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ORIGINAL PAPER

Understanding Others' Minds: Social Inference in Preschool Children with Autism Spectrum Disorder

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Abstract
The study used an eye-tracking task to investigate whether preschool children with autism spectrum disorder (ASD) are able to make inferences about others' behavior in terms of their mental states in a social setting. Fifty typically developing (TD) 4- and 5-year-olds and 22 5-year-olds with ASD participated in the study, where their eye-movements were recorded as automatic responses to given situations. The results show that unlike their TD peers, children with ASD failed to exhibit eye gaze patterns that reflect their ability to infer about others' behavior by spontaneously encoding socially relevant information and attributing mental states to others. Implications of the findings were discussed in relation to the proposal that implicit/spontaneous Theory of Mind is persistently impaired in ASD.

Keywords Social inference · Theory of mind · Autism spectrum disorder · Eye-tracking · Preschool children

Humans are highly social beings. The abilities to share feelings, to exchange ideas, and to anticipate each other's behaviors are essential for our social life. When people fail to demonstrate the capacity to engage in social interactions with others, they are often thought to be "in their own world". One special population that has long been categorised as being "in their own world" is people with autism spectrum disorder (ASD). In fact, persistent deficits in social communication and social interaction are one of the two diagnostic criteria for ASD (*DSM-5*; American Psychiatric Association 2013). Deficits in social communication are often attributed to more general difficulties with attributing mental states to others, and the ability to attribute mental states to others is often referred to as Theory of Mind (ToM) (Premack and Woodruff 1978). It is generally acknowledged that individuals with ASD have poor ToM (e.g., Baron-Cohen 1988; Baron-Cohen et al. 1985; Frith and Happé 1994; Happé 1993, 1995; Heavey et al. 2000; Jolliffe and Baron-Cohen 1999; Liu et al. 2008; Peterson et al. 2009; Roeyers and Demurie 2010; Wellman et al. 2001; Wellman and Liu 2004; Wellman et al. 2006; Wimmer and Perner 1983; Yirmiya et al. 1998; Zhang et al. 2016).

ToM has often been investigated using the false-belief task or its variants (Baron-Cohen et al. 1985; Wellman et al. 2001; Wellman and Liu 2004; Wellman et al. 2006; Wimmer and Perner 1983). In the standard false-belief task, an experimenter presents an event in which an object is moved during the absence of a protagonist and then asks the child where the protagonist will look for the object when she returns. The assumption is that if children have ToM, then they should predict the protagonist's behavior on the basis of her belief and thus pointing out that she would look for the original location where she left the object. If children lack ToM, then they might predict the protagonist's behavior based on their own belief of where the object really was and thus pointing out the current location of the object. Prior research has shown that TD children as young as 4 years can pass the standard false-belief task, whereas TD children younger than 4 and much older children with ASD often fail the task.

Note that the standard false-belief task requires explicit verbal responses, which might pose difficulties for younger TD children and children with ASD. It has been reported that children's performance in the standard false-belief

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task is highly relevant to their language ability, in particular their verbal abilities (e.g., Happé 1995; Hoogenhout and Malcolm-Smith 2014; Tager-Flusberg 2007). To overcome the problems of the standard false-belief task, recent studies used non-verbal tasks to investigate children's attribution of false belief (Baillargeon et al. 2010; Buttelmann et al. 2009; Clements and Perner 1994; Onishi and Baillargeon 2005; Ruffman et al. 2001; Southgate et al. 2007). The results of these non-verbal tasks have shown that TD children younger than 4 years of age exhibit spontaneous behavioral patterns that reflect their ability to attribute false beliefs to others. The non-verbal eye-tracking paradigm developed by Southgate et al. (2007) has also been used to study false belief attribution in ASD (Schuwerk et al. 2015; Schuwerk et al. 2016; Senju et al. 2009, 2010; Senju 2012).

In the task, participants were presented with video stimuli in which an actor was watching an object being hidden in a box; the object was then displaced while the actor was looking away. Participants' eye movements were recorded and analyzed to see whether they spontaneously anticipated the actor's subsequent behavior on the basis of his false belief of the location of the box. There were two key findings. First, 8-years-old high-functioning children with ASD failed to exhibit looking patterns that reflect their spontaneous attribution of a false belief to the actor, but their TD peers that were matched on verbal abilities as well as performance in the standard false-belief task were able to do so (Schuwerk et al. 2016; Senju et al. 2010). Second, adults with ASD with relatively high verbal abilities also failed to exhibit looking patterns that reflect their false belief attribution, although they could pass the standard false-belief task (Senju et al. 2009; Senju 2012).

To summarize, prior studies using non-verbal tasks have demonstrated that TD children younger than 4 years of age, who consistently fail the standard verbal false-belief task, generate spontaneous behavioral patterns associated with false belief attribution. By contrast, highly verbal 8-year-old children and adults with ASD, who can pass the standard false-belief task, fail to exhibit looking patterns that reflect spontaneous false belief attribution. This contrast between the standard verbal false-belief task and the non-verbal measures is often attributed to the distinction between explicit ToM versus implicit/spontaneous ToM. Senju and colleagues proposed that individuals with ASD exhibit a deficit in implicit/spontaneous ToM and this deficit is presumably causing the social and communicative deficits in ASD (Senju et al. 2009, 2010; Senju 2012). In addition, the fact that this deficit is observed in older highly verbal children and adults with ASD seems to suggest that implicit/spontaneous ToM is relatively independent of verbal abilities (Schuwerk et al. 2015; Schuwerk et al. 2016; Senju et al. 2009, 2010; Senju 2012).

The use of non-verbal false-belief tasks makes it possible to investigate the early development of ToM in both typical and atypical populations, in particular in children with ASD. Unlike the standard false-belief task, non-verbal tasks require minimal task demands involving language and other cognitive abilities, thus ideally suited for testing this special population.

However, most prior research using non-verbal eye tracking tasks focused on older children (i.e., 8-year-olds) and adults with ASD. There is a paucity of research investigating the implicit/spontaneous ToM in preschool children with ASD. In order to see whether the implicit/spontaneous ToM is persistently impaired in ASD, it is crucial to explore whether this ability is impaired in much younger children with ASD (e.g., preschoolers with ASD).

In addition, most previous studies examined children's ability to attribute false beliefs to others. Reasoning about mental states is more than reasoning about false beliefs (Bloom and German 2000; Fodor 1992). Attribution of false belief is just one aspect of ToM, and there are other more fundamental aspects of ToM, aspects that do not involve false beliefs. False-belief tasks, either in the form of verbal or non-verbal measures, require participants to reason about a belief that is false. As Leslie and colleagues pointed out, people's mundane beliefs are generally true, so the best guess about others' beliefs is that they are the same as one's own, which is referred to as the true-belief default by Leslie and colleagues (Leslie 1987, 1994; Leslie et al. 2005). Therefore, in false-belief tasks the successful reasoning about a false belief requires the inhibition of the true-belief default. It is generally acknowledged that many aspects of children's cognitive abilities, such as inhibitory control and working memory, are limited compared to that of adults (e.g., Diamond 2006; Diamond and Gilbert 1989; Diamond et al. 2002; Gathercole et al. 2004). Cognitive abilities, like inhibition and working memory, are particularly impaired in children with ASD (Christ et al. 2007; Hill 2004; Luna et al. 2007; Ozonoff et al. 1991; Williams et al. 2005). It is, therefore, not surprising that younger TD children and children with ASD often fail to attribute false beliefs. To understand the development of social reasoning abilities in ASD, it is important to investigate other core aspects of ToM, in addition to false belief attribution.

To address these issues, the present study investigated implicit/spontaneous ToM in preschool children with ASD using a novel non-verbal eye-tracking task. In addition, instead of looking at false belief attribution, we explored a different, and presumably a more fundamental aspect of social reasoning, that is, the ability to make inferences about other people's behaviors in terms of their mental states in a given social situation. We refer to this ability as the capacity to make social inferences. This capacity is a crucial component of social communication skills.

Research has shown that reasoning about others' beliefs begins very early in infancy and preschool age. For example, even TD 8- to 9-months-old infants appear to consider whether or not a person is willing to help when they request objects and when they reach for objects (Behne et al. 2005; Liszkowski 2018; Ramenzoni and Liszkowski 2016; Tamis-LeMonda et al. 2008; Tomasello et al. 2007). However, it remains largely unclear whether preschool children with ASD can make social inferences in a given social context. As discussed, false-belief attribution involves cognitive abilities like inhibition and working memory, which might pose particular difficulties for children with ASD. So we were interested to see whether preschool children with ASD are able to make inferences about others' behaviors in terms of their mental states, when this ability does not involve false belief attribution.

To further minimize the task and communication demands for children with ASD, we developed a novel non-verbal eye-tracking task. The task does not require language responses and simply measures participants' eye movements that arise as automatic responses to a given social scenario. If preschool children with ASD exhibited a deficit in implicit/spontaneous ToM even when this ability does not involve the inhibition of false beliefs, then they might fail to exhibit eye gaze patterns that reflect their ability to infer about others' behavior by spontaneously encoding socially relevant information and attributing mental states to others.

Methods

Participants

Twenty-nine 5-year-old Mandarin-speaking children with ASD participated in the study, recruited from the Enqi Autism Platform in Beijing. Their diagnoses were confirmed at the age of 4 by paediatric neurologists at hospitals using both DSM-IV-TR (APA 2000) and DSM-5 (APA 2013). In addition, each of the 29 children was further evaluated independently by an expert clinician using the Autism Diagnostic Observation Schedule (ADOS; Lord et al. 1999). All the recruited children met the autism cut-off on the ADOS. Three of the 29 children did not proceed to the actual test, because they did not pass the two pre-test phases. Another two children did not complete the actual test, because they became distressed during the task, and refused to continue. Two additional children did not proceed to the actual test, because we were unable to calibrate them on the eye tracker. The other 22 children (14 boys and 8 girls, age range 5;2–5;5, mean 5;3) successfully completed the task and were included in the final analyses.[1] In addition, 50 TD children participated in the study: 25 (13 boys and 12 girls, age range 5;1–5;5, mean 5;3) were matched to the children with ASD for age, and 25 (13 boys and 12 girls, age range 4;2–4;9, mean 4;5) were matched for IQ. The TD children were recruited from the Beijing Taolifangyuan Kindergarten. This study was approved by the Ethics Committee of the School of Medicine, Tsinghua University, 20170018. Informed consent was obtained from all individual participants included in the study.

Table 1 IQ scores of each participant group

	ASD 5-year-olds	TD 4-year-olds	TD 5-year-olds
Number	22	25	25
Mean (SD)	103.24 (11.86)	103.38 (11.71)	109.66 (9.01)
Range	89–125	91–126	96–128

The participants' IQ was assessed using the Wechsler Preschool and Primary Scale of Intelligence™—IV (CN)—a standardised IQ test designed for Mandarin-speaking children between the ages of 2; 6 and 6;11 (Li and Zhu 2014). The mean IQ (a full scale IQ) score for each participant group is presented in Table 1. As indicated in the table, all the participants had an IQ score above 88. The 5-year-olds with ASD were matched with the TD 4-year-olds on IQ scores ($t(44) = 0.23$, $p = 0.86$, Cohen's $d = 0.01$). The 5-year-olds with ASD had significantly lower IQ scores than their age-matched TD peers ($t(44) = 3.55$, $p < .01$, Cohen's $d = 0.61$).

Materials and Design

A total of 16 items were constructed, each consisting of a spoken sentence and two visual images, one in which the boy character Kangkang was in the presence of a man and one in which Kangkang was in the presence of a tree. All the items used the same spoken sentence: "Look, which item do you think Kangkang is going to reach for?" Note that the original sentence was presented in Mandarin. The visual images always contained the boy character Kangkang, two boxes (a high box and a low box) and two items (one that Kangkang likes and one that he does not like). We refer to the item that Kangkang likes as the liked item and the one that he does not like as the disliked item. On half of the trials, the high box was on the left and the low

[1] One reviewer suggested that we include the IQ scores of the seven participants who were excluded from the actual study. We have now calculated the IQ scores of the seven participants (mean = 103.18, SD = 11.54, range 90–124), and we wish to note that the seven participants were comparable with those who participated in the study on IQ scores.

Fig. 1 A typical visual image containing a man

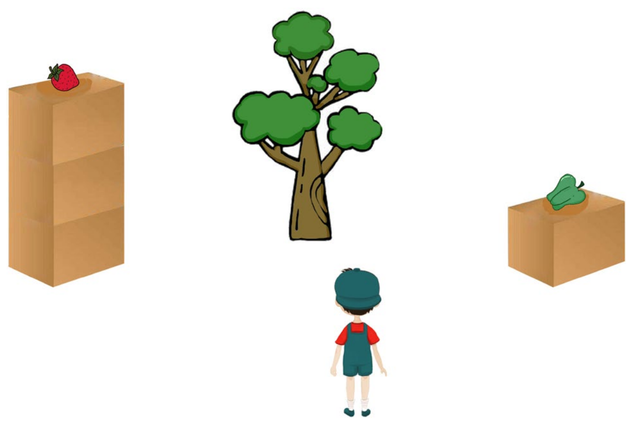

Fig. 2 A typical visual image containing a tree

box was on the right; and on the other half their positions were reversed. In addition, on half of the trials, the liked item was on the high box and the disliked item was on the low box, on the other half their positions were reversed. The crucial variable, the social meaning, was manipulated by presenting either a man or a tree in the visual images. On half of the trials, a man was present in the visual scene and on the other half a tree was present in the scene. To illustrate, consider the situations in Figs. 1, 2.

Figures 1, 2 represent two critical conditions in the study. In both figures, a strawberry was on the high box and a green pepper was on the low box. The strawberry was the liked item and it was outside Kangkang's reach. The crucial difference between the two conditions was that in Fig. 1 Kangkang was in the presence of a man whereas in Fig. 2 Kangkang was in the presence of a tree, representing a difference in social meaning: The man (but not the tree) can offer help and is willing to help. The study was designed to see whether both TD children and children with ASD were able to derive this social meaning from the visual scene and use the social meaning to predict Kangkang's behavior, i.e., which item Kangkang is going to reach for.

Fig. 3 An example picture used in Phase I

The 16 items were divided into two lists with each participant hearing the same spoken sentence but seeing only one of the two visual images that could accompany the spoken sentence (e.g., either Fig. 1 or Fig. 2). In each list, there were eight trials containing a man (e.g., Fig. 1) and eight trials containing a tree (e.g., Fig. 2). In addition, in each list there were an equal number of trials concerning which item occurring on which box: eight trials with the liked item on the high box and eight trials with the liked item on the low box. In each list, the 16 items were arranged in random order. Participants in each group were randomly assigned to one of the two lists, with eleven 5-year-olds with ASD, thirteen TD 5-year-olds and thirteen TD 4-year-olds run on List 1, and eleven 5-year-olds with ASD, twelve TD 5-year-olds and twelve TD 4-year-olds run on List 2.

Procedure

The experimental procedure consisted of three phases, two pre-test sessions and the actual test. In each phase, the participants including both TD children and children with ASD were tested individually.

Phase I was used to establish the contrast between the liked items versus the disliked items. The participants were presented with pictures that contained items of the two categories (see Fig. 3) and were explicitly instructed about which items Kangkang likes and which items he does not like. Altogether 16 pairs of items were presented to the participants. On half of the trials, the liked item occurred on the left and on the other half it occurred on the right. For example, when presented with a picture in Fig. 3, the participants were told that Kangkang likes watermelon but he does not like red peppers.

After the participants went through all the 16 pairs, 12 out the 16 pairs were randomly selected to test the participants whether they were able to distinguish the liked items from the disliked items. On half of the trials, the participants were asked to point to the item Kangkang likes and on the other half they were asked to point to the item Kangkang does not like. Only those participants who provided correct responses on all the 12 trials proceeded to Phase II.

In Phase II, the participants were first presented with a picture as in Fig. 4. As indicated in the figure, the giraffe was used as a yardstick to measure the height of the high box, the

Fig. 4 The yardstick used in Phase II

man, the tree, Kangkang and the low box. It was made clear to the participants that the man can reach the high box, but Kangkang cannot. Kangkang can only reach the low box. To test whether the participants understand that the high box was outside the reach of Kangkang and the low box was within his reach, 12 trials were constructed. An example trial is given in Fig. 5, where the liked item (the watermelon) was on the low box and the disliked item (the red pepper) was on the high box. On half of the trials, the liked item was placed on the high box, and on the other half it was on the low box. In addition, the position of the high box and the low box was counterbalanced across trials. The 12 trials were presented to the participants in random order. On half of the trials, the participants were asked to point to the item that Kangkang can reach for and on the other half they were ask to point to the one that Kangkang cannot reach for. Only the participants who responded correctly on all the 12 trials were included in Phase III, the actual test.

In Phase III, the actual test, the participants were presented with visual images as in Figs. 1, 2 accompanied with the spoken sentence "Look, which item do you think Kangkang is going to reach for?" (see details in the "Materials and Design" section). Their eye movements were recorded using an EyeLink 1000 plus eye tracker (by SR Research Ltd., Mississauga, Ontario, Canada). The EyeLink 1000 plus allows remote eye tracking, without a head support. It provides information about the participant's point of gaze at a sampling rate of 500 Hz, and it has accuracy of 0.5° of visual angle. The visual stimuli were displayed on the monitor. Spoken sentences were presented to the participants through the PC computer connected to two external speakers. The distance between the participants' eyes and the monitor was about 60 cm. During the test, two experimenters were involved, one monitoring the participant on the computer, and one standing behind the participant and gently resting her hands on the participant's shoulders to minimise the participant's sudden movements. The experimenter who monitored data collection used the live viewer mode to observe the participants' looking behavior in real time and signalled to the second experimenter to reorient the participants when their eye gaze wandered off the computer screen. We measured participants' eye movements associated with their inferences about Kangkang's behavior in situations where the social meaning was manipulated (a man vs. a tree). To minimise the computational burden of the participants, we did not ask them to make any conscious judgements about the situations presented in the visual scenes; instead, they were simply told to listen to the spoken sentences while viewing the visual scenes and their eye movements were recorded as automatic responses to the scenes. The spoken sentence started 500 ms after the appearance of the visual stimulus. Participants' eye movements were recorded from the onset the verb "reach" (*gou* in Mandarin) for 1000 ms. We believed that once the participants heard the verb of the sentence, they should be able to make their inferences about Kangkang's behavior.

Predictions

If the participants were able to make inferences about Kangkang' behavior in terms of his mental states in the given situations, then different eye gaze patterns should be expected when a man was present in situations where the liked item

Fig. 5 An example picture used in Phase II

was on the high box versus when a tree was present in the same situations. But no difference should be expected in situations where the liked item was on the low box regardless of whether a man or a tree was present.

Consider the situations in Fig. 1 versus Fig. 2. In both figures, the liked item (strawberry) was on the high box and thus was out of Kangkang's reach. However, in Fig. 1 Kangkang was in the presence of a man who can offer help and is willing to help, so in order for the participants to make successful inferences about Kangkang's behavior, a three-step process is required: first, to make an inference about the man's action: the man is willing to help and is going to help Kangkang; then, to infer about Kangkang's belief: Kangkang believes that the man is willing and is going to help him, and on the basis of that, to predict Kangkang's behavior: Kangkang is going to reach for the liked item on the high box, because he believes that the man is going to help him achieve the goal. In Fig. 2 the man was replaced with a tree, the participants should understand that Kangkang cannot reach the liked item, and nobody would come to help. Therefore, the participants might infer that Kangkang would probably reach for the item on the low box because that item was within his reach. The difference in the inference processes would lead to different eye gaze patterns in the two critical conditions. More specifically, in situations where the liked item was on the high box, the participants should look at the high box area significantly more often when a man was present than when a tree was present. By contrast, in situations where the liked item was on the low box, the participants would be expected to look at the low box area equally often when a man was present versus when a tree was present, because the liked item was within Kangkang's reach and thus he should be able to obtain it on his own. The participants' eye gaze patterns should enable us to understand whether they can make social inferences successfully.

Results

In preparing the data, we pooled the fixations shorter than 80 ms with the preceding or following fixations if they were within 0.5° of visual angle, otherwise we deleted them, because short fixations are often a result of false saccade planning rather than meaningful information processing, and participants do not extract much information during such short fixations (Rayner and Pollatsek 1989). In addition, following the convention of analysing eye gaze data, trials were excluded if there was more than 33% track loss from the onset of the sentence until the sentence was completed. No trials were excluded for both the ASD and the TD groups. The time course of the eye gaze patterns is not our concern here. For our purposes, we were interested to see whether participants exhibited looking patterns that reflect their ability to infer about Kangkang' behavior by spontaneously encoding socially relevant information and attributing mental states to Kangkang. So, in analysing the eye movement data, participants' fixations were coded in four areas of interest: the high box area (containing the high box and the item on its top), the low box area (containing the low box and the item on its top), the social element/agent (the man or the tree) and the boy character (containing Kangkang). For each trial, the proportion of fixations[2] in the four areas was time-locked to the onset of the verb "reach" (*gou* in Mandarin). The proportion of fixations following the onset of the verb for each area was then computed in a time window of 1000 ms per trial per participant. The proportion of fixations on a particular interest area in this time window was treated as the dependent variable. For example, if we recorded four fixation points in this time window, with 1 fixation point located in a specific interest area, then the proportion of fixations on that area was ¼.

As discussed in the predictions, the two critical conditions are the one with the liked item on the high box, and the one with the liked item on the low box. When the liked item was on the high box, the presence of a man versus a tree should make a difference in the participants' fixation proportions. But when the liked item was on the low box, the participants' fixation proportions should not be affected by the presence of a man versus a tree. Figure 6 shows the average proportion of fixations of the three participant groups on the high box with the liked item (the left panel for each group), on the low box with the liked item (the middle panel for each group) and on the agent (the right panel for each group) in scenes where a man was present versus in scenes where a tree was present.

As indicated in the figure, a higher proportion of fixations was observed on the high box with the liked item when a man was present in the scene than when a tree was present in the scene, for both the TD 4-year-olds and the TD 5-year-olds, but not for the 5-year-olds with ASD. No difference in fixation proportions was observed on the low box with the liked item when a man was present in the scene versus when a tree was present in the scene, for all the three groups. In addition, no difference in fixation proportions was observed on the two agents (the man versus the tree) for all the three groups.[3]

[2] Proportion of fixations is a now standard measure in assessing both children's and adults' cognitive abilities like language. We wish to extend this measure to other domains of cognition like ToM. We wanted to show that proportion of fixations is also a reliable eye gaze measure for assessing children's social cognition like ToM. This is another novelty of the present study, in addition to using a novel task.

[3] This comparison of fixation proportions on the man versus the tree was a response to one reviewer's concern. The reviewer asked whether the lack an effect in the ASD group as compared to the TD groups could be due to the ASD group's reduced tendency to fixate

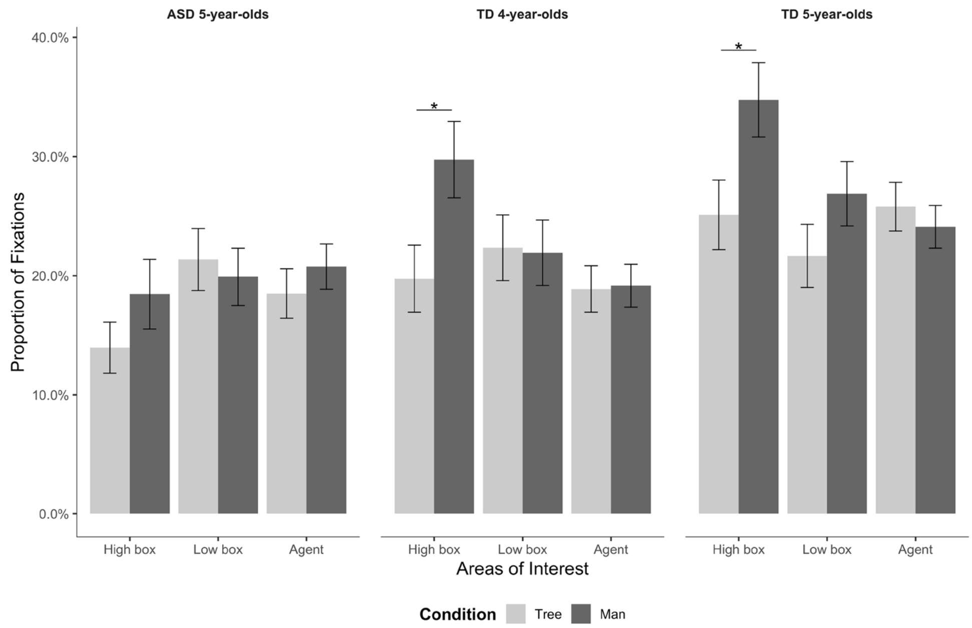

Fig. 6 Proportion of fixations of the 5-year-olds with ASD, the TD 4-year-olds and the TD 5-year-olds on the high box with the liked item (the left panel for each group), on the low box with the liked item (the middle panel for each group) and on the agent (the right panel for each group) in scenes where a man was present vs. in scenes where a tree was present. Error bars indicate SEs. *Indicates that there was a significant difference between the two conditions, at the significance level of .05 (p < .05)

Table 2 The statistical results of the observed effects

Area of interest	Group	Fixed effect	Estimate	Std. error	z value	Pr (>|z|)	Sig.
High box							
	ASD 5-year-olds	(Intercept)	−2.83	0.51	−5.51	0.00	***
		Man versus tree	0.75	0.64	1.18	0.24	
	TD 4-year-olds	(Intercept)	−2.34	0.40	−5.93	0.00	***
		Man versus tree	1.11	0.48	2.32	0.02	*
	TD 5-year-olds	(Intercept)	−1.79	0.31	−5.72	0.00	***
		Man versus tree	0.89	0.40	2.24	0.02	*
Low box							
	ASD 5-year-olds	(Intercept)	−2.24	0.40	−5.57	0.00	***
		Man versus tree	−0.57	0.65	−0.87	0.38	
	TD 4-year-olds	(Intercept)	−1.73	0.31	−5.54	0.00	***
		Man versus tree	−0.61	0.50	−1.21	0.23	
	TD 5-year-olds	(Intercept)	−1.89	0.32	−5.85	0.00	***
		Man versus tree	0.37	0.43	0.85	0.40	
Agent							
	ASD 5-year-olds	(Intercept)	−2.15	0.28	−7.83	0.00	***
		Man versus tree	0.27	0.37	0.73	0.47	
	TD 4-year-olds	(Intercept)	−2.01	0.24	−8.20	0.00	***
		Man versus tree	−0.19	0.36	−0.53	0.59	
	TD 5-year-olds	(Intercept)	−1.46	0.20	−7.24	0.00	***
		Man versus tree	−0.26	0.30	−0.87	0.38	

The R formula used in the glmer function is: Proportion ~ condition + (1 + condition|condition/trial) + (1 + condition|Participant)

*p < .05; ***p < .001

Footnote 3 (continued)

on the man as compared to the tree. The comparison showed that no difference in fixation proportions was observed on the two agents for all the three groups (see also Fig. 6; Table 2), excluding this alternative explanation.

To assess the statistical significance of these fixation patterns, we fitted generalised linear mixed models (GLMMs)[4] to the data set in each area of interest for each group. The GLMMs were applied to the obtained data without aggregation. The models include one fixed effect and two random terms. The fixed effect is *condition*, i.e., when a man was present in the scene or when a tree was present in the scene. The two random terms are *trial* and *participant*. The random effects of the models include both the intercept and the slope of the fixed effect with respect to the two random terms. The model fitting processes were realised with the *glmer* function in the lme4 package (v1.1.19) (Bates et al. 2013) under the R (v3.5.2) software environment (R Development Core Team 2017). There were three areas of interest and three participant groups, so the same model was run 9 times in total. The exact formula we used in R is given in the footnote of Table 2. The fitting results are summarised in Table 2. As shown in the table, when the liked item was on the high box (upper panel), the TD 4-year-olds and the TD 5-year-olds looked significantly more at the high box when the agent in the scene was a man as compared to when the agent was a tree (the TD 4-year-olds: $b=1.11$, $z=2.32$, $p=.02$; the TD 5-year-olds: $b=0.89$, $z=2.24$, $p=.02$). No such effect was observed for the 5-year-olds with ASD ($b=0.75$, $z=1.18$, $p=.24$). When the liked item was on the low box (middle panel) the TD 4-year-olds, the TD 5-year-olds and the 5-year-olds with ASD exhibited similar fixation patterns regardless of whether the agent was a man or a tree. In addition, for all the three groups no statistical difference was observed in the fixation proportions on the two agents, the man versus the tree (lower panel).[5]

[4] In an eye tracking study using the visual world paradigm, participants' current fixation in a specific area is heavily dependent on their previous fixation, both on the temporal dimension and on the spatial dimension. In addition, proportion of fixations (based on fixation count) is categorical in nature and bounded by the values 0 and 1, which follows a multinomial distribution rather than a normal distribution. Therefore, traditional statistical methods based on the hypotheses of independent sampling and normal distribution such as *t* tests and ANOVAs cannot be directly applied. It has now become a standard procedure to analyse the fixation data using generalised linear mixed models (GLMMs) that do not require the assumption of normal distribution (Barr 2008; Jaeger 2008; Zhan 2018).

[5] One reviewer suggested that we could also run t-tests on differential looking scores. We have followed the reviewer's suggestion and analysed the differential looking scores using *t* tests. The *t* tests yielded similar statistical results and thus confirmed our observations using GLMMs. The t-tests results are provided in "Appendix A" section.

Discussion

In the present study, we devised a novel non-verbal eye-tracking task to investigate whether preschool children with ASD are able to make inferences about others' behavior in terms of their mental states in a given social situation. The capacity to make social inferences like this is essential for navigating the social world. More specifically, we measured the eye gaze patterns associated with children's inferences about the boy character Kangkang's behavior in situations where a man was present versus where a tree was present. The presence of a man versus a tree leads to a crucial difference in social meaning: the man (but not the tree) can offer help and is willing to help. The derivation of this social meaning informs children's inferences about Kangkang's behavior. As discussed, this is a three-step process: first, to infer about the man's action that he is going to help Kangkang; then, to make an inference about Kangkang's belief that the man is going to help him, and on the basis of that, to predict Kangkang's behavior. The results show that both the TD 4-year-olds and the TD 5-year-olds looked at the high box with the liked item significantly more often when Kangkang was in the presence of a man than when he was in the presence of a tree. The eye gaze patterns clearly reflect their ability to perform this three-step social inference. This is evidence that by age 4, TD children are able to make predictions about others' behaviors in terms of their mental states in a given social situation. By contrast, the fixation proportions of the 5-year-olds with ASD were not affected by the presence of a man versus a tree, indicating that they are not able to make the same social inference as their TD peers. The findings have important theoretical and practical implications.

First, our findings advance previous research by showing that the deficit in implicit/spontaneous ToM, documented in 8-year-olds and adults with ASD (Schuwerk et al. 2015, 2016; Senju et al. 2009, 2010; Senju 2012), is also observed in preschool children with ASD (i.e., 5-year-olds). In addition, previous research mainly focused on false belief attribution when examining ToM in ASD. The present study extends the investigation of ToM to a more fundamental aspect of ToM—the ability to make social inferences and this ability does not involve false belief attribution. The findings show that children with ASD also exhibit a deficit in this more fundamental level of ToM, in addition to the impairment in spontaneous false belief attribution documented in previous research. The findings provide further evidence for the proposal that implicit/spontaneous ToM is persistently impaired in ASD[6] (Schuwerk et al. 2015, 2016; Senju et al. 2009, 2010; Senju 2012).

The comparison between the TD 4-year-olds and the 5-year-olds with ASD suggests that the ability to make social inferences might not be directly relevant to IQ levels. Note that the 5-year-olds with ASD were highly verbal and they were matched with the TD 4-year-olds on IQ scores (see the "Participants" section). Yet, unlike the TD 4-year-olds, they failed to exhibit an eye gaze pattern that reflects their ability to infer about Kangkang' behavior by spontaneously encoding socially relevant information and attributing mental states to Kangkang. The results suggest that implicit/spontaneous ToM is perhaps relatively independent of IQ levels or verbal abilities as previously documented (Schuwerk et al. 2015, 2016; Senju et al. 2009, 2010; Senju 2012).

The findings are also evidence that the eye-tracking task we developed can effectively assess young children's ability to make social inferences. The paradigm can also successfully distinguish preschool children with ASD from their TD peers in terms of their capacity to make social inferences. Thus, the task has the potential of becoming a component of a standardized test for assessing children's social cognition. The task also opens up a possibility for use with minimally verbal children with ASD, because it requires minimal task and communication demands, and it does not require explicit verbal responses from the participants. Of course, the validity and sensitivity of the task require further studies based on large samples. To establish eye gaze patterns associated with specific cognitive processes will help to identify early clinical markers for ASD and social impairment in general. In recent years, researchers have started to explore the possibility of using atypical visual search patterns as early risk markers for ASD (Falck-Ytter et al. 2013; Gliga et al. 2015; Guillon et al. 2014; Jones and Klin 2013; Kaldy et al. 2011, 2016). We believe that the current study presents a nice paradigm for exploring atypical eye gaze patterns associated with social impairment.

The findings also lead us to think about the nature of social communication deficits in ASD. Social communication deficits are a defining feature of ASD, along with restricted, repetitive patterns of behavior or interests. Social communication encompasses social interaction, social cognition, pragmatics, and language processing (American Speech-Language-Hearing Association 2018). For understanding the nature of the deficits, it is crucial to identify which of these components are impaired, which are preserved, and which one/ones lead to the overall deficits. The present study suggests that the social cognition of children with ASD is impaired. Social cognition depends on our capacity to understand others' behavior in terms of their mental states in a given social situation. The eye gaze patterns obtained from the present study indicate that the ability to understand someone's behavior socially is impaired in children with ASD. Developing a model of how each component interacts with the other in social communication in both TD and ASD populations is an important direction for future work.

Although our work broadens the available data on ToM and social cognition in children with ASD, like previous work our sample of children is highly verbal and does not represent a broader spectrum sample (e.g., our sample does not include minimally verbal children with ASD), so inferences about the overall spectrum should be made with caution. Further research is required to investigate ToM and social cognition in minimally verbal children with ASD. In addition, the observed eye gaze patterns in the present study were based on 22 preschool children with ASD. To further confirm the obtained eye gaze patterns, studies based on larger sample size are required.

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Author Contributions PZ conceived of the study, designed and implemented the study, performed the statistical analysis and the interpretation of the data, and drafted and revised the manuscript; LZ participated in designing and implementing the study, performing the statistical analysis and interpreting the data; HM participated in designing the study and interpreting the data.

Compliance with Ethical Standards

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

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

[6] One reviewer pointed out that the recognition of this deficit in making social inferences by parents and teachers should have an effect on how they respond to an affected child with ASD in both classroom and social settings, and then suggested that feedback in a cognitive remediation paradigm might have beneficial effects on high-functioning children with ASD. The idea is to improve their abilities to pause and think if they have correctly utilized information that they know in making social inferences, and in making children aware of their deficit in the capacity to make social inferences, we might improve their abilities to socially interact and communicate. We thank the reviewer for this helpful suggestion in designing treatment plans and this is definitely a future direction that is worth exploring.

Appendix A

T-Tests Results on the Differential Looking Scores Between the Two Critical Conditions

Following one reviewer's suggestion, we conducted a series of *t* tests on the differential looking scores between the two critical conditions. To conduct the analyses, we first calculated the differential scores between participants' fixations when the agent was a man versus when the agent was a tree. We then used *t* tests to determine whether the difference was significantly different from zero. If it was, then this was treated as a significant difference between the two critical conditions. The results are summarized in the table below. The *t* tests yielded similar statistical results and thus confirmed our observations using GLMMs.

Area of interest	Group	Difference	*t* value	df	p value	Sig.
High box						
	ASD 5-year-olds	0.18	1.47	21	0.16	
	TD 4-year-olds	0.40	3.16	24	0.00	**
	TD 5-year-olds	0.38	4.63	24	0.00	***
Low box						
	ASD 5-year-olds	−0.06	−0.51	21	0.62	
	TD 4-year-olds	−0.02	−0.12	24	0.91	
	TD 5-year-olds	0.21	1.36	24	0.19	
Agent						
	ASD 5-year-olds	0.18	0.70	21	0.49	
	TD 4-year-olds	0.02	0.15	24	0.88	
	TD 5-year-olds	−0.14	−0.63	24	0.53	

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