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Gaze Response to Others' Gaze Following in Children With and Without Autism

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Joint attention (JA) is an important developmental precursor to overall social and cognitive abilities. Most previous studies on JA have focused on participants' passive responses to others' gaze directions. Using a computer-based gaze-contingent eye-tracking task, we explored time-course differences in the reciprocity of social gaze patterns in children with autism spectrum disorder (ASD) and in typically developing (TD) children. Specifically, we explored ASD and TD children's gaze responses to others' gaze following. In a trial, children first looked at one of two objects, and then a virtual face followed the children's gaze toward the object that children looked at (congruent condition), looked toward another object instead (incongruent condition), or closed its eyes (closed-eye gaze condition). Eye movements were recorded during the experiment. We found that (a) TD children, but not children with ASD, showed different object-looking times across conditions, suggesting their sensitivity to virtual faces' following their gaze; (b) children with ASD looked at eyes less than TD children; and (c) eye-looking time improved subsequent object-looking time in TD children, whereas it interfered with object-looking time in children with ASD. This study contributes to an understanding of the process of a more complex and reciprocal JA in TD children and the impairments of JA in children with ASD. Furthermore, it provides data relevant to understanding how JA may influence information processing and which aspects of JA are problematic for children with ASD.

General Scientific Summary

Most studies on joint attention have focused on participants' passive responses to others' pointing or gaze directions. This study explored the gaze responses of children with autism spectrum disorder (ASD) and typically developing (TD) children to others' gaze following in a reciprocal context. We found that children with ASD, but not TD children, responded less effectively to others' gaze following of their own gaze, possibly due to their smaller eye-looking time and to impairments in understanding the social meaning of eyes.

Keywords: joint attention, gaze following, face scanning, eye movement, autism spectrum disorder

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Joint attention (JA), emerging as early as 6 to 9 months, is a prelinguistic social-communicative skill to share experiences of some third objects or events by directing (initiating JA; JA) or following (responding to JA; RJA) the eye gaze or pointing to social partners (Mundy & Jarrold, 2010). As an important developmental precursor to overall social and cognitive abilities (Mundy & Jarrold, 2010), JA is found to be associated with later language development in both typical and atypical development (e.g., Bottema-Beutel, 2016; Brooks & Meltzoff, 2005; Mundy et al., 2007), as well as the symptom severity in autism spectrum disorder (ASD), a neurodevelopmental disorder characterized by social-communication impairments (Charman, 2003; Nation & Penny, 2008).

Most studies on JA, especially RJA, only measure participants' passive responses to others' pointing or gaze directions (e.g., Okumura, Kanakogi, Kanda, & Ishiguro, 2013; Pfeiffer, Vogeley, & Schilbach, 2013; Pitskel et al., 2011). In real life, JA has an interactive and reciprocal nature—we not only respond to others' gazes passively but also interpret others' responses to the direction of our own gazes and modify our attention accordingly. Therefore, it is important to study gaze following in a reciprocal context. Here, we studied children's gaze following when they initiated a JA and tested whether children could effectively adjust their gaze according to others' gaze states (following or not following children's gaze). Effectively adjusting gaze to the dynamics of interaction could be challenging for children with ASD and could keep them from effectively learning from their social context. Improving such sensitivity is also important for many aspects of development and learning, such as word learning. For example, when infants are focusing on an object, the caregivers disregard their gazes, look at a new object, and utter a novel word. If infants are not sensitive to the caregivers' gaze responses and do not adjust their gaze accordingly, it might result in a word being mistakenly linked to an incorrect object. Such a phenomenon is very common in daily life, as parents usually produce a label for an object that is not at the center of children's attention (Collis, 1977), although research has been surprisingly scant on this topic. Our first aim was to bridge this significant gap in the literature by examining whether typically developing (TD) children were sensitive to others' gaze following. That is, we explored whether children would follow others' gaze when children themselves initiated a JA, as reflected in children's gaze duration on the cued and uncued objects; furthermore, we examined whether attention to eyes would influence subsequent attention to the object. It has been suggested that people, even infants, regularly monitor the eyes of their social partner to establish a smooth social interaction (Bayliss et al., 2013; Brooks & Meltzoff, 2005; Carpenter, Nagell, Tomasello, Butterworth, & Moore, 1998; Mundy & Newell, 2007), including JA (Frischen, Bayliss, & Tipper 2007). The relation between eye-looking time and subsequent object-looking time, which has rarely been explored in previous studies in part due to methodology limitations, was addressed in the current study.

The second aim of the present study was to examine whether detecting and effectively responding to others' gaze following were impaired in children with ASD. Despite their syndrome-specific deficits in initiating and responding to JA based on clinical observations (e.g., Chawarska, Klin, & Volkmar, 2003; Sigman, 1998), their gaze following has been found to be relatively intact in Posner-cueing tasks (Frischen et al., 2007; Rutherford & Krysko, 2008; Uono, Sato, & Toichi, 2009) and in eye-tracking studies (Bedford et al., 2012; Falck-Ytter, Thorup, & Bölte, 2015; Kuhn et al., 2010). Previous empirical evidence is based on measuring participants' passive responses to others' gaze direction, and individuals with ASD may have difficulties in appropriately adjusting gaze to the dynamics of interaction. Unlike the simple stimulus–response patterns in previous studies, the current study requires participants to disengage from the object they initially attend and to check-back the partner's face/eyes to know his or her responses, as well as to generate adaptive behavior to respond accordingly. Studying this reciprocal and complex process might further reveal deficient JA in individuals with ASD and contribute to a more sophisticated understanding of the nature of JA.

To address these questions, we used the interactive eye-tracking paradigm based on the gaze-contingent approach. This approach has been used to explore information processing, affective, and neural responses to others' gaze following among individuals with and without ASD (Bayliss et al., 2013; Caruana et al., 2018; Mundy, Kim, Mcintyre, Lerro, & Jarrold, 2016; Oberwelland et al., 2016, 2017). In this paradigm, participants initiate a simulated JA by looking at one object, and a virtual face controlled by computers follows or does not follow the participants' gaze (Pfeiffer et al., 2013). Bayliss and colleagues (2013) found that TD adults were more likely to favor the cued object when their gaze was followed by the interactive partner and lose interest in the cued object when their gaze was not followed (Bayliss et al., 2013). A more recent study found abnormal neural activities in responses to others' gaze following in the brain regions responsible for social cognition (e.g., superior temporal sulcus) in adolescents with ASD compared to TD adolescents (Oberwelland et al., 2017). However, previous research did not reveal how individuals with and without ASD allocated their visual attention according to others' following or not following their gaze, an important component of JA.

This study implemented a computer-based gaze-contingent approach to investigate eye movements of ASD and TD children, especially attention paid to objects when observing a face that followed or did not follow their own gaze. We predicted that TD children would seek to gain information from others' gaze direction and bias their gaze toward the object cued by the face. However, children with ASD, without a fully developed sensitivity to others' gaze directions, may be relatively unaffected by gaze directions. Thus, we hypothesized that TD children would show sensitivity to others' gaze following. Specifically, when a face followed children's gaze, TD children would look more at the object than when the face did not follow their gaze. When the face did not follow children's gaze and looked at the object children had not looked at initially, TD children would look more at this object than when the face followed their gaze. Such sensitivity to others' gaze following was expected to be absent for children with ASD. Based on the importance of monitoring the eyes of the social partner in a smooth social interaction (e.g., Brooks & Meltzoff, 2005; Carpenter et al., 1998; Mundy & Newell, 2007), we predicted more attention to the eyes to be related to subsequent longer inspecting time on cued objects in TD children. We did not expect such a relationship in children with ASD, to whom eyes are not as meaningful as they are to TD children (Chevallier, Kohls, Troiani, Brodkin, & Schultz, 2012).

Method

Participants

Given the novel research questions and data analysis methods in our study, it was difficult to rely on previous effect sizes when designing the current study. Thus, the current sample size was determined by previous studies using the gaze-contingent approach combined with the JA/gaze-following paradigm (Bayliss et al., 2013; Caruana et al., 2018; Mundy et al., 2016; Oberwelland et al., 2016, 2017). The sample size for one participant group ranged between 16 and 32 in those studies, with M = 23.11 and SD = 6.64. Furthermore, when we opted for a moderate effect size (η_p^2 = .06), 0.85 power, an alpha of .05, and 0.5 as a correlation among repeated measures to perform power analysis using G*Power software (Faul, Erdfelder, Lang, & Buchner, 2007), a total sample of at least 32 individuals was required by a repeated-measures ANOVA with Group (ASD and TD) as the between-subjects factor and Condition (congruent, incongruent, and closed-eye gaze) as the within-subjects factor.

In the current study, after excluding four children with ASD who had an IQ lower than 65 as measured by the Wechsler Intelligence Scale, 26 Chinese children with ASD (24 boys) and 24 Chinese TD children (23 boys) participated in our study. They were approximately 7 years old (see Table 1 for details). We selected children at this age since it is a potentially sensitive developmental period for gaze perception among children whose more basic visual mechanisms are presumably in place (Mihalache et al., 2019). Furthermore, Thorup, Kleberg, and Falck-Ytter (2017) found that children with ASD at approximately 7 years old could follow others' gaze based on measuring children's passive responses to others' gaze directions (Thorup et al., 2017). However, it remains unclear whether children with ASD at this age are sensitive to other's gaze following. Two children with ASD were excluded from our analysis due to the poor quality of the data on their eye movements (see the Data Analysis section for details), resulting in 24 children with ASD (22 boys) in the final sample (see Table 1 for details). The two groups were matched by chronological age and IQ (see Table 1). Detailed descriptions of participant characteristics are provided in Table 1 and the online supplemental materials. The present protocol (protocol number: 2016–03-03e) was approved by the Committee for Protecting Human and Animal Subjects at the School of Psychological and Cognitive Sciences at Peking University, China. We obtained oral consent from all of the children and written consent from all of their parents before conducting the experiment.

Materials

Sixty images of fruits and vegetables were taken from the Internet. Three images of male faces were selected from six images of faces created by FaceGen, a commercial software program (https://facegen.com/). The three images were rated on a scale from 1 (*very unattractive*) to 5 (*very attractive*) by a group of college students (N = 20) and matched for attractiveness (mean attractiveness = 2.6, 2.4, and 2.2, SD = 1.19, 0.88, and 0.83, respectively). We used virtual faces rather than real faces due to the advantages of a high degree of standardization and systematic manipulability. Each face was digitally edited using FaceGen to produce three versions of 26 continua for each of the following: direct gaze to left averted gaze, direct gaze to right averted gaze, and direct gaze to closed-eye gaze. These continua were used to present dynamic gaze-shifting.

Eye movement data were recorded using a Tobii Pro X3-120 eye tracker (sampling rate: 120 Hz; Tobiitech Technology, Stockholm, Sweden). The Psychtoolbox (http://psychtoolbox.org) and Tobii Analytics Software Development Kit (Tobiitech Technology, Stockholm, Sweden) on the MATLAB platform were used to control stimulus presentation and data recording.

Procedure

The children sat approximately 60 cm away from a 21.5-in. LCD monitor (1920 × 1080 pixels resolution). Their eye movements were first calibrated using a 5-point calibration procedure. During the calibration, an animated cartoon character paired with an engaging sound appeared sequentially in the center and four

Table 1
Characteristics of the Participants

Variable	ASD (N = 24)			TD (N = 24)				
	M	SD	Range	M	SD	Range	t	p
Age (years)	7.22	1.58	5.08–11.57	7.49	.66	6.50–8.65	−.769	.446
Full Scale IQ[a]	98.54	18.58	69–136	95.96	10.5	77–117	.592	.557
ADOS[b] total severity	8.37	1.53	5–10					
SA severity[c]	8.46	1.47	5–10					
RRB severity[d]	7.75	1.11	5–10					
ADI-R[e]								
Social interaction	21.88	5.57	10–30					
Communication	17.75	4.80	9–26					
RRB	8.67	2.08	5–12					
D Scale[f]	3.25	1.15	1–5					

Note. ASD = autism spectrum disorder; TD = typically developing. [a] IQ was measured using the abbreviated Chinese Fourth Edition version of the Wechsler Intelligence Scale for Preschool and Primary Children (Wechsler, 2014b) for children under 6 years old, and the abbreviated Chinese Fourth Edition version of the Wechsler Intelligence Scale for Children (Wechsler, 2014a) for children over 6 years old. [b] ADOS = Autism Diagnostic Observation Schedule. [c] SA Severity = ADOS Social Affect Severity. [d] RRB Severity = ADOS Restricted, Repetitive Behavior Severity. SA and RRB Severity were calculated according to Hus, Gotham, and Lord (2014). [e] ADI-R = Autism Diagnostic Interview—Revised. [f] The D Scale is abnormality of development evident at/before 36 months.

corners of the screen. The children were instructed to fixate on the character. The calibration process was repeated when necessary until both eyes achieved good mapping on all five test positions (smaller than 1° visual angle).

Each trial was preceded by an attention-getter (a cartoon character subtending a visual angle of 4°×4°) at the center of the monitor to attract children's attention. The attention-getter disappeared once the children's gaze was detected to be within the attention-getter region. Next, one face with a direct gaze (10°×10° visual angle) appeared at the center of the screen along with two objects (8°×8° visual angle) randomly chosen from the fruit and vegetable images pool, which appeared at the left and right sides of the face (the center of object images appeared approximately 10° from the center of screen; Figure 1). Children were instructed to look at one of the two objects they preferred. When gaze was detected continually within the first-looked-at object (FLO) for 30 ms, the virtual face began to shift its gaze to look at the FLO (congruent condition), to shift its gaze to look at another object (non-first-looked at object, NFLO; incongruent condition), or to close its eyes (closed-eye gaze condition). These dynamic gaze-shifting movements lasted approximately 1.2 s, followed by 3 s of the final gaze phase, during which the face gazing at the object continued as a still frame. The children were given no further instructions and could view the scene freely.

For a given child, each virtual face was randomly assigned to one type of condition (congruent, incongruent, or closed-eye gaze condition) and appeared 10 times, resulting in 30 trials in total. The trials were randomly presented with the constraint that the same condition could not occur more than three times in a row. Eye movement data were recorded during the whole experiment.

Eye Movement Data Analysis

Data preprocessing. Missing gaze data with a gap shorter than 75 ms were filled in using linear interpolation, whereas those with a gap that exceeded 75 ms, which was regarded as an eyeblink (Olsen, 2012), were kept and coded as looking at nothing. Trials for which more than 30% of the gaze data was interpolated were excluded from the analysis. After the exclusion, the average proportion of the interpolated data was similar for the ASD (M = 0.02, SD = 0.03) and TD (M = 0.02, SD = 0.01) groups, $t(46)$ = 0.66, p = .515, Cohen's d = 0.19, 95% CI [−0.38, 0.76]. The average gaze positions of the left and right eyes were used as an analytical unit. Trials were also excluded if the gaze shifting of the virtual faces was not induced by children's fixations (e.g., saccades, noises, etc.). The proportion of trials that were excluded for this reason was higher for the ASD group (M = 0.15, SD = 0.11) than that for the TD group (M = 0.08, SD = 0.08), $t(46)$ = 2.53, p = .015, Cohen's d = 0.73, 95% CI [0.14, 1.31]. Fixation was calculated based on an I-VT fixation filter (Olsen, 2012; Wang, Hu, et al., 2018) with the following parameter settings as follows: (1) Velocity threshold was set at 30°/s; (2) fixations that were spatially and temporally (<0.5°, <75 ms) close were merged to prevent longer fixations from being separated into shorter fixations because of data loss or noise; and (3) duration threshold was set to 60 ms.

To ensure the quality of the data, two children in the ASD group with fewer than five valid trials for each condition after trial rejection were excluded from further analyses. The average number of valid trials for each condition was quite high for both the ASD (M = 8.49, SD = 1.09) and TD (M = 9.21, SD = 0.83) groups, with a significant group difference, $t(46)$ = −2.59, p = .013, Cohen's d = 0.75, 95% CI [0.16, 1.33]. The average proportional total looking time on the screen relative to the trial duration analyzed (i.e., 4 s) was similar in the ASD (M = 0.74, SD = 0.16) and TD (M = 0.81, SD = 0.15) groups, $t(46)$ = −1.63, p = .110, Cohen's d = −0.47, 95% CI [−1.04, 0.11]. Areas of interest (AOIs) for the two objects (FLO and NFLO) and eyes are illustrated in Figure 2.

Attention to objects. Our major concern was whether children with and without ASD were sensitive to others' gaze re-

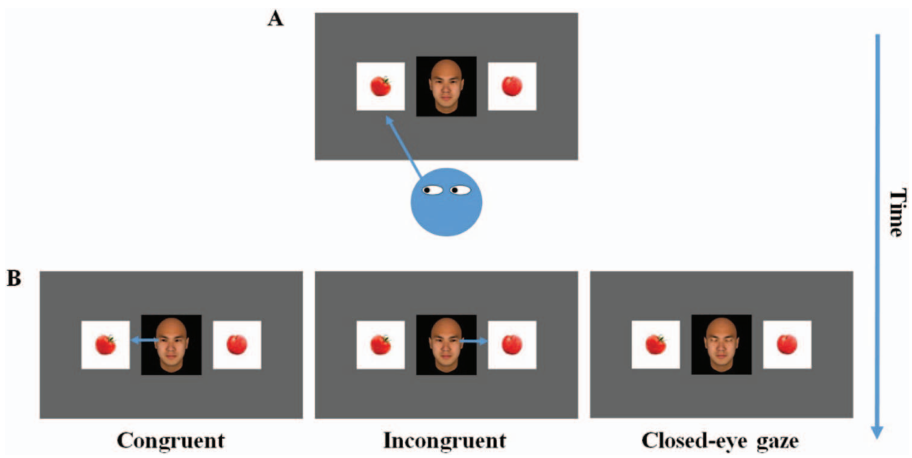

Figure 1. Experiment design. Children (cartoon face) initiate a joint attention by looking at one of the two objects (A), then the virtual face shifts its gaze (1.2 s) to follow the children's gaze in the congruent condition, to disregard the gaze and look at another object in the incongruent condition, or to close its eyes in the closed-eye gaze condition, followed by 3 s of the final gaze phase, during which the face gazing at the object continued as a still frame (B). Data from phase B were analyzed. See the online article for the color version of this figure.

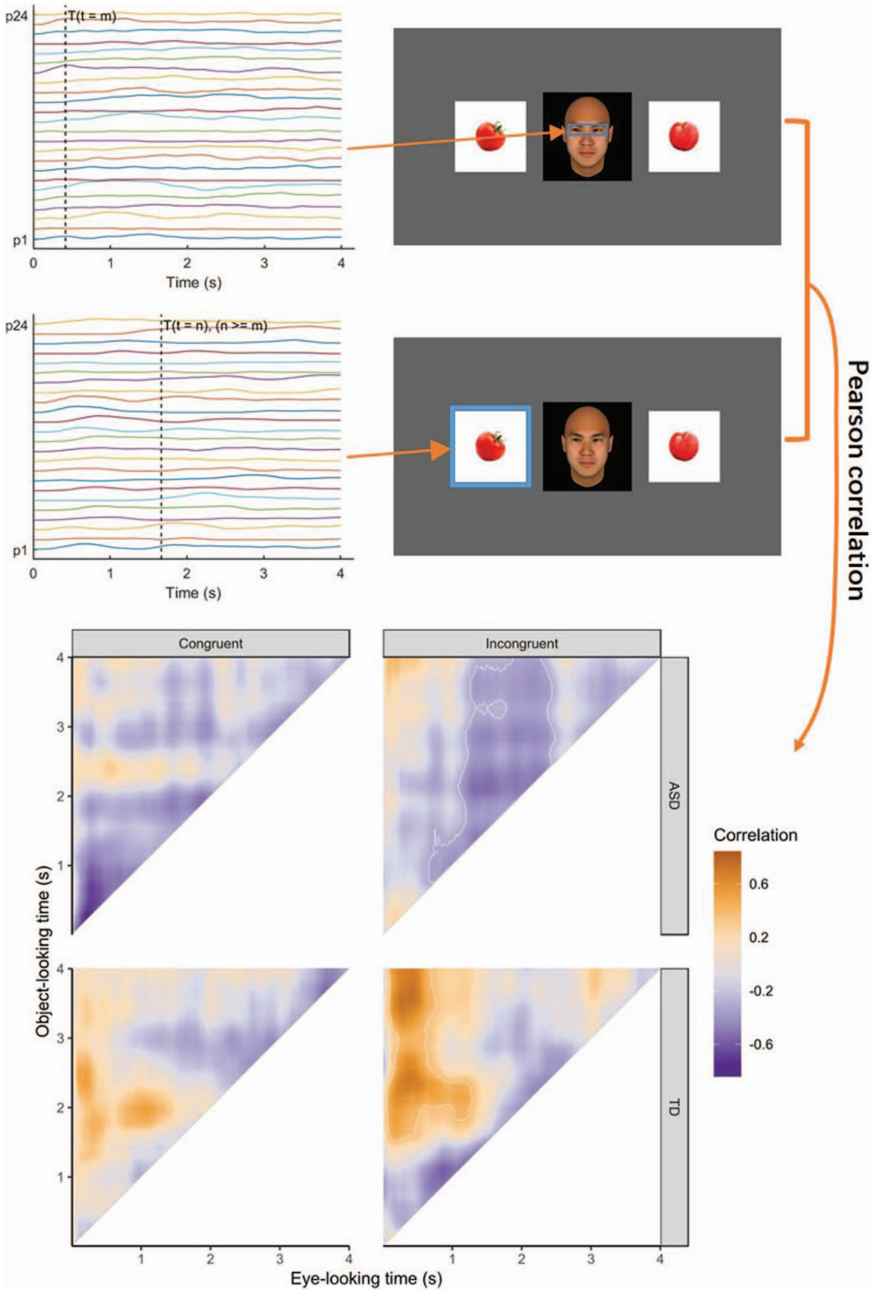

Figure 2. Results of the novel data-driven correlation method. For each data point of the time series signals, we correlated proportional eye-looking time across participants at time m with proportional looking time on the gazed-at object (FLO in the congruent condition or NFLO in the incongruent condition) at time n ($0 \leq m \leq n \leq 4$ s; top panel). This results in a 480 (data points) $\times$ 480 (data points) upper triangular matrix (bottom panel). Each value in the matrix represents a correlation coefficient between eye-looking time pattern at time m and looking time on gazed-at object at time n ($0 \leq m \leq n \leq 4$ s). That is, correlations are between the proportion of time spent looking at eyes and proportion of time spent looking at objects at any given time point throughout the trial, with the restriction that eye-looking time happens before object-looking time. Areas showing significant correlations are delimited by white borders (multiple comparisons were controlled by using the cluster-based permutation test). This analysis was done separately for each participant group and experimental condition. AOIs for the object and eyes (within the blue rectangles or regions pointed by arrows) are also illustrated in this figure. ASD = autism spectrum disorder; TD = typically developing. See the online article for the color version of this figure.

sponses, that is, whether their looking time at the object would be modulated by others' following or not following their own gaze. This attention effect, if any, could emerge at any time during a trial. For example, in the congruent condition, children might sustain their attention on the FLO when others follow their gaze, and the effect would therefore appear early in a trial. It is also possible that children might look at the face to extract gaze information after they have looked at the FLO, and then pay attention to the FLO again. In this case, the effect would appear late in a trial. Since we had no prior hypothesis about when the effect would happen, we employed a novel data-driven time-course analysis to investigate the effect (for a similar method, see Wang, Lu, et al., 2018). In brief, we created a time series signal of the proportional object-looking time by calculating the proportional trial toward a particular object relative to the total number of valid trials for each data point. Next, we conducted a 2 (Group: ASD vs. TD) × 3 (Condition: congruent, incongruent, and closed-eye gaze) repeated-measures analysis of variance (rmANOVA) for each data point, and applied a cluster-based permutation test (Groppe, Urbach, & Kutas, 2011; Maris & Oostenveld, 2007) to control for the family-wise error rates. We explain this method in detail in the online supplemental materials.

Attention to eyes. Attention to eyes might play an important role in successful responses to others' gaze following (Brooks & Meltzoff, 2005; Carpenter et al., 1998; Mundy & Newell, 2007). Thus, the sensitivity of TD children, but not children with ASD, to others' gaze direction would be reflected by TD children's enhanced attention to the eyes. Here, we used the same time-course analysis to examine the main effects of Group and Condition and the interaction effect on attention to eyes (see the online supplemental materials for more information).

Correlation between eye-looking time and object-looking time. Lastly, we used a novel data-driven method to explore whether attention to eyes would influence subsequent object-looking time. Such an effect would reflect the important role of attention to eyes in successful responses to others' gaze direction. In this new method (see Figure 2), for each data point, we correlated proportional eye-looking time across participants at time m with proportional looking time on the gazed-at object (FLO in the congruent condition or NFLO in the incongruent condition) at time n ($0 \leq m \leq n \leq 4$ s). This outcome resulted in a 480 (data points) × 480 (data points) upper triangular matrix (see Figure 2). Each value in the matrix represents a correlation coefficient between the eye-looking time at time m and looking time on gazed-at object at time n ($0 \leq m \leq n \leq 4$ s). We controlled for multiple comparisons using the cluster-based permutation test. This analysis was carried out separately for each participant group and experimental condition. For details of this method, see the online supplemental materials.

Results

Attention to Objects

As shown in Figure 3A, only TD children showed sensitivity to virtual faces' gaze direction. For the proportional FLO-looking time, the time-course analysis revealed the main effect of Condition during the windows 0.83–1.46 s and 1.78–3.15 s after the virtual face shifted its gaze, $F_{sum} = 399.95$, $p = .028$ and $F_{sum} = 795.59$, $p = .004$, respectively. More importantly, the interaction between Group and Condition occurred during the window of 1.87–2.77 s after the virtual face shifted its gaze, $F_{sum} = 400.27$, $p = .038$. Data in these time periods revealing the interaction effect were extracted and averaged accordingly. A 2 (Group: ASD vs. TD) × 3 (Condition: congruent, incongruent, closed-eye gaze) rmANOVA was conducted on the average data and confirmed the time-course analysis result (Figure 3B): The interaction between Group and Condition was significant, $F(2, 92) = 5.10$, $p = .008$, $\eta_p^2 = 0.10$, 90% CI [0.02, 0.19]. This interaction effect remained significant when rerunning the analysis with the average proportional total looking time on the screen as an additional covariate, $F(2, 90) = 4.74$, $p = .011$, $\eta_p^2 = 0.10$, 90% CI [0.01, 0.19]. Simple effects analysis further revealed that during this period, TD children looked more at the FLO in the congruent condition than in the incongruent and closed-eye gaze conditions, $t(23) = 3.66$, $p = .001$, Cohen's $d = 0.75$, 95% CI [0.29, 1.19]; $t(23) = 3.79$, $p = .001$, Cohen's $d = 0.77$, 95% CI [0.31, 1.22], respectively, whereas no significant difference was found between the incongruent and closed-eye gaze conditions, $t(23) = -0.46$, $p = .65$, Cohen's $d = -0.09$, 95% CI [−0.49, 0.31]. Children with ASD, however, showed no significant differences among the three conditions: congruent versus incongruent, $t(23) = -0.02$, $p = .985$, Cohen's $d = -0.004$, 95% CI [−0.16, 0.16]; congruent versus closed-eye gaze, $t(23) = 0.90$, $p = .377$, Cohen's $d = 0.18$, 95% CI [−0.22, 0.59]; or incongruent versus closed-eye gaze, $t(23) = 0.84$, $p = .409$, Cohen's $d = 0.17$, 95% CI [−0.23, 0.57].

For the proportional NFLO-looking time, the main effect of Condition was revealed during the window 1.81–4.00 s, $F_{sum} = 1908.66$, $p < .001$. More importantly, the interaction between Group and Condition during 1.83–2.67 s was revealed, $F_{sum} = 391.44$, $p = .036$. A 2 (Group: ASD vs. TD) × 3 (Condition: congruent, incongruent, closed-eye gaze) rmANOVA was conducted on the significant time period, revealing an interaction effect and confirming the time-course analysis result (Figure 3B): The interaction between Group and Condition was significant, $F(2, 92) = 4.62$, $p = .012$, $\eta_p^2 = 0.09$, 90% CI [0.01, 0.18]. This interaction effect remained significant when rerunning the analysis to include the average proportional total looking time on the screen as a covariate, $F(2, 90) = 3.81$, $p = .026$, $\eta_p^2 = 0.08$, 90% CI [0.01, 0.17]. Simple effects analysis further revealed that during this period, TD children looked more at the NFLO in the incongruent condition than they did in the congruent and closed-eye gaze conditions, $t(23) = 3.46$, $p = .002$, Cohen's $d = 0.71$, 95% CI [0.25, 1.15]; $t(23) = 2.85$, $p = .009$, Cohen's $d = 0.58$, 95% CI [0.14, 1.01], respectively, whereas no significant difference was found between the congruent and closed-eye gaze conditions, $t(23) = -1.24$, $p = .229$, Cohen's $d = -0.25$, 95% CI [−0.66, 0.16]. Children with ASD, however, showed no significant differences among the three conditions: congruent versus incongruent, $t(23) = 0.07$, $p = .946$, Cohen's $d = 0.01$, 95% CI [−0.39, 0.41]; incongruent versus closed-eye gaze, $t(23) = 1.10$, $p = .28$, Cohen's $d = 0.23$, 95% CI [−0.18, 0.63]; or congruent versus closed-eye gaze, $t(23) = 1.44$, $p = .163$, Cohen's $d = 0.29$, 95% CI [−0.12, 0.70], suggesting their insensitivity to the virtual faces' gaze direction.

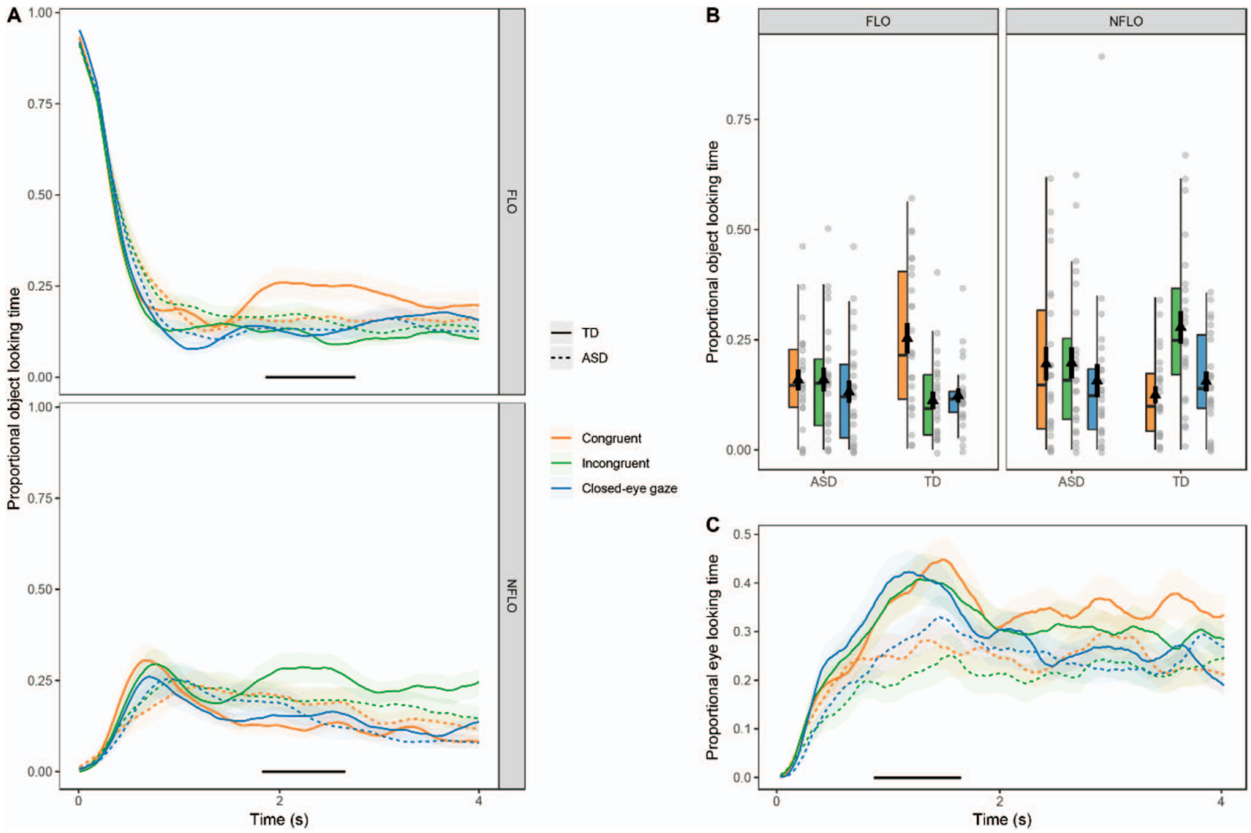

Figure 3. Results of the eye- and object-looking time. Time-course of proportional object-looking time (A) and eye-looking time (C). Time series signals of proportional AOI-looking time were created by calculating the proportional trial toward a particular AOI relative to the total number of valid trials for each data point. Multiple comparisons were corrected by using a cluster-based permutation test. Black horizontal line illustrates the cluster of time when the Condition × Group interaction effect (A) or Group main effect (C) is significant. Shaded area indicates standard errors. Time zero is the start of the face's gaze shifting. (B) Boxplot of object-looking time during significant time periods revealing interaction effect in Figure 3A, with each triangle representing mean value, each thick black vertical line representing error bar (standard error), and each point representing one child. ASD = autism spectrum disorder; TD = typically developing; FLO = first-looked-at object; NFLO = non-first-looked at object. See the online article for the color version of this figure.

Attention to Eyes

The time-course analysis only found the main effect of Group on the proportional eye-looking time during 0.88–1.66 s, F_{sum} = 607.89, p = .046. Data in the significant time period revealing the Group main effect were extracted and averaged accordingly. A 2 (Group: ASD vs. TD) × 3 (Condition: congruent, incongruent, closed-eye gaze) rmANOVA was conducted on the average data and confirmed the time-course analysis result: Only the main effect of Group was significant, $F(1, 46) = 6.93$, $p = .011$, $\eta_p^2 =$ 0.13, 90% CI [0.02, 0.28]. This main effect remained significant when rerunning the analysis to include the average proportional total looking time on the screen as a covariate, $F(1, 45) = 4.26$, $p = .045$, $\eta_p^2 = 0.09$, 90% CI [0.00, 0.23]. Therefore, children with ASD looked at the eyes less than TD children during 0.88–1.66 s (after the virtual face shifted its gaze), which was earlier than the time period that revealed the Condition difference.

Correlation Between Eye-Looking Time and Object-Looking Time

Data-driven correlation analysis (see Figure 2) revealed that for the TD group, there was one cluster showing significant positive correlations between proportional eye-looking time and proportional looking time on the gazed-at object in the incongruent condition: Eye-looking time in the period from 0.07 to 1.29 s positively predicted object-looking time in the period from 1.51 to 4.00 s, Z_{sum} = 54,092, p = .041. Correlations were not significant after correction in the congruent condition.

For the ASD group, there was one cluster showing significant negative correlations between proportional eye-looking time and proportional looking time on the gazed-at object in the incongruent condition: Eye-looking time in the period from 0.66 to 2.48 s negatively predicted object-looking time in the period from 0.75 to 4.00 s, $Z_{sum} = -80{,}820$, $p = .046$. Correlations were not significant after correction in the congruent condition.

Discussion

Using a computer-based gaze-contingent design and novel time-course analyses, we investigated the eye movements in TD and ASD children in response to others' gaze following with respect to their own gazes. Specifically, we tested (1) how children attended to the objects in response to others' gaze following or failure to follow, (2) whether children with ASD displayed atypical attention to the partners' eyes during JA, and (3) whether attention to eyes influenced subsequent attention to objects.

First, we found that TD children's attention to the objects was modulated by others' gaze responses: They spent higher proportional FLO-looking time in the congruent condition than they did in the incongruent and closed-eye gaze conditions, and they spent higher proportional NFLO-looking time in the incongruent condition than they did in the congruent and closed-eye gaze conditions. Such sensitivities occurred approximately 1.8 s after the virtual face started to shift its gaze. Given that the virtual face's gaze-shifting lasted approximately 1.2 s, this finding suggests that TD children made gaze responses after fully extracting the face's gaze information. However, children with ASD did not differentiate their attention to objects among the three conditions, suggesting their insensitivity to virtual faces' gaze response. Contrary to the findings in our study, previous studies suggest that the ability to follow others' gazes is intact in children with ASD (e.g., Bedford et al., 2012; Falck-Ytter et al., 2015; Kuhn et al., 2010). In those studies, children's attention was always attracted to a face before the face began to shift its gaze, which made it easier for children with ASD to notice this gaze-shifting and follow the gaze accordingly due to their intact reflexive orienting (e.g., Frischen et al., 2007; Kylliäinen & Hietanen, 2004; Rutherford & Krysko, 2008; Uono et al., 2009). However, unlike previous studies that measured participants' passive gaze following when others initiated a JA, we studied participants' gaze following when participants themselves initiated a JA. Our gaze-following paradigm had a more interactive and reciprocal nature than those in previous studies. In our paradigm, after children initiated a gaze, they had to actively monitor the interactive face's gaze to respond to the gaze effectively. Our findings reveal, going beyond the previous literature, the impairments in a more complex, dynamic, and reciprocal JA paradigm in ASDs.

Second, consistent with previous studies (Frazier et al., 2017), we found that children with ASD looked at eyes less than TD children, especially between 0.88–1.66 s, a period immediately before the sensitive period to gaze following in the TD group (after 1.8 s). This finding is possibly attributable to diminished social motivation to actively attend to eyes in ASD (Chevallier et al., 2012). Diminished eye-looking time in children with ASD might be one possible cause (not the only one, on which more later) for their failure to respond to the virtual faces' gaze following.

Third, we found a positive correlation between eye-looking time and subsequent attention on the object in TD children, suggesting an important role of monitoring the interactive face's gaze in subsequent social behavior. In contrast, for children with ASD, more eye-looking time led to less looking time at the cued object. These results suggest that TD children have prior knowledge about the meaning of gaze direction and will actively use the gaze information to determine their attention, yielding a positive correlation between eye- and object-looking time. Children with ASD, however, are impaired in their understanding of the social meaning of gazes (Chevallier et al., 2012; Falck-Ytter et al., 2015) and may thus be less prone to use gaze information even if they look more at others' eyes. Moreover, the negative correlations we found may even imply that eye-viewing may be confusing or distracting for children with ASD, rather than being informative about the object for TD children. It is worth noting that the correlations were only found in the incongruent condition, not in the congruent condition. One possible reason is that eye monitoring and understanding others' attention become particularly important during the incongruent condition, since the interaction is more complex in this condition than that in the congruent condition. Our findings obtained from the correlation analysis imply that interventions that address social impairments in children with ASD should target not only improving their eye contact but also promoting an understanding of the social meaning of eyes.

Exploring children's gaze responses to others' gaze following has significant theoretical contributions to developmental psychology. Traditionally, JA has been investigated from an observational perspective, whereby participants need only passively respond to others' gazes. These studies are insufficient for a comprehensive understanding of JA, as active engagement is an important component of JA in real life. People not only react to others' gaze behavior but also have the opportunity to initiate a gaze behavior and monitor their partners' reactions to their own gaze behavior, further adjusting and responding to their partners' reactions (Schilbach et al., 2013). Research in developmental psychology and psychopathology could undoubtedly benefit from our research framework and analytical methods, which offer highly reliable measures of children's tendency to engage in a more complex JA situation in a temporally dynamic fashion. These measures provide a useful means of examining theories on how impairments in eye-looking and gaze understanding in ASD children may relate to their ineffective gaze responses.

Several potentially significant future directions should be considered. First, what is the relationship between gaze following when others initiate a JA, as previous studies have focused on, and gaze following when participants themselves initiate a JA in our study? Future studies should consider these two types of gaze following in one study to clarify the relationship. Second, while the present study only included children at approximately 7 years old, an important challenge for future studies is to elucidate the emergence and development of a capacity to respond to others' gaze following, as well as those factors that contribute to deficient gaze response to others' gaze following in children with ASD. This development would further our understanding of JA and its related typical and atypical development, and thus how these may impact other skills critical for social interaction in later childhood. Third, we used eye-looking time to predict future object-looking time and discovered the importance of monitoring eyes during JA in TD children but not in children with ASD. However, the results were based on correlation analysis, and more work is needed to explore the real causal relationship between eye-looking time and object-looking time (e.g., through manipulating the duration of eye-looking time), further elucidating the exact functional role that eyes play during gaze-based interactions in both TD and ASD children. A related issue is whether the relationship between eye-looking time and object-looking time during JA is relevant to theory of mind. Since monitoring a person's gaze/attention is an example of monitoring a person's mental state (Baron-Cohen, 1991), the absence of positive correlations between eye-looking time and object-looking time in ASD children might be attributed to their deficits in theory of mind. However, we did not examine what kind of role theory of mind played in children's gaze following in our study, a topic that could be further investigated by follow-up studies. Fourth, as in a real-life situation, we did not instruct children to attend to the faces or eyes. Whether instructing children with ASD to attend to the interactive face's gaze will improve their JA is an interesting question and may shed light on developing intervention methods aiming to improve JA in individuals with ASD. Fifth, having one's own gaze followed affects how a social partner is perceived (Bayliss et al., 2013); for example, adults favor others who follow their gaze (Bayliss et al., 2013). Likewise, children could also learn and establish that association (e.g., face in the congruent condition = good face, face in the incongruent condition = bad face, and face in the closed-eye gaze condition = ignorant face). It would be interesting to test how learning outcome influences children's gaze following and how gaze following changes during learning course. However, these issues were not testable in our current study due to the limited trial numbers and absence of learning outcome measurements, making them a topic for future research. Lastly, previous fMRI studies using a similar paradigm set both the gaze-shift duration and the final gaze phase duration for 1 s (Oberwelland et al., 2016, 2017). We used similar gaze-shift durations (1.2 s) but longer final-gaze durations (3 s) to collect more eye-movement data. The length of the stimulus presentation time might influence the outcome, which could be examined in future investigations.

In conclusion, this study bridged a significant gap in the literature by studying gaze response to others' gaze following in children with and without ASD. TD children, but not ASD children, responded effectively and flexibly to others' gaze following of their own gazes. This study contributes to an understanding of the process of a more complex and reciprocal JA in TD children and abnormal social cognition in children with ASD in the context of ecologically valid social interactions.

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