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Altered sense of gaze leading in autism

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Abstract:

Background: Impairments in joint attention are considered a hallmark of the Autism Spectrum Disorder (ASD). Yet, the ability of people with ASD to lead the attentional focus of others has been scarcely investigated.

Method: To address this issue, we designed virtual avatars that can follow the gaze of participants with head and eye movements in real time using eye-tracking. During a training phase, participants were alternately exposed to an avatar that followed their gaze and an avatar that did not. In a subsequent test phase, they were facing the two avatars at the same time.

Results: Eye-tracking data showed that, unlike typical controls, participants with ASD focused more on the gaze-following avatar. They were also less inclined to report that their gaze had been followed by this avatar.

Conclusions: These results suggest that adults with ASD fail to sense themselves as agents leading the attentional focus of others during joint attention episodes. Practitioners should not expect individuals with ASD to spontaneously understand the contingency between their attentional focus and someone else's, even if the link is highly ostensible.

Keywords: social behavior; joint attention; gaze-following; self-monitoring; avatar; eye-tracking

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Introduction

Impairments in joint attention are considered a hallmark of the Autism Spectrum Disorder (ASD). Joint attention involves sets of non-verbal communicative behaviors such as finger pointing or gaze cueing that start emerging by six months of age (Scaife & Bruner, 1975). Deficits in joint attention appear early in the development of the disorder as revealed by retrospective studies (Adrien et al., 1993; Gillberg et al., 1990; Osterling & Dawson, 1994). They allow to discriminate ASD from other atypical developmental courses (Dawson et al., 2004) and have been shown to predict language ability and communication symptom severity in infants and toddlers (Charman, 2003; Dawson et al., 2004; Toth, Munson, Meltzoff, & Dawson, 2006). Joint attention deficits are core targets for assessment instruments, such as the Checklist for Autism in Toddlers and the Autism Diagnostic Observation Schedule (Lord et al., 2000).

Emery (2000) characterized joint attention as a sequence of gaze behaviors where one individual follows the line of sight of another individual and then focuses on the same object as her/him. The ability to follow gaze has been extensively studied in typically developing individuals using a gaze cueing paradigm (for a review see Frischen, Bayliss, & Tipper, 2007) that was adapted from Posner's task (Posner, 1980): Participants were exposed to eyes or faces (referred to as gaze cues) that deviated laterally before a target appeared on one side. Although the orientation of the gaze cue was unrelated to the subsequent location of the target, participants showed a congruency effect whereby they were quicker to detect the target when its position was congruent with the gaze cue. Hence, these experiments revealed the existence of an automatic orientation of visual attention in the direction prompted by gaze cues (Driver, 1999; Friesen & Kingstone, 1998).

A sizeable literature has been devoted to studying gaze following in ASD. Experiments that applied Posner's adapted gaze cueing paradigm showed a congruency effect in school-aged children with ASD that was of the same magnitude as in typical controls (Kylliäinen & Hietanen, 2004; Swettenham, Condie, Campbell, Milne, & Coleman, 2003). Studies on infants and toddlers also confirmed that this automatic orientation of attention was preserved in ASD (Bedford et al., 2012; Chawarska, Klin, & Volkmar, 2003). In an eye-tracking study, Freeth, Chapman, Ropar and Mitchell (2010) reported that,

by adolescence, people with ASD with no intellectual disorder were spontaneously captured by a person's gaze and followed its direction in ecologically complex scenes. Nevertheless, additional studies indicated that people with autism had an atypical sensitivity to gaze cues, relying more than control participants on head and body orientation (Ashwin, Hietanen, & Baron-Cohen, 2015; Thorup et al., 2016). Experiments that used Posner's paradigm to compare gaze cues with arrow cues suggest that, contrasting with typically developing individuals, children and adults with autism process these two types of cues similarly (Senju, Tojo, Dairoku, & Hasegawa, 2004; Vlamings, Stauder, Son, & Mottron, 2005). Gaze cueing in ASD was reported to be predominantly driven by perceptual features (e.g. the position of the iris in the sclera) rather than by the referential meaning of social gaze (Chawarska et al., 2003; Congiu, Fadda, Doneddu, & Striano, 2016; Ristic et al., 2005). These results echoed the deficit in understanding the mentalistic significance of gaze cueing that was evidenced by Baron-Cohen, Campbell, Karmiloff-Smith, Grant and Walker (1995) with the Charlie task. This task presented children with a schematic representation of a face called "Charlie" whose eyes were directed towards one of four sweets and participants had to guess which one was Charlie's choice. Children with ASD scored lower on this task compared to peers with mental handicap and typical controls.

The literature on sensitivity to social gaze in ASD portrays a complex picture where preserved abilities in detecting and following gaze direction are paired with profound difficulties to engage in joint attention (Nation & Penny, 2008). Early work by Leekam, Baron-Cohen, Perrett, Milders and Brown (1997) pointed out the dissociation between correct identification of eye direction and spontaneous monitoring of gaze. Reduced visual attention to faces and eyes has been supported by recent eye-tracking studies of individuals with ASD watching social scenes (for a review see Chita-Tegmark, 2016). Although earlier eye-tracking experiments by Klin, Jones, Schultz, Volkmar and Cohen (2002a, 2002b) suggested that adults with ASD attended less to the eye region, later studies showed that such outcomes depended on the social context depicted in the visual stimuli (Speer, Cook, McMahon, & Clark, 2007). In addition, Rice, Moriuchi, Jones and Klin (2012) reported that the link between social disability and eye-looking was modulated by cognitive proficiency in children with ASD and Fletcher-Watson, Leekam, Findlay and Stanton (2008) indicated that, by adulthood, individuals with ASD displayed typical eye-gaze change detection abilities. However, Grynspan, Nadel, Martin, Simonin, Bailleul, Wang et al. (2012) suggested that people with ASD had difficulties in self-monitoring their own

gaze during social interactions. They designed a task where a virtual human telling a story was displayed on a screen that was entirely blurred except for a clear viewing window, which was controlled by an eye-tracker to follow the participant's focal gaze point. The viewing window thus provided participants with biofeedback about their gaze. Contrasting with typical controls, adults with ASD failed to adapt their eye movements to this biofeedback.

The goal of the present study was to investigate self-monitoring abilities in individuals with ASD when their gaze leads the attentional focus of another person during joint attention episodes. Studying gaze leading in controlled lab experiments requires that participants face a human like stimulus that reliably and consistently follows their gaze. A human performer cannot be expected to control her/his gaze in a systematic and timely manner while simultaneously observing the participant. We therefore used a virtual human (i.e. avatar) that followed the gaze of participants, which was detected in real-time with an eye-tracker. Similar setups have already been used to investigate gaze leading in typical adults: For instance, gaze leading has been reported to involve reward-related neural regions and was associated with enhanced liking of the gaze-following avatar (Bayliss et al., 2013; Grynszpan, Martin, & Fossati, 2017; Schilbach et al., 2010). Kim and Mundy (2012) revealed that gaze leading fostered memory of faces. Gaze-contingent avatars have also been used to investigate the sense of agency, that is, the sense of controlling one's actions and their effects on one's environment (Haggard & Chambon, 2012): Typical adults were shown to elicit a sense of agency for the eye movements of faces that followed their gaze (Grynszpan, Nadel, Martin, & Fossati, 2017; Pfeiffer et al., 2012; Recht & Grynszpan, 2019; Stephenson, Edwards, Howard, & Bayliss, 2018). . A couple of studies have used gaze-contingent avatars in ASD research to investigate the effect of gaze leading in memorizing cued images (Little, Bonnar, Kelly, Lohan, & Rajendran, 2016) and in deictic communication (Caruana et al., 2017). The later study reported that adults with ASD were not impaired in their ability to voluntarily use their eyes to point towards an object in order to socially share their interest for this object. Joint attention however is not limited to pointing behaviors. It also involves monitoring another person's reactions with respect to one's own pointing behaviors. As just mentioned, typical individuals develop a sense of agency when they lead the gaze of a person facing them (Grynszpan, Nadel, et al., 2017; Pfeiffer et al., 2012; Recht & Grynszpan, 2019; Stephenson et al., 2018). In addition, Edwards, Stephenson, Dalmaso and Bayliss (2015) showed that people's attention was captured by faces that followed their gaze and that this phenomenon was weaker in individuals with higher autistic traits. Our

study sought to test the hypothesis that adults with ASD have difficulties in sensing that another person is following their gaze. Participants were first administered a training task where they were alternately exposed to two avatars: One avatar was systematically following their gaze, while the other was not. Participants were then tested in a task where the two avatars appeared together. We tentatively expected that participants with ASD would not notice that one of the avatar followed their gaze and that their attention would be less captured by it. To increase joint attention demands, the two sequential tasks were inspired from the “Charlie” task (Baron-Cohen et al., 1995), which we upgraded to be suitable for adults: Participants were asked to choose their preferred object from a set of possible choices and guess what the avatars had preferred.

Method

Participants

Seventeen adults with ASD were recruited for this study (4 females and 13 males). Their mean age was 24.06 years ($SD = 9.99$). They had been diagnosed by psychiatrists based on DSM-IV R criteria (American Psychiatric Association, 2000). Five of them had their diagnosis confirmed by the Autism Diagnostic Interview-Revised (ADI-R) (Lord, Rutter, & Le Couteur, 1994) and 12 by the Autism Diagnostic Observation Schedule (ADOS-2) (Lord et al., 2000). Seventeen typical participants were also recruited (7 females and 10 males). Their mean age was 22.94 ($SD = 6.49$). They were screened with the Autism-Spectrum Quotient (AQ) test (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001) to exclude those who could potentially be on the Autism Spectrum, broadly speaking. They all scored in the range associated with the typical nonclinical population, that is, below 23 (Ruzich et al., 2015). Their mean AQ score was 13.29 ($SD = 5.92$).

Participants were administered the Raven’s Progressive Matrices (Raven & Court, 1986) to assess their inferential abilities and the Vocabulary sub-test of the Wechsler Adult Intelligence Scale – 4th edition (WAIS IV) (Wechsler, Coalson, & Raiford, 2008) to assess their verbal proficiency. As shown in Table 1, the scores of the typical and ASD groups were not significantly different on these two tests. The age and gender ratio of the groups did not differ significantly either. The two groups were thus considered to be matched on these variables. This research was reviewed and approved by the institutional ethics committee in accordance with the Declaration of Helsinki. An informed consent was obtained from each participant.

Table 1: Participants' characteristics

		ASD group	Typical group	<i>Statistic</i>	<i>p</i>
<i>N</i>		17	17		
Age					
	Mean	24.06	22.94	$t(32) = 0.387$	0.09
	SD	9.99	6.49		
Gender ratio					
	Females	4	7	$\chi^2 = 1.21$	0.27
	Males	13	10		
Raven's Matrices (standardized percentiles)					
	Mean	31.18	36.76	$t(32) = 0.659$	0.35
	SD	27.49	21.60		
WAIS IV Vocabulary sub-test (standardized scores)					
	Mean	10.88	12.41	$t(32) = 1.326$	0.68
	SD	3.18	3.54		

Material

Participants were seated in front of a computer screen equipped with an eye-tracker that remotely detected the direction of their eyes without them having to wear a helmet or a chin rest. The eye-tracker was an X2-60 model from Tobii (www.tobii.com) with a sampling frequency of 60 Hz and an accuracy of 0.4°. The dimension of the screen was 380 x 215 mm² with a resolution of 1920 x 1080 pixels. The distance between the participants and the screen was approximately 60-65 cm.

The bust of a male avatar was modeled and programmed to follow the gaze of the participant, according to the procedure explained in (Courgeon, Rautureau, Martin, & Grynszpan, 2014). The avatar only produced eyes and neck movements to change the orientation of its gaze. To minimize potential erratic movements due to micro-saccades or eye-tracking errors, the gaze positions of the participant were averaged on a sliding window of 100 milliseconds. The computation of rotation angles for the neck and eyes of the avatar were based on polynomial equations derived from calibration values according to the procedure detailed in (Courgeon et al., 2014). The sense of agency in typical participants when this avatar followed their gaze had been previously assessed in a separate study (Recht & Grynszpan, 2019). A latency of 500 milliseconds was introduced between the participant's gaze movements and the ensuing redirection of the avatar's gaze orientation. This latency is in the range that has been shown to yield effective sense of agency for gaze movements in typical people (Pfeiffer et al., 2012; Recht & Grynszpan, 2019). It also left enough time for participants to see the unfolding of the avatar's gaze-following movement when they would look at it. In addition to the avatar,

the virtual scene included three pictures of items that were placed in front of the avatar, below its head (Figure 2). The items were laid out on a circular arc around the avatar, one on the right, one on the left and the third one mid-way. The items were consumer goods that changed with every new trial. The avatar's head measured $7.7^\circ \times 10.1^\circ$ in visual angle and each item's dimension was $6.9^\circ \times 6.9^\circ$. The items on the right and on the left were each located 11.7° from the central axis of the screen. The third item was placed 5.9° below the center of the screen. The present study comprised two tasks (Figure 2). In task 1, the avatar was displayed alone in the center of the virtual scene. In task 2, the avatar was duplicated as two twins placed side by side and separated by 11.5° .

The avatar behaved according to two modes: It would either follow the gaze of the participant (gaze-following mode) or it was moving autonomously, that is, independently from the participant (autonomous mode). In the autonomous mode, the avatar was animated by replaying gaze movements recorded from a real person before the experiment. When replaying a sequence, the avatar would look back and forth at the items and at the participant, and stay focused on one of the items for the final second. This final item was randomly counterbalanced across sequences. Twelve sequences lasting 15s each were recorded for task 1 and ten sequences of 20s were recorded for task 2.

Procedure

To introduce the experiment, participants were told that they would be viewing twin brothers represented as virtual humans that looked exactly alike. Before each task, participants underwent a standard eye-tracking calibration procedure based on five points. Task 1 served as a learning phase where participants were exposed to the two gaze behavior modes and task 2 was meant to test the effect of learning.

Task 1 (training)

Participants were told that each twin would alternately appear alone on the screen, that is, the first twin would appear during blocks 1 and 3, while the second twin would appear during blocks 2 and 4 (Figure 1). Although both twins had exactly the same physical features, they differed with respect to their gaze behavior mode: One twin was always following the participant's gaze, while the other was always gazing independently. Participants were left uninformed of this association, as we wanted to see if they would notice it by themselves. They were nevertheless reminded of the change of twin at

the beginning of each block. The order of appearance of the two gaze behavior modes was counterbalanced across participants.

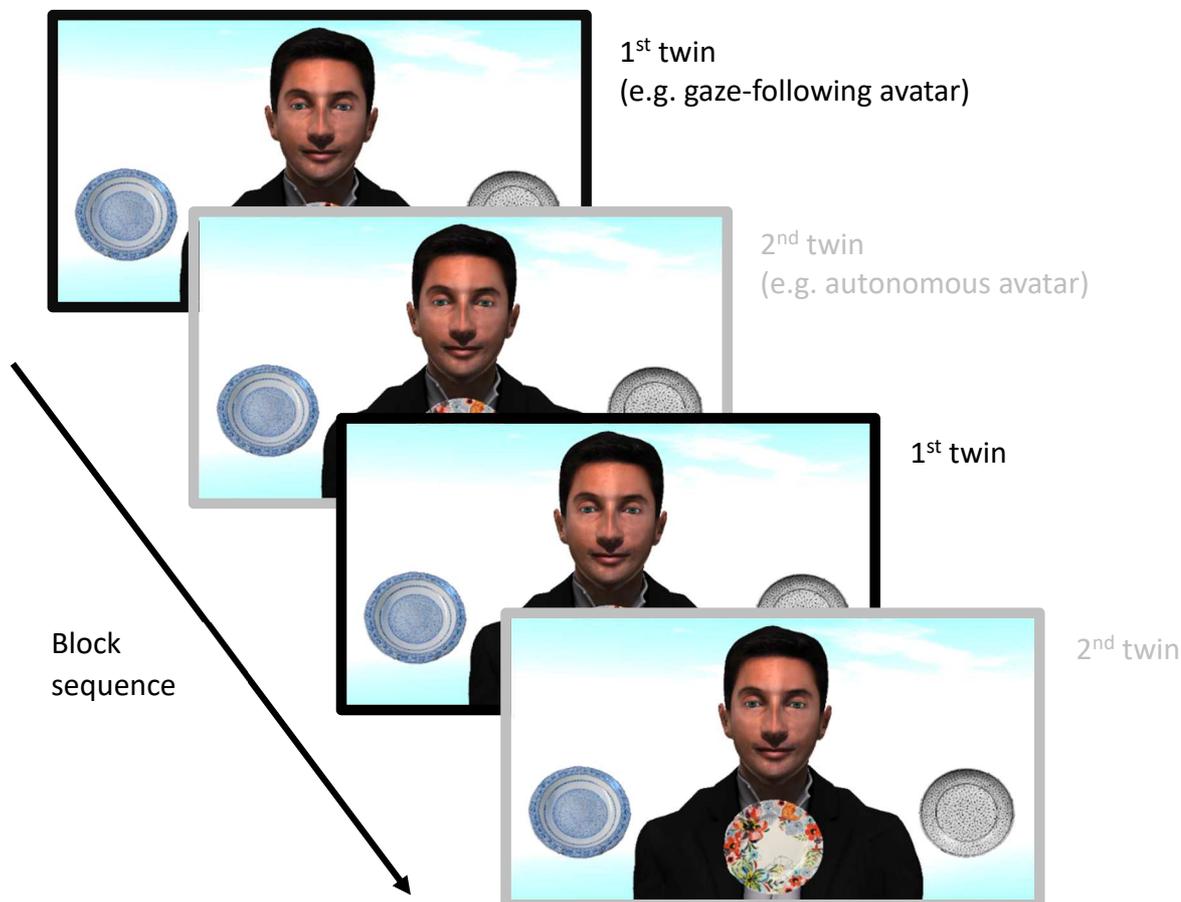


Figure 1: Sequence of blocks in task 1 (training). The two twins were alternately presented across blocks.

Each block of task 1 encompassed 6 trials. Each trial started with a fixation cross displayed for two seconds, before the virtual scene appeared. Participants were instructed to choose their favorite item and devise which one was preferred by the avatar. After being exposed to the scene for 15s, participants had to answer two close-choice questions that appeared sequentially on the screen. The first question required them to select their favorite item and the second one to make a guess regarding the favorite item of the avatar. The items were displayed under the question and participants clicked on their choice. The gaze-following mode of the avatar was meant to give the impression to the participants that the avatar's preferences depended on hers/his. We assumed that this mode would

prompt participants to guess that the avatar's favorite item was the same as theirs. In the autonomous mode, as explained earlier, the avatar would stay focused on a particular item for the final second. This last 1-second long gaze was supposed to help participants make a guess about the avatar's preference. Without this gaze cue, the task would have been more difficult and potentially discouraging for participants with ASD.

Task 2 (test)

The two twins were displayed together during task 2 (Figure 2). As before, one twin would always follow the gaze of the participant, while the other moved its gaze independently. The left or right positions of the twins were counterbalanced across participants. The task was separated in two blocks to allow for a break. Each block contained 5 trials. Each trial began with a fixation cross for two seconds. Participants were then exposed to the virtual scene for 20s. This duration was longer than in task 1, because participants had to attend to two avatars instead of one. After being exposed to the virtual scene, participants had to answer three questions: The first required them to select their favorite item, the second to select the favorite item of the avatar on the left and the third to select the favorite item of the avatar on the right.

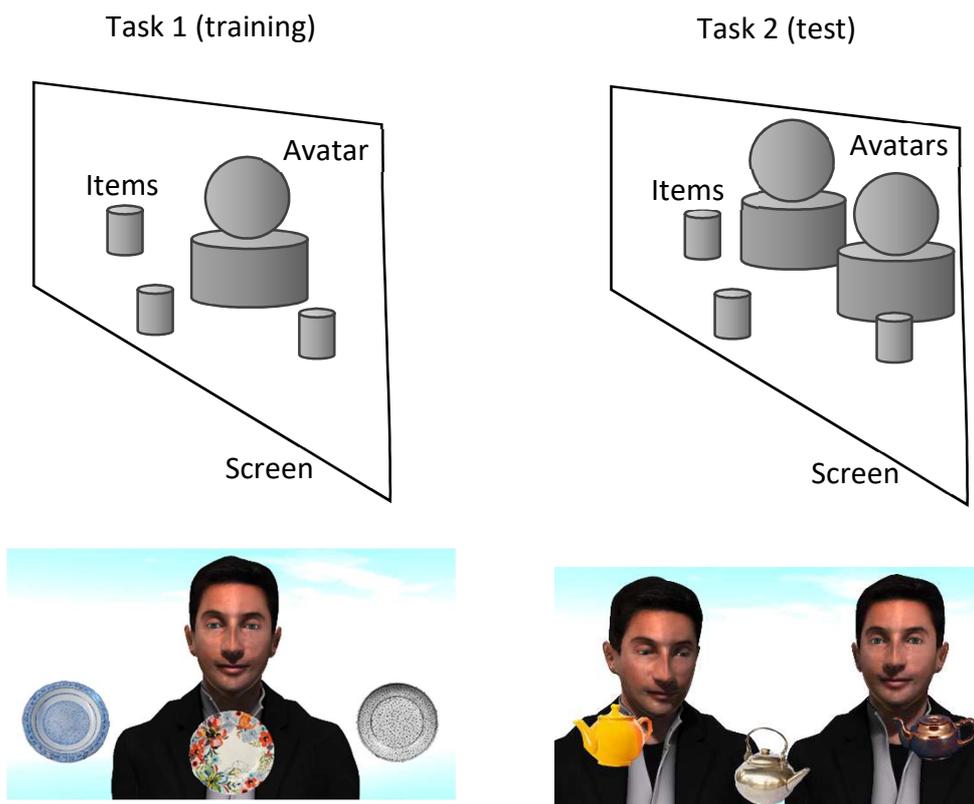


Figure 2: The virtual scenes displayed during task 1 (left) and task 2 (right). During task 1, each twin was alternately displayed alone, while in task 2, the two twin were displayed side by side.

At the end of task 2, a static picture of the two avatars positioned as before appeared on the screen and participants were asked to choose which twin they preferred. If participants preferred the twin on the left, they were to press the letter “A” (the furthest letter to the left on the keyboard). If they preferred the twin on the right, they had to press “P” (the furthest letter to the right on the keyboard). The purpose of this question was to check if gaze behavior had an influence on how much participants liked the avatars. Once participants had made their choice, they were asked orally why they had made such a choice and their answers were recorded. This final question was meant to assess if they would mention that one of the avatar was following their gaze.

Data analysis

We developed a velocity-threshold identification (VT-I) algorithm (Salvucci & Goldberg, 2000) to compute gaze fixations. The saccade velocity threshold was set at $35^\circ/s$ in compliance with Wass, Smith and Johnson (2013). Gaps due to gaze data loss smaller than 75ms were bridged by linear interpolations. The data was smoothed with a 3 points median noise reduction filter. Adjacent fixations

were merged when separated by less than 0.5° and 75ms. Fixations shorter than 75ms were discarded. This threshold was chosen, because it has been reported as the upper boundary of the interval necessary to encode the available foveal information during a fixation when viewing realistic scenes (van Diepen, De Graef, & d'Ydewalle, 1995).

We were interested in fixations on the avatars' faces. We aggregated all the fixations that fell on an area of interest (AOI) defined by a rectangle that circumscribed the face of each avatar. A fixation was associated with this AOI when the center of the fixation belonged to this AOI. The dimensions of this AOI were adjusted so that it would encompass the face even when the orientation of the head changed ($9.2^\circ \times 11.6^\circ$ in visual angle): We derived extreme points by setting the avatar's head to its maximum rotations in the upper-right, lower-right, upper-left and lower left directions and circumscribed the AOI around these points. For each avatar, the following metrics were derived from the eye-tracking data: The total duration of fixations on the face area (sum of the durations of individual fixations) and the mean fixation duration on the face (average duration of individual fixations). The total duration of fixations provided a measure of the amount of attention devoted to each avatar and the mean fixation duration informed on the processing time required when fixating it. Repeated measures analyses of variance (ANOVA) were conducted on these two eye-tracking variables. For each ANOVA, post-hoc *t*-tests were performed using the Tukey procedure. Statistical computations were conducted with the Statistica software (www.statsoft.com).

In addition to eye-tracking metrics, we defined two ordinal dependent variables to account for participants' responses during the tasks. They were called the "similarity score" and the "self-reference rating". Given that these variables were discrete numbers with a limited range, we used non-parametric tests to analyze them. The "similarity score" variable was associated with each avatar based on the responses to questions asked after each trial. This score was meant to characterize the degree to which participants tended to select the same favorite item for the avatar as for themselves. Participants scored one point each time they guessed that the avatar's favorite item was the same as theirs. The second variable called "self-reference ratings" was derived from an analysis of the answers given orally by participants when they were asked the reason for their choice of avatar. Answers were rated according to the following 6 points scale that increased with how explicitly participants referred to the fact that their gaze was being followed by an avatar:

- 1: No reasons given, e.g. “I do not know”.
- 2: Reasons based on how difficult the task was to complete, e.g. “It was easier to know what object the avatar chose”.
- 3: Reasons based on the physical aspect of the avatar, e.g. “He was better shaved than his twin” (this was an actual answer given).
- 4: Reason based on personality, e.g. “He seemed to be nicer”.
- 5: Reason based on a link between the avatar and the participant, e.g. “He chose the same items as me”.
- 6: Reason explicitly acknowledging that the avatar was following the participant’s gaze, e.g. “Because he was following my gaze the most”.

The answers were rated by two independent coders that had not contributed to the experiment. Inter-rater reliability was assessed using the inter-class correlation (ICC) (Hallgren, 2012), which showed excellent agreement between raters: $ICC = 0.98$ (Confidence Interval: 0.96 – 0.99).

Results

Task 1 (training)

Eye-tracking data

The between factor of the ANOVA used to analyze eye-tracking variables was the group (ASD vs Typical) and the within factors were the gaze behavior mode of the avatar (gaze-following vs autonomous) and the order of the block. Task 1 comprised 4 blocks and each gaze behavior mode appeared in two blocks that were associated with the same twin. The order factor of the ANOVA was the sequential number of blocks associated with a given gaze behavior, that is, the first vs the second block displaying the same twin.

The ANOVA on the total duration of fixations yielded a main effect of the order of the block, $F(1, 32) = 15.01$ $p < 0.001$ $\eta_p^2 = 0.32$. The average total duration of fixations for the first couple of blocks was 5.82s ($SD = 5.88$) and it decreased to 4.68s ($SD = 5.70$) in the second couple of blocks. There were no other effects or interactions.

Similarly, the ANOVA on the mean fixation duration only showed a main effect of the order of the block, $F(1, 32) = 6.42$ $p = 0.016$ $\eta_p^2 = 0.17$. The average mean fixation duration was 0.39s ($SD = 0.04$) for the first couple of blocks and 0.34s ($SD = 0.03$) for the second couple of blocks.

Similarity scores

For task 1, there was only one avatar appearing in each block, therefore there was only one preference similarity score in each block. Given that each block comprised 6 trials, the scale of similarity scores ranged from 0 to 6.

The preference similarity score was expected to rise for the gaze-following avatar as participants would begin to realize that this avatar was following their gaze and devise that its favorite item was the same as theirs. The first couple of blocks were meant to let participants discover the two avatars' respective gaze behaviors. Participants were not expected to notice the gaze-following behavior straightaway and we assumed that the effect on similarity scores would thus be tenuous during the first couple of blocks. By contrast, participants were expected to be familiar with the specific gaze behavior of each avatar during the second couple of blocks. The effect of the gaze-following behavior on similarity scores was therefore assumed to be more pronounced during those blocks. Hence, we only considered the second couple of blocks for analysis. The Wilcoxon's test for paired samples revealed that typical participants' similarity scores were significantly higher with the gaze-following avatar than with the autonomous avatar, $N = 12$ $T = 12.5$ $p = 0.038$ (see Figure 3). By contrast, there was no such difference for the ASD group, $N = 10$ $T = 11.5$ $p = 0.103$.

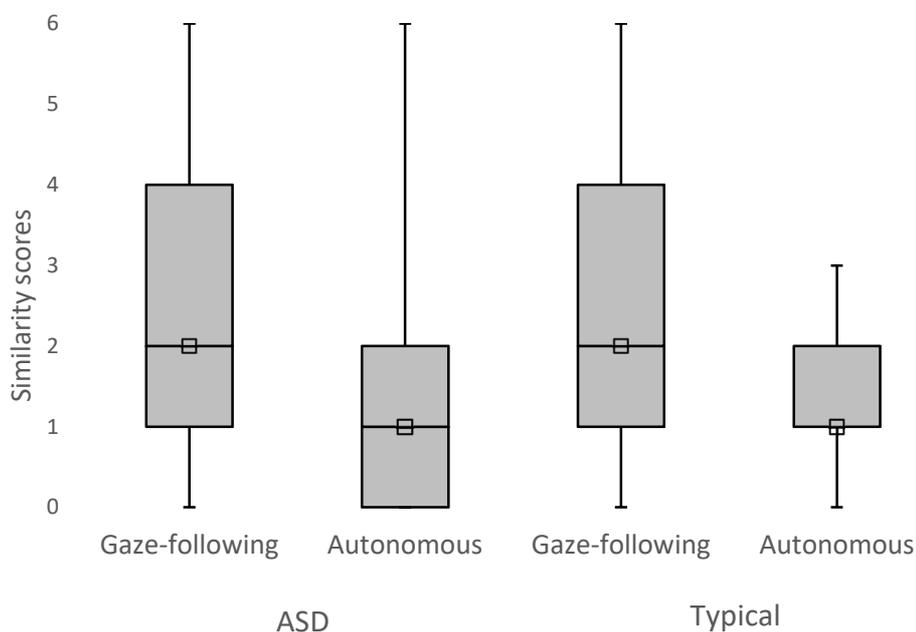


Figure 3: Similarity scores for the second couple of blocks (blocks 3 and 4) of task 1. The boxplots represent the medians, interquartile intervals and range of scores. The scores for the gaze-following avatar were higher than those for the autonomous avatar only for the typical group ($p < 0.05$).

Task 2 (test)

Eye-tracking data

As before, the between factor of the ANOVA for eye-tracking variables was the group (ASD vs Typical) and the first within factor was the gaze behavior mode of the avatars (gaze-following vs autonomous).

We added the trial as a second within factor to provide a finer analysis of the evolution of visual attention. As the two avatars/twins were displayed together during this task, the trial factor simply represented the sequential ordering of the trials. It ranged from 1 to 10. The Huynh-Feldt correction procedure was applied on the ANOVA to account for possible violations of the assumption of sphericity.

For the total duration of fixations, the ANOVA yielded a main effect of trial, $F(9, 288) = 2.33$ $p = 0.025$ (Huynh-Feldt corrected, $\epsilon = 0.786$) $\eta_p^2 = 0.07$. Post-hoc t -tests indicated that the total duration of fixations was greater during the first trial [mean = 4.74s $SD = 0.31$] than during trials 8 [mean = 3.76s

$SD = 0.31$] and 10 [mean = 3.81 $SD = 0.36$] ($p < 0.05$). The ANOVA also revealed an interaction between the gaze behavior mode and trial factors, $F(9, 288) = 2.43$ $p = 0.020$ (Huynh-Feldt corrected, $\epsilon = 0.792$) $\eta_p^2 = 0.07$. Post-hoc t -tests showed that the total duration of fixations on the gaze-following avatar was higher during the first trial [mean = 5.42s $SD = 0.42$] than during trials 7 [mean = 3.58s $SD = 0.48$] and 10 [mean = 3.54s $SD = 0.39$] ($p < 0.05$). No such differences were found for the autonomous avatar. More importantly for our hypotheses, there was an interaction between the gaze behavior mode and the group, $F(1, 32) = 5.15$ $p = 0.030$ $\eta_p^2 = 0.14$. The post-hoc t -tests yielded a difference that was on the threshold of significance ($p = 0.05$) between the two groups for the autonomous avatar, with the total duration of fixations for the typical group [mean = 4.85s $SD = 0.50$] being higher than for the ASD group [mean = 2.94s $SD = 0.50$]. Finally, the interaction between the gaze mode behavior, the trial and group factors was just above the threshold of significance, $F(9, 288) = 2.033$ $p = 0.051$ (Huynh-Feldt corrected, $\epsilon = 0.792$) $\eta_p^2 = 0.06$. Trial per trial post-hoc t -tests showed that participants with ASD spent more time fixating the gaze-following avatar than the autonomous avatar during trial 5 ($p < 0.001$). Such differences were not found for the typical group. Additionally, different patterns can be observed for the two groups when total fixation durations are plotted across trials (Figure 4): The ASD group seemed to pay more attention to the gaze-following avatar than to the autonomous avatar at the beginning of the task, but this difference tended to lessen towards the end of the task.

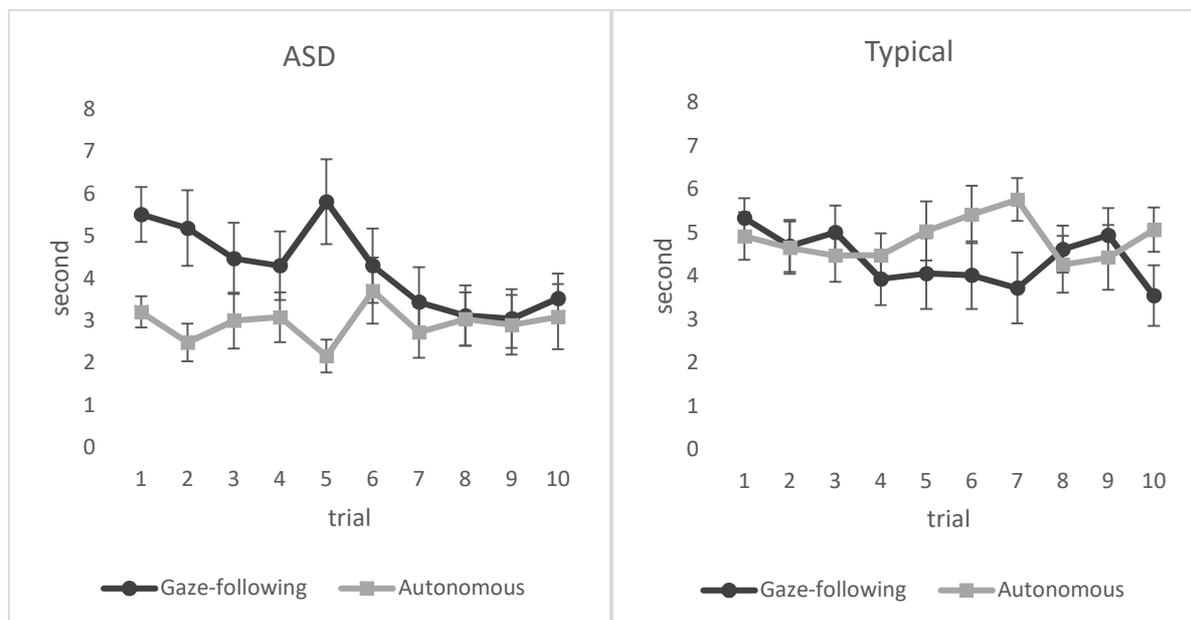


Figure 4: Total duration of fixations on the gaze-following and autonomous avatars across trials for the ASD group (left) and typical group (right). The error bars are the standard errors.

Regarding the mean fixation duration, the only significant outcome of the ANOVA was the interaction between the gaze behavior mode and the group, $F(1, 32) = 4.23$ $p = 0.048$ $\eta_p^2 = 0.12$ (see Figure 5). The post-hoc t -tests showed that the ASD participants had significantly longer mean fixation durations for the gaze-following avatar [mean = 0.32s $SD = 0.03$] than for the autonomous avatar [mean = 0.25 $SD = 0.03$] ($p < 0.05$). There was no difference between the two avatars for the typical group.

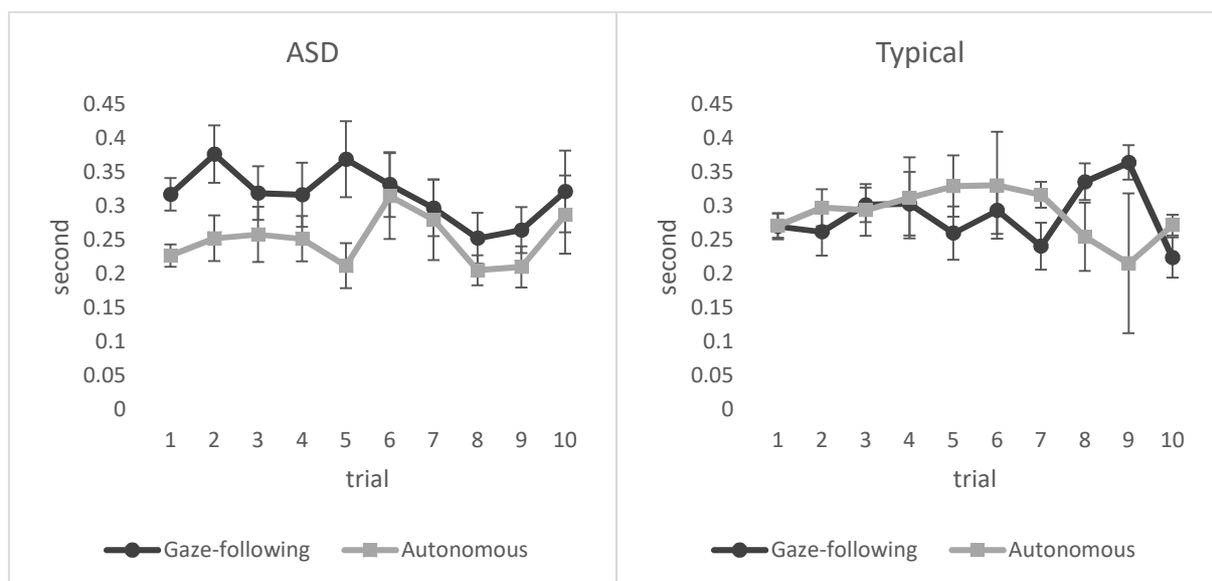


Figure 5: Mean duration of fixations on the gaze-following and autonomous avatars across trials for the ASD group (left) and typical group (right). The error bars are the standard errors.

Similarity scores

As the two avatars were displayed together during each trial of task 2, the preference similarity score associated with each avatar was computed over the 10 trials of the task and thus ranged from 0 to 10. We compared the scores of the gaze-following avatar with those of the autonomous avatar for each group using the Wilcoxon's test for paired samples. There was no significant difference for the ASD group, $N = 13$ $T = 45$ $p = 0.972$. The difference for the typical group did not reach significance either, although it was close, $N = 14$ $T = 23$ $p = 0.064$ (See Figure 6).

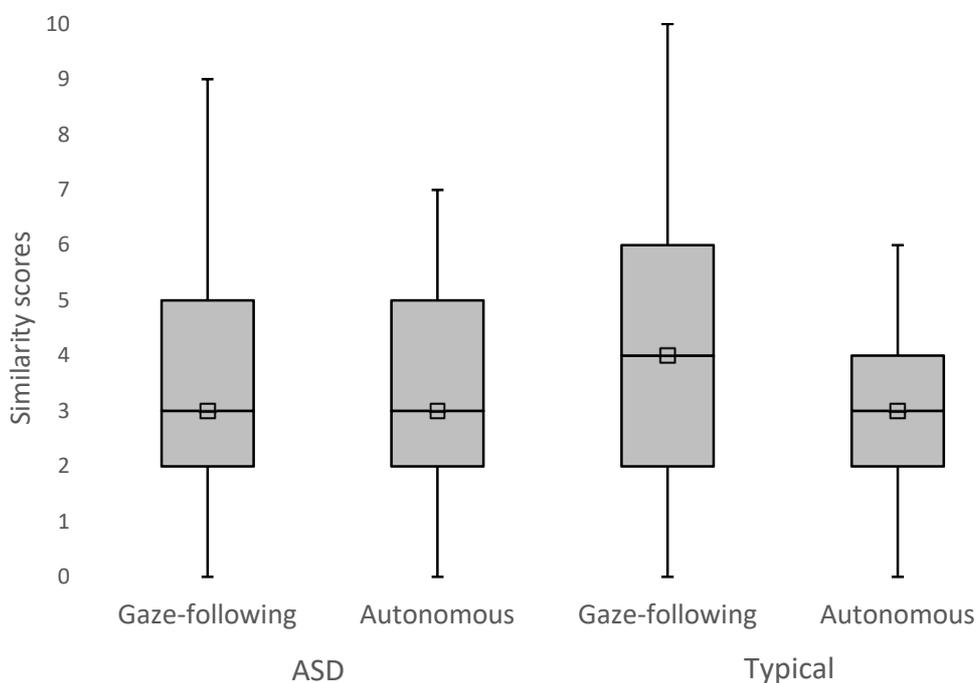


Figure 6: Similarity scores for task 2. The boxplots represent the medians, interquartile intervals and range of scores. The difference between the gaze-following and autonomous avatars came close to significance only for the typical group ($p = 0.064$).

Final question

At the end of the experiment, participants were asked to select the avatar that they preferred. In the ASD group, 10 participants preferred the gaze-following avatar and 7 preferred the autonomous avatar. In the typical group, 8 participants preferred the gaze-following avatar and 9 the autonomous avatar. There was no significant difference between groups, $\chi^2 = 0.47$ $p = 0.49$.

The “self-reference scores” derived from the reasons given orally by participants for their choice were compared between groups with the Wilcoxon-Mann-Whitney test. The scores of participants with ASD were significantly lower than those of typical participants, $U = 69$ $p < 0.01$ (See Figure 7).

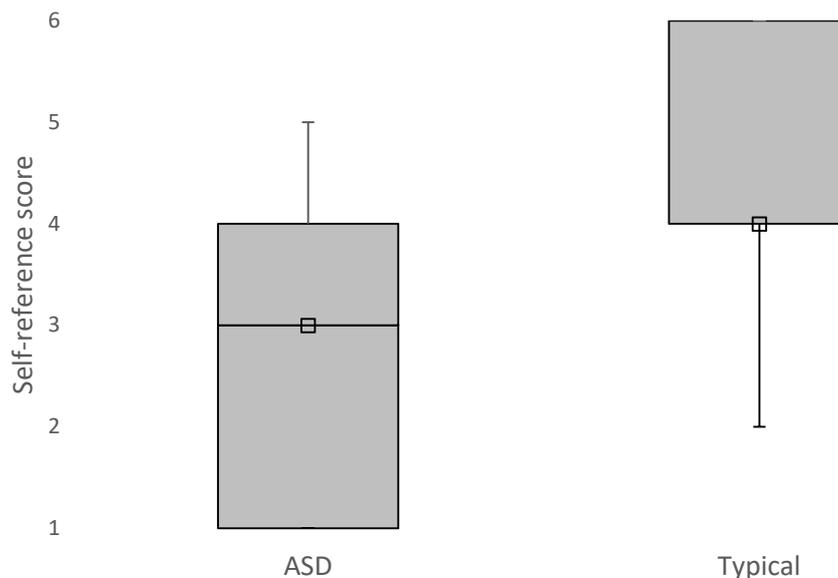


Figure 7: Self-reference scores for the typical and ASD groups. The boxplots represent the medians, interquartile intervals and range of scores. The scores of the ASD group were significantly lower than those of the typical group ($p < 0.01$)

Discussion

The above analyses showed an interaction effect between the gaze behavior mode of the avatar and the groups in task 2. This interaction was significant for the two measures derived from eye-tracking data. The ASD group spent less time fixating the autonomous avatar than the typical group and, contrasting with typical participants, those with ASD had longer mean fixation duration when looking at the gaze-following avatar than at the autonomous avatar. The patterns of visual attention on the avatars thus differed between the two groups, with the ASD group focusing more on the gaze-following avatar and attending less to the autonomous avatar compared to the typical group. This difference cannot be attributed to a reduced exposition to the gaze-following avatar during the training task as there was no difference between groups in the time spent attending to the avatars during this task. When examining the evolution of gaze fixations across trials in task 2, the ANOVA on the total duration of fixations yielded an interaction on the verge of significance between the trials' order, the gaze behavior mode of the avatar and the groups. The graphs displayed on Figure 4 suggest that participants with ASD paid more attention to the gaze-following avatar than to the autonomous avatar, before their attention to the gaze-following avatar eventually dropped towards the end of the task. This

final drop in visual attention can presumably be attributed to fatigue with the task. Contrasting with the ASD group, the distribution of fixation time across trials observed in typical participants tends to indicate that they did not favor looking more at the gaze-following avatar than at the autonomous avatar.

The fact that participants with ASD allocated more attention resources to the gaze-following avatar does not seem to be related to a preference for this avatar. When asked which one of the two avatars they preferred at the end of the experiment, their responses were equally balanced between the two. The answers to the subsequent question where they had to explain their choice of preferred avatar did however yield a significant difference between groups. Participants with ASD answered using significantly less self-referred reasons such as “the avatar followed my gaze” or “the avatar made the same choices as mine”. In other words, participants with ASD showed a lesser tendency to spontaneously mention the fact that one of the avatar was following their gaze, even though this was the only difference between the two avatars. We may thus assume that, contrasting with typical participants, those with ASD either did not realize that one of the two avatars was following their gaze or did not regard it as worth acknowledging. This assumption appears to be in line with the results yielded by the similarity scores in task 1. The fact that significantly more typical participants selected the same favorite item for them and the avatar when facing the gaze-following avatar than the autonomous avatar suggests that they had already noticed the link between them and the gaze-following avatar during task 1. This difference between the gaze-following avatar and the autonomous avatar seemed to be less obvious for participants with ASD. In the ASD group, the lack of acknowledgement that one avatar was consistently following their gaze comes in pair with an increase in attentional resources devoted to this avatar. Participants with ASD seemed to be much intrigued by the gaze-following avatar, while not fully appreciating its behavior. They seemed to not experience the same sense of agency for the avatar’s gaze movements as did typical participants.

The outcome of the present study lends support to an impairment in sensing oneself as leading gaze during joint attention episodes in ASD. We advance two tentative explanations for the results observed here. The first and most straightforward one is that participants with ASD may have been insensible to the action-effect association between their gaze movements and the ensuing reaction of the gaze-following avatar. This possibility is consistent with reports showing impairments in self-monitoring of gaze movements (Grynszpan, Nadel, Martin, Simonin, Bailleul, Wang et al., 2012) and mechanisms

of oculomotor learning (Mosconi et al., 2013). Indeed, Grynszpan et al. (2012) provided evidence suggesting that individuals with ASD failed to adapt to a visual biofeedback of their eye movements in a virtual environment simulating a social encounter. To test oculomotor learning, Mosconi et al. (2013) used an intrasaccadic target step paradigm where participants were to produce saccades towards targets that were displaced while they were shifting their eyes. The authors showed that participants with ASD were slower to adjust their saccades to the target error position. The present study however did not involve tasks that relied as heavily on gaze movement control as the two studies just mentioned. Ideomotor learning should suffice to bind one's gaze actions with the subsequent gaze-following reactions of the avatar. Literature on ideomotor learning in the typical population reveals that action-effect binding is spontaneously acquired when changes in facial expressions are systematically associated with eye movements (Herwig & Horstmann, 2011). Furthermore, ideomotor learning associated with gaze movements has been shown to appear as early as the first year of life in typical development (Verschoor, Spapé, Biro, & Hommel, 2013). It therefore appears somewhat surprising that such basic learning abilities would be altered in adults who are in the average range of intelligence scores, even though they have ASD. Additionally, Nadel et al. (2000) have shown that individuals with ASD spontaneously detect and react to social contingency in tasks where they are being imitated. In the present study, the gaze-following avatar was reproducing the eye movements of the participant, which can be viewed as an imitative behavior. Accordingly, participants with ASD should have been able to detect the contingency between them and the gaze-following avatar. This contingency seemed to indeed grab their visual attention as they were more focused on the gaze-following avatar than on the autonomous avatar. Yet, their answers to the final question suggested that they had more difficulties than typical participants in making sense out of this contingency and that they did not fully appreciate their role as leaders of the gaze-following behavior displayed by one of the two avatars. The ability to develop a sense of oneself as leading the attentional focus of another person may conceivably play an important role in one's representation of the other person's mental state (Recht & Grynszpan, 2019). Our results tend to suggest that individuals with ASD continue to struggle with the mentalistic significance of gaze (Baron-Cohen et al., 1995) even in adulthood.

Implications

The present study emphasizes a phenomenon that should be of interest for caregivers in that individuals with ASD should not be expected to spontaneously make sense of the contingency

between their attentional focus and someone else's, even if the link is highly ostensible. When trying to engage a person with ASD, even an adult, by showing shared interest in surrounding objects, practitioners may need to do so explicitly rather than solely relying on gaze following behaviors. Impairments in sensing that they are leading others' gaze may echo the difficulties of people with ASD in using gaze to regulate social interactions, which is an important behavioral hallmark used when diagnosing autism (Lord et al., 2000).

If the pilot work presented here is confirmed by future research, then difficulties people with ASD have in sensing that they are leading the gaze of others could be used to help clinicians in identifying ASD in adults. The technological setup that we used in the present experiment could serve such a purpose. Indeed, individuals with ASD who were exposed to the gaze-following avatar in our experiment displayed specific gazing patterns that could potentially form behavioral markers of ASD.

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Conflict of interest

Authors declare that they have no conflict of interest.

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