $p = 0.02$, $\eta^2 = 0.265$. Stability of coordination was higher when the child interacted with the human rather than with the robot ($M = 0.240$, $SD = 0.03$ vs. $M = 0.106$, $SD = .02$). Regarding accuracy (see Figure 6, panel B), a 2 (Partner) \times 2 (Attention) ANOVA carried out on absolute error revealed a main effect of Attention, $F(1, 18) = 16.056$, $p = 0.001$, $\eta^2 = 0.104$, and of Partner, $F(1, 18) = 10.473$, $p < 0.005$, $\eta^2 = 0.07$. The absolute error was largest, and accuracy, therefore, lowest for the child-human dyad than for the child-robot dyad ($t = -5.122$, $p = 0.001$). Hypothesis 3 was supported for accuracy, but not for stability.

4.3 Leader follower strategy Measures

There was a negative correlation between NegPos and VABS.P ($r = -0.49$, $p = 0.029$): children with the best autonomy skills tended to follow (RPs in $0^\circ - 180^\circ$ range), rather than lead (RPs in $180^\circ - 360^\circ$ range) the coordination, in line with Hypothesis 4.

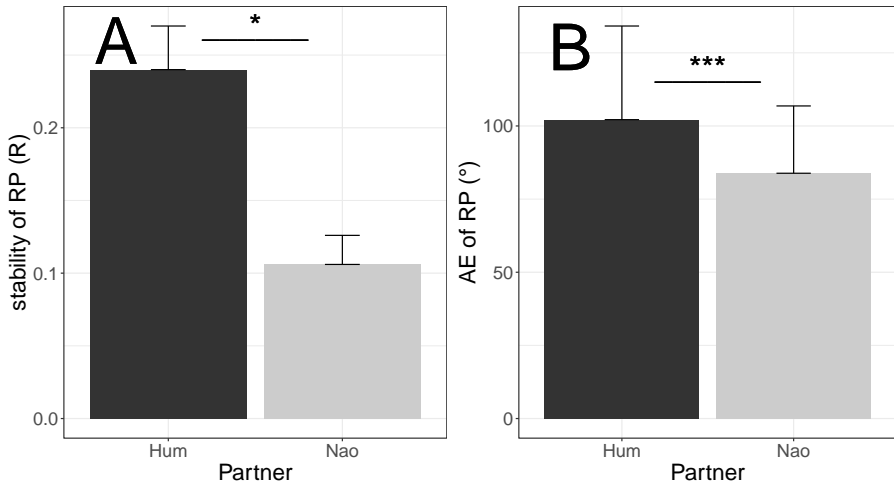


Fig. 6 Coordination accuracy and stability: RP absolute error (Panel A) and RP stability (Panel B) as a function of partner.

4.4 Motor and Psychological Measures

Figure 7 displays correlations between the number of RPs produced, an social and attentional measures. Circles refer to variables and edges to significant relationships linking them. Of particular interest here are the relationships between social or attentional and coordination measures. Using the post-hoc Benjamini Hochberg adjustment for multiple comparisons, analysis showed that the number of RPs produced overall and in the beat condition was positively correlated with the posttest helping task, HT2 ($r = 0.62$, $p = 0.002$, $r = 0.68$, $r = 0.002$): children who produced more coordination patterns performed better on the posttest helping task, in line with Hypothesis 5. Progress on the helping task was also inversely related to attentional disorders: impulsiveness (C4) and hyperactivity (C6).

5 Discussion

Children with ASD were involved in a coordination cooperation learning paradigm, where they first had to beat the rhythm of a refrain sung by a social partner, then cooperate with the latter by bringing him/her an object. The effect of learning to cooperate was assessed by administering a helping task before and after the learning paradigm. We showed that contrary to our expectations (Hypothesis 1 and 3, see Table 1), children who played with the robot produced least stable coordination and made least progress in helping task. In line with our hypotheses, motor and social skills were related: progress on the helping task was related to initial motor skills (Hypothesis 2), and the involvement in coordination task (Hypothesis 5); children displaying the best social skills adopted the follower strategy (Hypothesis 4).

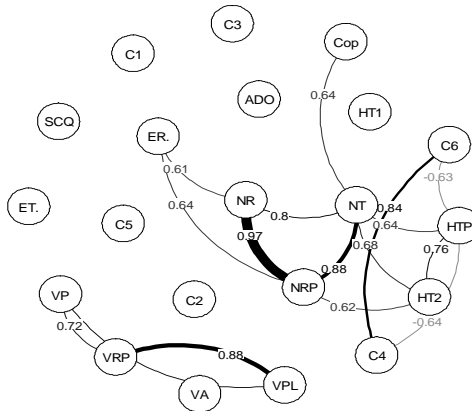


Fig. 7 Correlations between the numbers of RPs produced, and social and attentional measures. Edges illustrates significant BH-adjusted relationships. Cop = cooperation; HT1 = pretest helping task; HT2 = posttest helping task; HTP = progress in helping task; ADO = ADOS.Interaction; V = VABS; C = Conners (see Table 2 for details); NRP = number of RPs produced overall; NB = number of RPs produced in the beat condition; NR = number of RPs produced in the refrain condition; EB = entropy in the beat condition; ER = entropy in in the refrain condition.

5.1 Social Skill Transfer

Our study came in the wake of a series of failed attempts at demonstrating the efficacy of robot-assisted interventions (for reviews, see [36] [38] [40]). While both groups performed equally well in the cooperation task, it was observed that children who interacted with Nao exhibited a lower degree of transfer of the recently practiced skill from the cooperation task to the helping task. It is possible to suggest that when interacting with a human partner, children have developed a social relationship that subsequently facilitated their performance in the post-test helping task. In contrast, such a transfer of social connection did not occur in the robot situation. Thus, even if it were true that robots facilitate social skills learning, the challenge remains in effectively transferring these skills from interactions with robots to interactions with humans. Given the well-established challenges faced by persons with ASD during transfer [116], it is crucial to explore and develop effective strategies that can facilitate this process in the field of social robotics dedicated to ASD.

Attempting to explain our data, we can also speculate that despite Nao's human-like appearance, the robot may have failed to be perceived as an agent capable of generating its own motions and intentions. When the attribution of intentions is cued by the kinematics of the 'body', self-propulsion and rapid reactive movements are necessary to attribute intentions to artifacts [117] [118]. In our robotic platform, each action of Nao had to be manually controlled by an operator who had to press a button to initiate a command. The cables

connecting Nao to the computer were visible, the double-click launching each action was clearly audible, and the interval between the selection and execution of a command took could be as long as 1300 ms. These perceptual facts may not have escaped our children's notice, prompting them to perceive Nao as a human-driven machine rather than as an intentional agent.

5.2 Coordination

Contrary to our predictions, coordination varied least when the children interacted with the human. The regularity of the program-produced beats in the robot and beat conditions did not enhance coordination stability. Why was that? The point is that the stability of coordination depends on partners being able to pick up visual information from each other to compensate for their deviations [119]. Human partners are capable of this adjustment [94], thereby acting as coordination stabilizers. In contrast, the program-generated beats only acted as a metronome, so if a child's motion varied, the program did not adjust the interbeat interval to maintain a steady coordination state. In terms of Coordination Dynamics [22], human-child dyads demonstrated stability at the macroscopic, group level of relative phase, whereas the stability observed in robot-child dyads occurred at the microscopic, individual level of the partner.

Fortunately, it is possible now to overcome this limit. Recently, Kelso's group introduced a mathematical model that can effectively coordinate itself with unpredictable human motion [119]. However, utilizing this algorithm requires a system capable of minimizing spatial errors to the micrometers and processing latency to microseconds. Regrettably, our Nao platform failed to meet these requirements. The motion capture system of our Nao proved too imprecise to accurately track a child's movements, and the latency between command execution often exceeded 1000 seconds.

5.3 Robot-assisted and human-led intervention

To date, the studies examining robot-assisted interventions dedicated to teaching social or motor skills have yielded mixed results, primarily due to inconsistencies in the methodologies employed. In previous studies where motor or social improvements were reported in the robot group, either the control group was absent [120] [121] [122] or the robot group was compared to children who did not receive the intervention [123]. When the difference between the experimental and control groups was assessed, either no significant between-group difference was found [123] [124] or better performance was observed in children paired with a living companion [125] [126] [127]. Struggling to adhere to the guidelines of experimental methodology, we compared robot-assisted to human-led intervention and found analogous results.

To be valuable, however, robots should not aim to surpass humans and replace them. Instead, they should be designed as collaborative tools, capable of taking on tasks that they excel at and that are challenging for humans. Robots have demonstrated proficiency in repetitive tasks, data collection, and

computational power. Therefore, it is worth considering their utilization in areas such as monitoring child attention, using gestures to enhance engagement with educators, facilitating movement production in children with motor difficulties, recording and analyzing a child's performance, generating progress reports, and even predicting a child's real-time reactions to suggest appropriate next exercises or moments of rest. Comparing robot-assisted and human-directed interventions can be rather helpful in simulating human capabilities, thus deepening our understanding of ourselves and of ASD.

5.4 Motor, Attentional and Social skills

From the standpoint of Coordination Dynamics, the present study has successfully replicated several well-established features of coordination in children with ASD. In line with our predictions, the enhanced stability of coordination in the human condition went hand in hand with lower accuracy. This illustrates the well-known finding in typical individuals [128] that stability is preserved at the expense of accuracy.

Stable coordination brings indeed various benefits to individuals. For a start, most stable coordination states recruit a very small network of brain regions [129], and can be maintained at a very low attentional cost [130] and with very little expenditure of metabolic energy [131]. Stability may also be viewed as a precondition for adaptation and learning [128]. If the interpersonal coordination state is too unstable, that is, if its rate of change is faster than the rate of learning, individuals never settle on a given coordination state long enough to explore its advantages or drawbacks.

As expected, our data also pointed to a two-way relationship between motor, attentional, and social skills. Children with poorer motor and attentional abilities, as well as limited involvement in the coordination task, exhibited lesser progress in the helping task. These findings imply that social skill difficulties may arise from underlying challenges related to attention and perceptual-motor processes, which aligns with prior research [132] [133] [134] [135]. These findings provide a compelling incentive to embark on a deep investigation of the development of social skills while meticulously considering its intricate relationship with perceptual-motor processing.

5.5 Leader Follower Strategy

Instead of the expected relationship between follower strategy and social score, we found that children who adopted the follower strategy displayed better autonomy skills. One explanation for this relationship is that followers monitor their partner's action more closely than leaders do [136]. Children who have acquired autonomy may attend more closely to the information coming from the environment, and may thus be more able to follow than to lead.

5.6 Limitations

The present study had several limitations. First, Nao cannot sing. Although we were able to use a boy's voice for Nao's song, it proved impossible to exploit the robot's text-to-speech synthesis function to produce a different voice. All the sentences produced by Nao should have been recorded before the experiment in the presence of a human co-experimenter to provide verbal guidance. Second, Nao did not move along the floor because of the risk of losing balance, and his gestures were too limited for him to be able to take an object from a child's hand. This restricted child-robot interactions, which was unfortunate, given that the main added value of social robots over computers is the experience of physical interaction. Third, because of the variable delays in the execution of commands, it was impossible for us to set up a reactive robot that autonomously coordinated himself with the children.

Another limitation of our study was the short duration of the cooperation-coordination task. When children with ASD encounter a new and unfamiliar entity such as a robot, the novelty may have led to potential distractions from the learning task at hand. To mitigate this potential effect, longer periods of robot-assisted training would be necessary. However, in practice, achieving this would require the operation of a more autonomous robot. Considering the need to integrate educational sessions into the busy schedule of a psychology clinic, it becomes impractical to spend 30 minutes on robot setup and involve two people in the execution of the intervention.

Designing a robot-assisted intervention is a tremendous experimental challenge. Robot-led and human-led trials conditions differ by a large set of variables that cannot be controlled, unless to multiply control conditions to infinity, forget the specific goal of a specific attempt, or lose the sense of ecological value. For instance, while conducting the coordination task, despite being instructed to avoid engaging in nonverbal behaviors that could aid the children, the experimenters were not consistently successful in doing so. On occasion, they would cast glances at the child, bow their heads, and rock their chests. It should be noted, however, that the extent to which the humans involved in the control situation should avoid typical nonverbal human behaviors and instead try to mimic robot-like behavior remains an open question. Further studies may involve a human acting as a robot, a robot acting as a varying human, they may compare child-like to adult-like robot or human to robot experimenter administrating helping tasks (eg. [137]. Here, we only touched the surface of deeper theoretical issues regarding the benefits and shortcomings of human/robot interaction.

Another lingering concern in social robotics dedicated to ASD are sample sizes. In the studies on persons with ASD reviewed by Pennisi et al. [136], the median sample size amounts to 4.5 (mean = 7.14, SD = 4). Those small samples are explained by the tremendous effort required to program and administrate a robot-assisted intervention and research focus on technical issues. For ethical reasons, we need to scope technical limits and develop mature robotic platforms

before engaging in fully-fledged studies on large samples. Our pilot study is meant to serve as a feasibility test for a larger efficacy trial in the future.

At the beginning of the study, our team of researchers specialized in ASD made the common mistake of placing unrealistic expectations on the robot's skills [138]. In reality, robot functions remain within the narrow confines defined by the specifications of available sensors, actuators, the internal model subserving sensor reading, and the actualization of motor controllers via inverse kinematics solutions. A tremendous engineering effort is required to develop a robot for an apparently narrowly defined task. For instance, Dyson 360 eye, a mere vacuum cleaner capable of mapping out and navigating a room, required over 100 000 hours of production time and 16 years of development [139].

Regarding perceptual motor issues, we did not attempt to improve motor performance on the coordination task. We provided neither rewards nor feedback pertaining to the accuracy or stability of coordination. Our paradigm involved learning to cooperate, not coordinate. This leaves open the question of whether learning to coordinate is effective in children with ASD, and whether it promotes cooperation.

5.7 Conclusion

Although coordination was more accurate with the robot partner, it was more stable, and learning to understand social intentions was more efficient, when the children with ASD interacted with a human. Simply replacing a human with a robot is therefore not enough to facilitate social skills. Our data suggests that the ability to actively maintain stable coordination at the macroscopic group level could play a pivotal role in facilitating the learning of social skills in ASD.

Supplementary information. A video (in French) displaying the robot-assisted experimental conditions, filmed by B. Bastard and M. Albert from UT2J-DICE, is available at youtu.be/eWwccVz17ME. Data will be made available at personal request.

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Declarations

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Conflict of interest. The authors declare they have no conflict of interest.

Ethics approval. The studies involving human participants were reviewed and approved by the Research Ethics Committee for Non-Invasive Procedures (CERNI-2016-003) of the University of Toulouse Midi-Pyrénées.

Consent to participate. The interventionist and the families of all the children received a letter explaining the goals, experimental procedure, and rights of parents and children, and provided their written informed consent, in accordance with the Declaration of Helsinki. Each parent completed a form provided by the University of Toulouse informing them of their rights and predictable risks in comparison with foreseeable benefits. Written informed consent was obtained from the individual(s) or the individuals' legal guardian/next of kin for the publication of any potentially identifiable images or data included in this article.

Authors' contributions. VK and JK designed the study. PVP programmed the robot, and VK the application used in the control condition. JK supervised the data collection. CL participated in the data collection. VK analyzed the results and wrote the manuscript. JK, VK and PVP critically reviewed and edited the manuscript. All authors approved the final manuscript.

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Appendix A Circular Statistics Formulas

For a set of angles θ_i , the circular index of dispersion R ($0 < R < 1$) is calculated as follows :

$$C = \sum_{i=1}^n \cos(\theta_i) \quad (\text{A1})$$

$$S = \sum_{i=1}^n \sin(\theta_i) \quad (\text{A2})$$

$$R = \frac{\sqrt{C^2 + S^2}}{n} \quad (\text{A3})$$

The formula for entropy H is :

$$H = - \sum_i p_i \log_2(p_i) \quad (\text{A4})$$

where the p_i represents the probability of each angle.