Research Article

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Robot-mediated intervention can assist children with autism to develop visual perspective taking skills

https://doi.org/10.1515/pjbr-2021-0007
received October 14, 2019; accepted September 11, 2020

Abstract: In this work, we tested a recently developed novel methodology to assist children with Autism Spectrum Disorder (ASD) improve their Visual Perspective Taking (VPT) and Theory of Mind (ToM) skills using the humanoid robot Kaspar. VPT is the ability to see the world from another person's perspective, drawing upon both social and spatial information. Children with ASD often find it difficult to understand that others might have perspectives, viewpoints and beliefs that are different from their own, which is a fundamental aspect of both VPT and ToM. The games we designed were implemented as the first attempt to study if these skills can be improved in children with ASD through interacting with a humanoid robot in a series of trials. The games involved a number of different actions with the common goal of helping the children to see the world from the robot's perspective. Children with ASD were recruited to the study according to specific inclusion criteria that were determined in a previous pilot study. In order to measure the potential impact of the games on the children, three pre- and post-tests (Smarties, Sally–Anne and Charlie tests) were conducted with the children. Our findings suggest that children with ASD can indeed benefit from this approach of robot-assisted therapy.

Keywords: visual perspective taking, theory of mind, assistive robotics, autism, human–robot interaction

1 Introduction

Visual Perspective Taking (VPT) is the ability to view the world from another individual's perspective, taking into consideration what they see and the way they see it [1]. This means one must successfully utilise both social and spatial information. The social information relevant to VPT includes the simultaneous representation of two differing perspectives, taking into consideration if and how the other person can see an object [2]. The spatial information utilised for VPT includes taking into account the exact location of the other viewer and that of the target in relation to one's self and the other [3–5].

There are two different levels of VPT which are typically developing in succession [1]. The first level (VPT1) is the ability to understand what another individual can and cannot see, i.e. if an object is occluded from their view. The second level (VPT2) is the ability to understand that two or more people looking at the same object from different positions might not see the same thing [1].

Currently, the literature suggests that VPT1 develops at around 18–24 months of age in typically developing children [6–9], while VPT2 develops later in age, at around 4–5 years of age [10]. VPT is also thought to be a component of theory of mind (ToM) – also referred to as cognitive perspective taking [11] – the ability to attribute mental states (i.e. beliefs, intentions, desires) to others, and to understand that those beliefs, desires, intentions and perspectives may be different from one's own [12]. ToM was thought to develop at around 4–5 years of age [13]; however, more recent research suggested that by using different methods one might find evi-

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dence of ToM skills even earlier in infancy [14]. This may further suggest that VPT might also develop earlier than previously thought in typically developing children [15].

Some researchers suggest that ToM and VPT share common cognitive processes [16], while others suggest that they are entirely separate [17]. Although the exact relationship between ToM and VPT seems yet to be unclear, they both clearly rely on simultaneous representation of different perspectives [2].

Both VPT and ToM have been reported to be impaired in autism spectrum disorder (ASD) to some degree. While VPT1 abilities seem to be intact in people with ASD [11,18–23], both the abilities of VPT2 [16,24] and ToM [12,25–30] have been reported to be affected in people with ASD, suggesting that people living with ASD have difficulties with taking another person's perspective.

ASD is a lifelong developmental disorder that affects how people perceive the world and interact with others [31]. It is characterised by impaired ability for social communication and interaction along with restricted and repetitive behaviours. ASD has several different forms and can greatly vary in its degree of severity. The Autism Diagnostic Observation Schedule (ADOS-2) assessment differentiates three possible classifications: non-spectrum, ASD and autism. In *Diagnostic and Statistical Manual of Mental Disorders, 5th Edition*, autistic disorder, Asperger's disorder and pervasive developmental disorder – not otherwise specified (PDD-NOS) have been recently replaced by the collective diagnosis of ASD. Based on the degree of severity, three levels are identified: requiring support, requiring substantial support and requiring very substantial support.

Even though (visual and cognitive) perspective taking impairments in ASD have been widely researched and reported, only little research has been conducted regarding effective interventions for children with ASD; and most of them focusing solely on cognitive perspective taking, i.e. ToM.

Ozonoff and Miller [32] compared the effectiveness of regular social skills training and specific training in perspective taking strategies involving video feedback and role play. They found the specific training in perspective taking strategies is much more effective in improving the children's ToM abilities. LeBlanc et al. [33] utilised video modelling with reinforcement for teaching perspective taking abilities to three children with ASD. Video modelling means showing a video of a person demonstrating behaviours for the children to imitate. It was suggested that since video modelling is an engaging method that does not require social interactions, it might be especially useful in teaching children with ASD. The authors found the method effective in teaching perspective taking for the children (specifically, teaching children to pass the Sally–Anne task); however, they also found that generalisation of these new skills was limited. Gould et al. [34] used a different method. Instead of teaching the children to pass a ToM task, they rather focused on teaching a basic component of the perspective taking skill based on the understanding of others' head orientation and eye gaze. They tested the efficacy of multiple exemplar training for teaching three children with ASD about what other people can see and the level of generalisation they could achieve. Children in their study showed the ability to generalise to the novel tabletop tasks but generalisation to a natural environment was less consistent. Importantly though, the sample size was very low ($N = 3$) in both of these studies.

An alternative approach to promote social interaction skills of children with ASD – with increasing research interest over the past 15 years – is the use of social robots as assistive tools. Dautenhahn and Werry were pioneers in investigating how robots could be used to help children with ASD [35,36] and were followed by numerous research studies worldwide. Several different robotic systems have been developed recently to investigate a robot's usability in assisting social interaction skills, not just for people with ASD but for people with and without cognitive and/or physical impairments. These robotic systems include artificial pets like the baby seal robot Paro [37,38] or the teddy bear Huggable [39,40], the cartoon like robot Keepon [40] and humanoid robots such as Nao [41,42], the robotic doll Robota [43–45] and the child-sized robot Kaspar [46]. All these robots were designed to socially engage and stimulate users and have been used successfully with many children with ASD to evoke prosocial behaviours such as joint attention and imitation [47]. A large amount of research to date has been carried out with the Kaspar robot to encourage social interaction and collaborative play amongst children with ASD [48,49], demonstrating that a humanoid robot is suitable to engage, motivate and encourage children to interact with it and with each other [49].

2 Robot-assisted intervention targeting VPT skills – aims of the study

Even though robot-assisted therapy was suggested to be an effective medium to improve social and communicational skills of children with ASD, little research has been done on how social robots could help children with ASD to develop their VPT skills.

In a recent pilot study [50], we developed a novel methodology to assist children with ASD in developing their VPT skills using the humanoid robot, Kaspar. In the pilot study, we designed games specifically for improving both VPT1 and VPT2 skills and implemented them in Kaspar to see whether children with ASD can effectively learn about these skills through playing and interacting with Kaspar. The difficulty of the games increased gradually as they were presented to the children. Findings of this initial study suggested that intervention with Kaspar may be beneficial to some children in teaching them about VPT. Importantly though, since this was the first study of this kind, and it was necessary to make several changes at the time to the procedure during the course of the study, we could not run a thorough enough data analysis on the data collected throughout the games. Due to the exploratory nature of the pilot study and the absence of previous work on teaching children with ASD the VPT skills, no inclusion criteria was used for the participants at the time – in fact, the pilot study helped to finalise the methodology and determine suitable inclusion criteria for the VPT intervention with Kaspar.

In the light of this, the aims of the current research were to (1) eliminate the problems identified in the pilot study presented above and (2) collect further evidence to establish whether a humanoid robot like Kaspar can be used to assist children with ASD to develop VPT skills. In order to meet these goals, in the research presented in this article we used the scenarios developed in the above-mentioned pilot study [50] using the final experimental protocol derived from this study with a new set of participants and applying inclusion criteria.

3 Ethics statement

This research was approved by the University of Hertfordshire's ethics committee for studies involving human participants, protocol number: acCOM SF UH 02069. Informed consent was obtained in writing from all parents of the children participating in the study.

4 Methods

4.1 Participants

The study was conducted in a local special education primary school in Hertfordshire. Eighteen children with a diagnosis of ASD were recruited; of which 13 children participated in the study after the pre-test assessments.

Five children who did not fall within the inclusion criteria were excluded from participation in the study, two of them because their non-verbal mental age was below 3 years (which would be too early for VPT2 and ToM abilities to develop), one of them as a result of having a non-verbal mental age above 20 and two of them as a result of their perfect performance in the pre-test assessments (Smarties, Sally–Anne and the Charlie tests, see also below) showing that they had already developed VPT and ToM skills.

Mean chronological age of the 13 participants was 8.11 years; SD = 1.96 (range: 5 to 11 years), and 11 were male.

The Leiter-3 International Performance Scale [51,52] was used to establish each child's non-verbal mental age, while the ADOS-2 [53] was used to assess the degree of severity of their ASD. The assessments were carried out by two of the co-authors of this article who either already had or received relevant training required to administer the tests.

The children's mean non-verbal mental age was 6.09 years; SD = 3.10 (range: 3.3–10.8 years), their mean non-verbal IQ was 79.30; SD = 14.33 (range: 60–103), and their mean ADOS comparison score was 7.03; SD = 1.21 (range: 5–9). This latter score means that the children's level of autism-spectrum-related symptoms were "moderate" to "high" (see also Table 1 for more detailed demographics).

Thus, the children included in the study had an ADOS-2 score higher than 5 and a mental age above 3 years. According to the literature, VPT1 skills develop around 18–24 months of age and VPT2 skills develop at around 4 years of age or possibly earlier in typically developing children [10].

Verbal language skills of the children have not been tested; however, all our participants were verbal and had adequate receptive language skills with some level of expressive language.

4.2 General procedure

We used the exact same procedure as the one we developed and finalised in our pilot study reported in ref. [50]. The procedure is summarised below along with a short description of the Kaspar robot.

The child-sized humanoid robot, Kaspar, was developed in 2005 by the Adaptive Systems Research Group at the University of Hertfordshire to help children with ASD in developing their social interaction skills. Since its

Table 1: Participant demographics

	ADOS comparison score	Chronological age	Leiter mental age	Leiter non-verbal IQ
Participant 1	8	10	7.96	84
Participant 2	7	10	6.62	74
Participant 3	9	10	10.83	96
Participant 4	7	10	5.08	60
Participant 5	9	9	6.5	83
Participant 6	6	5	3.83	71
Participant 7	6	5.5	4.25	100
Participant 8	8	6	3.75	61
Participant 9	7	9	12.66	87
Participant 10	7	8	4.25	70
Participant 11	5	7	10.83	103
Participant 12	8	10	3.33	65
Participant 13	6	6	5.5	77

conception, Kaspar has been successfully used with an excess of 500 children – both children with and without ASD [50,54–66].

Kaspar is a fully programmable, 22-degrees of freedom (DOF) non-mobile humanoid robot. Although this robot cannot walk, it can move its neck, face and arms. In the current study, it was used in a semi-autonomous way, i.e. the researcher retained control over the robot's high-level behaviours – such as its speech – in order to ensure the learning objectives are being met.

In the present study, the general theme we selected for the games the children would play with Kaspar was "animals" since children are most often interested in animals regardless of their age or background (e.g. Wood et al. [50]). During the games the children would show Kaspar animal toys/images and in return Kaspar would make the sound of the respective animal and perform some gestures to accompany these sounds. In addition, the six animals we chose to use had distinctive sounds, which could be used as a sensory reward.

Figure 1: Generic equipment layout: the child is sitting in the red chair facing Kaspar, while the experimenter is sitting in the blue chair.

The games we developed to help children with ASD learn about VPT include elements of some well-known children's games such as "I Spy" and "Hide and Seek" (see below for detailed description of the games). The games involve a number of different combinations of actions, starting with moving objects into and out of the robot's field of view (see Figure 1), and even physically controlling the robot's line of sight by moving its head. The key to these games is giving the children the ability to see the world from the robot's perspective and to assist them in learning about VPT. The games were specifically developed to not be reliant on the child's ability to speak, in order to maximise the number of children that could play and benefit from the games. The development of these games was based on a number of factors. The primary factor that we initially considered was the literature on VPT and how this related to our previous experience of developing scenarios for children with ASD using a humanoid robot [46,67,68]. Further to this we also consulted teachers who specialised in working with children in special needs schools. To implement these games, along with the Kaspar robot, we used a screen that was placed next to the robot to display what the robot can see through its eyes. This way, using Kaspar to teach children about VPT has a distinct advantage in the fact that what the robot can see can be shown directly to the children, using the cameras in the robot's eyes and the screen next to Kaspar to present the robot's perspective.

Each session lasted about 15 to 20 min. The number of sessions and the length of the overall intervention depended on the children's skills and ability to progress in the games (see Section 7 for further details on this).

4.3 Equipment setup

The standard layout can be seen in Figure 1. The cameras used to record the sessions had wide-angled lenses to ensure that the child was always in view. The screen was placed next to the robot in order for the child to see what the robot could see. There were some small variations on this setup with additional equipment being used, and these changes are noted for each game.

4.4 Pre- and post-test assessments

Similar to our pilot study [50], following the Leiter-3 International Performance Scale and the ADOS-2, each child participated in the same pre-test assessments – Smarties, Sally–Anne and Charlie tests – before participating in the games. In order to measure the potential impact of the games on the children's VPT and ToM skills, the Smarties, Sally–Anne and the Charlie tests have been administered to the children once again after the intervention.

4.4.1 The Smarties test

The Smarties test is meant to establish whether the child has a ToM by asking a series of questions about the contents of a Smarties tube [69]. First the tube is shown to the child, then the child is asked "what do you think is inside." Very often the child would say either "chocolate," "sweets," or "smarties." When the tube is opened, the child can see that there are pencils inside rather than the sweets as they had expected. The pencils are then put back into the tube and the tube is closed. Once the tube has been closed, the child is then asked what their teacher (someone who had not seen the pencils being put into the tube) would think is inside. If the child has a ToM, they will answer smarties, chocolate or something to that effect; and if they do not then the child will say pencils, since the child knows that there are pencils inside the tube (see Figure 2).

Figure 2: A researcher administering the Smarties test.

4.4.2 The Sally–Anne test

The Sally–Anne test is a well-known test designed to establish whether the child has a ToM, in particular with regard to false beliefs [27]. The advantage of this test is that it is more accessible to non-verbal children because the children can simply point to answer questions rather than speak. Two dolls that look different are placed on the table, one is called Sally and the other is called Anne. The child has to confirm that they know which doll is called Sally at the beginning of the test. Sally has an empty basket, while Anne has an empty box. Sally places a ball into her basket while she goes out to play. Anne moves the ball from the basket into her box while Sally is out. The child then needs to indicate where the ball is and then where Sally left it. The child is finally asked where Sally will look for her ball when she is back. If the child says "the basket" then they have a ToM; but if they say "the box," then this is an indication that they do not (see Figure 3).

4.4.3 The Charlie test

The Charlie test is designed to examine the child's understanding of eye gaze [27], which is particularly important for VPT. In this test, the child answers a number of questions that revolve around the concept of eye gaze. For example, in one question the child is asked "Which face is looking at you?," while the image is directly in front of the child (Figure 4a). As the test becomes

Figure 3: A researcher administering the Sally–Anne test.

gradually more complex, the child is then presented with pictures of four different sweets and asked which one is their favourite. Once the child has selected a favourite, then a face referred to as Charlie is placed in the middle of the sweets looking at something different to what the child stated and an arrow is also placed on the sheet pointing at another selection that is not what the child stated or what Charlie is looking at (see Figure 4b). The child is then asked "What is Charlie looking at?." If the child states the sweet that the face is looking at, then this is coded as correct; if the child stated the sweet they chose themselves, this is coded as an egocentric response. If the child states one of the other sweets, this is coded as random. The Charlie test consists of 15 questions in total and similar to the Sally–Anne test can be performed with a non-verbal child. Results from the Charlie test are particularly relevant to our research, since it addresses eye gaze which is directly relevant to VPT tasks.

4.5 The games

4.5.1 Game 1: I'll ask for the animal, you find me the animal

The first game is a VPT1 exercise, during which the children learn that Kaspar has a different line of sight from

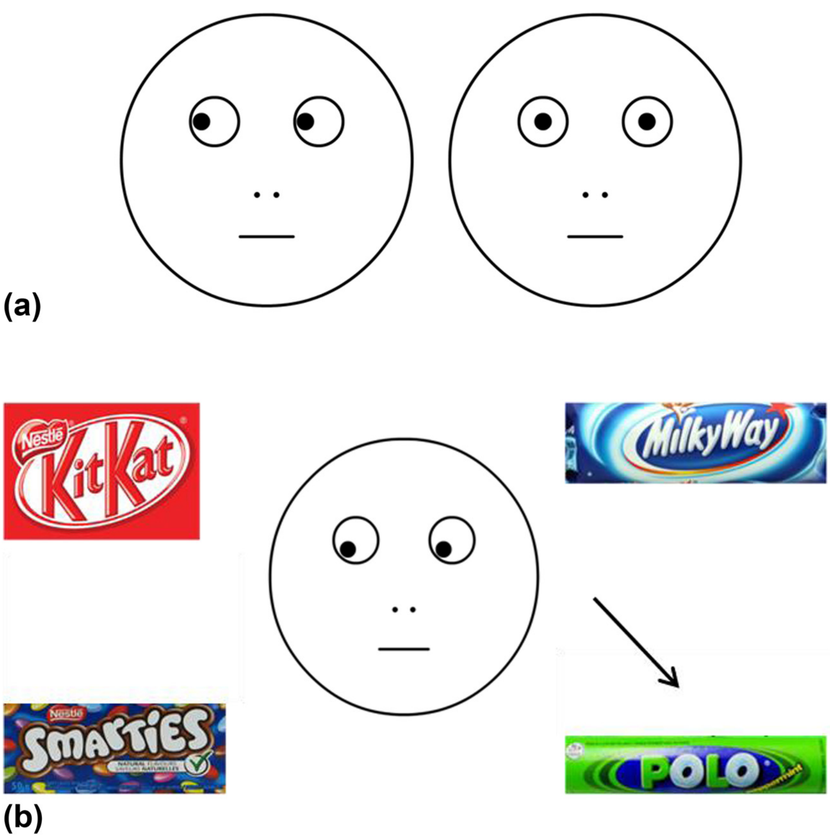

Figure 4: (a) Example question from the Charlie test: the child is asked "Which face is looking at you?." (b) Example question from the Charlie test: the child is first presented with the pictures of four sweets only and asked "Which one is your favourite?." Once the child gives an answer, the face referred to as Charlie is placed in the middle looking at one of the sweets, along with an arrow pointing at a third sweet, and the child is then asked "What is Charlie looking at?."

that of their own. This game involves showing Kaspar various animal themed toys that have been placed around the room. In this game, Kaspar does not move and looks straight ahead. The child therefore needs to locate and move the requested objects into Kaspar's field of view. A screen placed next to Kaspar displays what Kaspar can see. This game allows the children to explore what happens if they move a toy into the robot's field of view as the toy becomes immediately visible on the screen. Kaspar will ask the child to show it particular animals, and the child needs to find the corresponding animal and show it to Kaspar in an appropriate manner. Kaspar then rewards the child by making the sound of the animal. Kaspar only rewards the child though when the correct toy is shown to it appropriately (i.e. is placed in front of Kaspar's face and at an acceptable distance from the eyes/face).

Six trials were administered: three trials with the screen on and three trials with the screen off. The purpose was to encourage the children to work out what Kaspar can see without referring to the screen. This is an important step because in real-life interactions with other people the child cannot see what other people can see via a screen. In these games, the screen is simply used as a stepping stone to help teaching the children about VPT; and at this stage, we tried to get the children to complete the game without the assistance of a screen.

4.5.2 Game 2: I spy with my little eye [...]

This game is based on the well-known game "I spy." The toys are placed around the room (with sufficient spacing) and the child needs to work out and pick the toy that Kaspar is referring to and then show the toy to Kaspar. Kaspar then rewards the child by making the sound of the animal. Six trials were administered: three trials with the screen on and three trials with the screen off. This game is a VPT1 exercise.

4.5.3 Game 3: What you see is not the same as what I see

In this game, the child is given a cube with pictures of animals on the cube faces (Figure 5). When the child shows Kaspar one of the pictures of the animals on the face of the cube, Kaspar makes the sound of that animal as in the previous games. It is important to note that the face of the cube that is facing the child is different from

Figure 5: Children participating in the study with Kaspar.

the face of the cube that is facing the robot. This game is classed as a VPT2 exercise because the robot and the child are looking at the same object but see different things. The child needs to understand that what he/she sees is not the same as what Kaspar sees. Three trials were administered, and all three of them with the screen on.

4.5.4 Game 4: Show me an animal on the cube

Similar to the previous games, Kaspar looks in one direction only and the child is given the same cube as in Game 3 with pictures of animals on the cube face. However, in this game the child must show the animal on the cube face that Kaspar requests. Again this game is classed as a VPT2 exercise because the robot and the child are looking at the same object but see different things. This game helps reinforce the lessons from the previous game. Six trials were administered: three trials with the screen on and three trials with the screen off.

4.5.5 Game 5: I'll tell you what I want to see and you need to show me

Similar to Game 1, Kaspar states the name of the animal that it wants to see. However, in this setting the child has to direct where Kaspar looks rather than moving the objects into Kaspar's field of view. The toys are placed around the room, so that they are viewable by the robot from where it is located. The child needs to physically move the robot's head to make it look at the requested toy. Similar to the first two games this is classed as a VPT1 exercise, reinforcing what had been learnt in the first two games but in a different (interaction) context. Therefore, this game requires the children to transfer what they have learnt in Games 1 and 2 to a different game. An important new feature of this game is that here the children learn about how someone's physical head movement and orientation affect what they can see. Six trials were administered: three trials with the screen on and three trials with the screen off.

4.5.6 Game 6: When can I see?

In this game, we aimed to test whether the child understands that Kaspar cannot see when its eyes are covered. This game was introduced to prepare children for the next three games – during which we will utilise a turntable and a modified version of the Sally–Anne test – by teaching them about specific components of VPT. In addition, this game is an important step for us to understand the results of Game 9 later on as it helps us to exclude an important factor; namely, that in order to see, the eyes need to be open, which could make the child fail in Game 9. Different ways were used to cover Kaspar's eyes: eyes were covered with a sleeping mask, eyes were shut and covered by Kaspar's hands, eyes were shut only, Kaspar's line of sight was obstructed by a barrier in front of Kaspar's eyes and control trials with Kaspar's eyes open. The barrier used to obstruct Kaspar's view was a white plastic sheet, which was part of the turntable used in Games 7 and 8. During the game, the researcher showed an animal toy to Kaspar in each trial and the child decided whether Kaspar can see it or not. Similar to Game 5, this game is classed as a VPT1 exercise.

With each child 16 trials were conducted, i.e. 8 trials with the eyes open (4 trials with the screen on/4 with the screen off) and 2-2-2-2 trials with the eyes covered with a sleeping mask/hands + eyes shut/eyes shut only/barrier in front of Kaspar's eyes (1 trial of each with the screen on/1 trial of each with the screen off) in a predetermined semi-random order.

4.5.7 Game 7: What can we see?

Generally children with ASD struggle to view a situation from another person's perspective and realise that what they want, feel, know and think is different from another person's thoughts and feelings. In this game, a physical separator device (turntable) is placed on the table between Kaspar and the child. The separator in this game allows four positions: in the first two positions, the toy can be seen by both Kaspar and the child (toy is either on the right or on the left side of the barrier). In the second position, the toy can be seen by Kaspar only, while in the third position the toy can only be seen by the child (Figure 6). In this game, the child places one toy in the holder and the researcher moves the holder into one of three positions before Kaspar asks the child questions

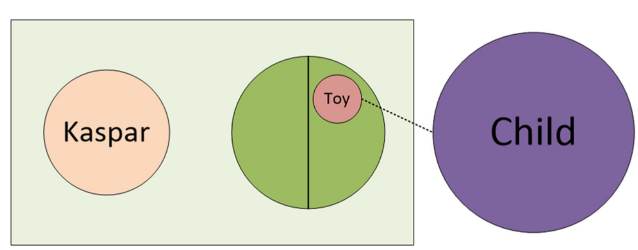

Figure 6: Equipment layout for Game 7.

about the visibility of the object. This game is classed as a VPT2 exercise. Eight trials were administered: four trials with the screen on and four trials with the screen off.

4.5.8 Game 8: Who can see what?

This game is similar to Game 7; however, in this game, the children place three toys into the holder and the holder has four different positions in terms of the toys' visibility to the robot and the child (Figure 7). In this game, the researcher asks the child to show Kaspar each one of the toys in the holder (or asks them to show Kaspar two of the toys at a time) and the child needs to turn the turntable accordingly, taking the visibility of the toys in the holder into consideration. Similar to Game 7, this game is classed as a VPT2 exercise. Six trials were administered: three trials with the screen on and three trials with the screen off.

4.5.9 Game 9: Where will I look?

This game is inspired by the well-established Sally–Anne test [27] (see above). This game consists of two boxes with lids, a blue box and a red box. The child picks one animal toy and Kaspar asks the child to put it into one of the boxes and then place the lid on it while Kaspar watches. The robot then says that it is tired and going to have a quick nap, Kaspar will close its eyes. While Kaspar's eyes are closed and the robot is "sleeping," the researcher encourages the child to move the toy into the opposite container and place the lid on it. The researcher then asks the child to wake Kaspar up to continue playing by calling or touching it. When the robot wakes up, the researcher asks the child to point where the robot would look for the toy. The child should point to the last place where Kaspar saw the object if the child developed ToM. Kaspar then states where it thinks the toy is, i.e. where it last saw the toy. If the child does not identify this correctly, then the researcher explains to the child that the robot did not see the child move the toy and would have looked in the other container. This game aims to assist the child in learning about ToM and to assess their progress. Four trials were administered: one trial with the screen on and three trials with the screen off.

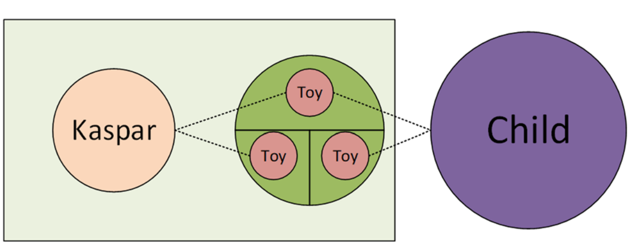

Figure 7: Equipment layout for Game 8.

5 Progression criteria in the games

Each child was required to pass a certain number of trials consecutively and unassisted both with and without the screen (showing what Kaspar could see through its eyes) in order to progress to the next game. The number of trials children needed to pass in order to progress depended on the difficulty and on the nature of the games. The progression criteria were first trialled in the pilot study [50].

Each child was required to pass three trials consecutively and unassisted both with and without the screen in order to progress to the next game in Games 1, 2, 3, 4, 5 (from the "I'll ask for the animal, you find me the animal" game to the "I'll tell you what I want to see and you need to show me" game) and in Game 8 ("Who can see what" game). Note, no trials were administered with the screen off in Game 3 ("What you see is not the same as what I see" game). Each child was required to pass 8 trials consecutively and unassisted both with and without the screen in order to progress to the next game in Game 6 ("When can I see?" game), and 4 trials consecutively and unassisted both with and without the screen in Game 7 ("What can we see?"). In Game 9 ("Where will I look" game), one trial was required to be completed successfully with the screen on and three further trials without the screen.

In case a child failed a game, we went back to the previous game and repeated it. In case the child failed the same game the second time as well, we skipped that game and moved on to the next one. In case the child passed the next game, we moved on according to the progression criteria above. However, when the child failed the following game too, in two consecutive sessions, in order to avoid the children to become frustrated or discouraged, we finished the trials and moved on to the post-test assessments.

In case the child failed in three consecutive trials in two consecutive sessions in Game 9 – "Where will I look" game, which was the last game of the study – we ended testing and moved on to the post-test assessments.

The progression criteria not only ensured that the child is developing the desired skills but provided us with an important measurement to establish how well the children were progressing.

6 Data analysis

Considering that our data were often measured on nominal or ordinal scales and were not continuous, non-parametric procedures were used.

The McNemar test [70], a test applicable to analyse paired nominal data, was utilised to compare the pre- and post-intervention results of the Smarties and the Sally–Anne tests. Wilcoxon signed rank test [71] was used to analyse participants' pre- and post-intervention performance in the Charlie test (in percentage).

Friedman ANOVA [72,73] – the non-parametric alternative of the repeated-measures ANOVA that allows the evaluation of the differences between three or more matched samples – was utilised to compare participants' progression in the different games. For further comparison of the participants' success rates in the games, binary data based on whether the participants successfully completed each game were analysed using the Cochran's Q test [73]. Dunn's *post hoc* test and Bonferroni corrections of significance for multiple comparisons were used for further pairwise comparisons.

Non-parametric Spearman correlation [74] was used to analyse the effect of mental age on participants' performance in the different games.

7 Results

The McNemar test yielded no significant differences in the results of the binomial data of the Smarties ($p > 0.05$) and the Sally–Anne tests ($p > 0.05$). However, we found significant improvement in the participants' success rates in the Charlie test ($Z = -2.04$; $p = 0.04$), suggesting that their VPT abilities did improve over the sessions with Kaspar (Table 2 and Figure 8).

Looking at the children's progress over the games in more detail, we analysed the number of trials necessary for them to proceed from one game to the next in order to define which games were the most difficult for them. Since the progression criteria were different for certain games and participants needed to complete three, four or eight successful trials consecutively in order to progress to the next game depending on the game, we calculated the ratio of the number of trials the children needed to progress and the progression criteria of each game, respectively (minimum number of trials to complete successfully in order to progress). This ratio was then used for the comparison of the different games. Friedman ANOVA revealed a significant difference among the games, $F(8) = 31.18$; $p < 0.001$. Pairwise comparisons with Dunn's *post hoc* test and Bonferroni corrections of significance for multiple comparisons showed that participants needed significantly more trials in Game 9 ("Where will I look") compared to that in Game 2 ("I spy with my little eye;" $p = 0.04$), Game 3 ("What you see is not the same as what I see;" $p = 0.03$), Game 4 ("Show me an animal on the cube;" $p = 0.02$) and Game 8 ("Who can see what;" $p = 0.01$; Figure 9). No further differences were found in the completion of the games. These findings suggest that Game 9 was significantly more difficult for the children to complete compared to Games 2, 3, 4 and 8. Whereas Games 1, 5, 6, and 7 were not significantly different from Game 9. This suggests that the children needed relatively more trials (not significantly fewer attempts than in the hardest Game 9) to progress at their first ever encounter with Kaspar, in the "Move my head" scenario, in the "When can I see" scenario and at their first encounter with the turntable.

Examining the success rates in the games, we find that every participant succeeded in each game but Games 6 and 9, which were successfully completed by 12 and 7 children of the 13 participants, respectively (Figure 10). Cochran's Q test revealed significant differences in the participants' success rates in the games ($\chi^2 = 42.07$; $p < 0.0001$), with Dunn's *post hoc* test – after Bonferroni corrections for multiple comparisons – showing that significantly fewer participants completed Game 9 successfully than any other game (G9 vs G1, 2, 3, 4, 5, 7, 8: $p < 0.001$; G9 vs G6: $p < 0.01$).

Children needed an average of 4.73 sessions (SD = 2.66; ranging from 1 to 10 sessions) to complete all games.

Table 2: Children's pre- and post-assessment performance. Results of the Smarties and the Sally–Anne tests are presented in the number of children who passed each time (pre- and post-intervention), while results of the Charlie test are presented in the mean percentage of participants' performance over the 15 trials of the test

Performance	Smarties test	Sally–Anne test	Charlie test
Pre-assessment	4	10	66.66% (SD = 24.34)
Post-assessment	4	6	78.94% (SD = 16.96)
Pre- vs post-assessment comparison	$p > 0.05$	$p > 0.05$	$p = 0.04$

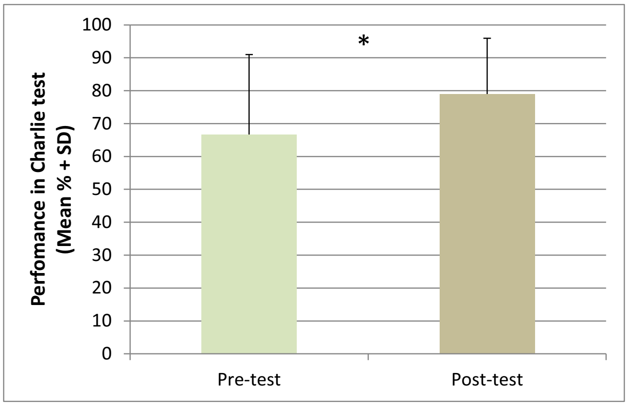

Figure 8: Participants' pre- and post-test performance in the Charlie test.

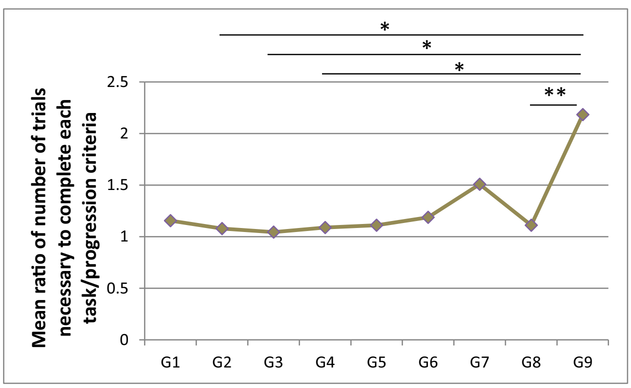

Figure 9: Progression rates in each game.

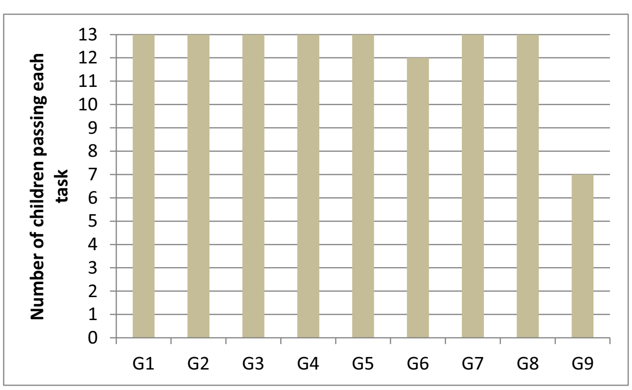

Figure 10: Success rates in each game.

Correlation results showed no correlation between mental age and the performance of children in any of the games but in Game 9 (Spearman's Rho $r = -0.57$; $p = 0.03$), where children's performance negatively correlated with their mental age. As performance was measured in the number of trials children needed to successfully complete the game, the correlation shows that the lower the children's mental age, the more trials they needed to succeed (if at all). This suggests that in our study mental age positively correlated with ToM abilities, higher mental age predicting more developed ToM abilities. As there was no such correlation in the other games, results did not suggest such correlation between mental age and VPT skills.

8 Discussion

While some earlier studies suggested that VPT1 skills may be intact in ASD [11,18–20], findings of Warreyn et al. [15,75] provided evidence that children with ASD have difficulties with VPT1 tasks as well as with VPT2 tasks, suggesting that these skills may develop in a slower and qualitatively different way in children with ASD. This is why we included both VPT1 and VPT2 tasks in our intervention with Kaspar. Although children progressed well in some of the games utilising VPT1 exercises during our intervention such as the "I spy" game, they needed relatively more trials to progress in the "move my head" and the "when can I see" games. Similarly, children progressed relatively easily in some of the Level 2 VPT games such as the "Show me an animal on the cube" game, while they found Game 6 – their first encounter with the turntable – and Game 9 – a game based on the Sally–Anne test – more difficult.

Difficulties with the turntable are not surprising. Yirmiya et al. [24] used a turntable to measure VPT2 skills of children with ASD and found that children with ASD showed a lower performance compared to chronological age and IQ matched typically developing children. More recently, Hamilton et al. [16] employed a turntable task in comparison with a matched mental rotation task. Their findings provided further support to earlier findings, showing that children with ASD had significant difficulties with the VPT2 turntable task compared to the mental rotation task. These results indicate that VPT2 skills are strongly affected in ASD – along with ToM – because they require mentalisation [16]. Mentalisation was also required to complete Game 9 (the "Where will I look" game based on the Sally–Anne test), which was a cognitive perspective taking task. This can explain why in our study Game 9 was significantly more difficult for the children to pass than any other games.

Furthermore, while children's VPT skills in our study did not correlate with mental age – which is in line with earlier findings of Dawson and Fernald [76] – cognitive perspective taking skills did correlate with the children's mental age as well, which can be explained with the fact that ToM develops more slowly and later in age.

Importantly, the robot-assisted intervention utilised in this study has shown promise to be an effective intervention to teach children about VPT skills. The intervention was not only effective in teaching children to successfully perform certain games but their skills progressively developed over the succession of games, and children even showed some level of generalisation by using the newly acquired skills in the slightly different context of one of three post-test assessment tasks (i.e. their performance significantly increased in the Charlie test compared to the pre-test assessments), even though the level of generalisation achieved might be limited.

These findings are especially important as very few previous studies have examined potential behavioural intervention procedures to assist children with ASD in developing VPT skills, and these previous studies typically applied a very small sample size working with only three children [32–34].

Our methods, however, did combine some elements of previously successfully utilised methods. Similar to the method applied by Gould et al. [34], our games were focusing on teaching different components of VPT, with e.g. Game 5 ("I'll tell you what I want to see and you need to show me") focusing on head orientation, while Game 6 ("When can I see?") focused on the comprehension of eye gaze and the obstructed view of others. Using the screen for teaching children about what the robot can see also shared some similarities with the video modelling method applied by LeBlanc et al. [33] as both methods provide engaging ways of teaching children with ASD that do not require direct social interactions with a therapist.

In fact, the robot-assisted intervention with Kaspar proved to be a very enjoyable way for children to learn about VPT. In fact, several children kept asking to return for playing more with Kaspar even after completion of the games. In the case of one specific child, teachers asked us to have regular sessions with him after his completion of the games as he could not stop talking about Kaspar. When this child returned, he knew every single game by heart. He reorganised the animal toys in the room according to the game he wanted to play and played the games with Kaspar with no assistance required from us. This provides some evidence that the games with Kaspar were intrinsically motivating for the children, which was previously proved to be beneficial – and potentially more efficient than extrinsic motivation – for the learning of children with and without ASD in classroom practice [77].

9 Limitations and future work

We have to note a serious limitation of the study, which is the lack of control groups. The lack of control groups makes it impossible to separate the impact of Kaspar on the children's VPT skills from the effects of other interventions practised in the school. However, the fact that the children completed the games in a relatively short time frame (in an average of 4.73 sessions) and that they received no other specifically VPT-oriented intervention during the study may suggest that the improvement measured over the study in their VPT skills is the result of our robot-mediated intervention with Kaspar.

Another potential factor we could not exclude in the lack of control groups is that children may have improved on the post-test assessment for the reason that they have already been exposed to the stimuli at the baseline (pre-test) assessment. In order to make sure that this practice effect is accounted for as a possible future direction, a wait-list controlled trial can be designed.

Further limitations of the current study include the sex ratio of the participants, i.e. the inclusion of 2 girls and 11 boys, and the lack of information on the participants' verbal language abilities, both of which have to be given more careful consideration in the design of the future studies.

In addition, we have to mention one more limitation of the study, namely, that the number of sessions was not standardised from child to child as each of them progressed in the games in their own pace. This, however, meant that we could not control how the number of sessions and the time elapsed between the pre- and post-test assessments may have affected their learning and memory. Another potential future direction could be to standardise this across children.

Additionally, as part of the future work we plan to develop semi-autonomous implementations of these games in order to make them more user friendly for both the child and the adult operator. Potential technologies we will use to facilitate this automation include the kinect sensor and ultra-high frequency radio-frequency identification to enable tracking of tagged objects. Those developments will help to make the scenarios more user-friendly for the therapist and reduce the cognitive load on him or her to administer the intervention.

10 Conclusion

In conclusion, our results suggest that robot-assisted therapy can be an effective intervention to teach children about VPT skills and may be preferable to methods requiring more direct interactions with therapists, since the mediation of a robot may be less stressful and more enjoyable to the children.

Acknowledgement: This work has been partially funded by the BabyRobot project supported by the EU Horizon 2020 Programme under grant 687831.

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