Received: 10 October 2018 | Revised: 23 January 2019 | Accepted: 18 April 2019
DOI: 10.1111/desc.12856

PAPER

Developmental Science WILEY

# Out of mind, out of sight? Investigating abnormal face scanning in autism spectrum disorder using gaze-contingent paradigm

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**Funding information**
National Natural Science Foundation of China, Grant/Award Number: 31571135 and 31871116; Beijing Municipal Science & Technology Commission, Grant/Award Number: Z171100000117015

## Abstract

Diminished social motivation is hypothesized to explain abnormal face scanning pattern in individuals with autism spectrum disorder (ASD), especially reduced eye-looking time in ASDs than typically developing (TD) people. Here, we tested an alternative explanation that children with ASD may use a compensatory strategy to avoid direct eye contact by processing the eyes through peripheral vision. We compared the face scanning patterns of children with and without ASD in two conditions: in the clear condition, the face was completely visible; in the blur condition, by using the gaze-contingent paradigm, the whole face was blurred except for a small region being fixated at, thus children could not rely on the peripheral information to process the eyes. We found that children with ASD fixated less on the eyes than TD children in both conditions. Temporal-course analyses further revealed the possible motivation-based guidance of attention to process the eyes in the TD group but not in the ASD group. Additionally, we found that children with ASD scanned faces more randomly and less strategically than TD children. These results have ruled out the alternative hypothesis that the abnormal face scanning pattern in ASDs was due to their compensatory strategy to process eyes through peripheral vision, furthering our understanding of the mechanisms underlying their abnormal face scanning.

**KEYWORDS**
autism spectrum disorder, eye avoidance, eye movement, face scanning, gaze-contingent, social motivation theory

## 1 | INTRODUCTION

Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterized by deficits in social interaction and communication, as well as the restricted interests and repetitive behaviours (American Psychiatric Association, 2013). Associated with their social deficits, individuals with ASD have displayed reduced social attention (Falck-Ytter & Von Hofsten, 2011; Frazier et al., 2017), including failure to orient to social stimuli (Chevallier, Kohls, Troiani, Brodkin, & Schultz, 2012), and visual preferences for repetitive movements (Pierce et al., 2015; Wang, Hu, et al., 2018). Particularly, individuals with ASD have shown abnormal face scanning patterns, especially the tendency to avoid looking at core face features, especially the eyes (Jones & Klin, 2013; Pelphrey et al., 2002; Yi et al., 2013). However, the mechanism underlying this eye avoidance pattern has not been fully uncovered (Jaswal & Akhtar, 2018).

One hypothesis that could help explain the atypical face scanning patterns found in individuals with ASD is the social motivation account (e.g. Chevallier et al., 2012), which suggests that ASD is associated with reduced social motivation and social reward sensitivity to social stimuli. Eyes play such an important role in daily social interaction and communication that typically developing (TD) individuals are very sensitive to the social information conveyed by the eyes (e.g. emotion, attention, intention, etc.). They find eye contacts rewarding and show higher motivation to look at the direct gaze over objects and averted gaze (Dubey, Ropar, & de C Hamilton, 2015). Individuals with ASD, on the contrary, are suggested to be insensitive to the social saliency of the eyes (Moriuchi, Klin, & Jones, 2017), resulting in diminished motivation or intention to look at the eyes (Dubey et al., 2015). However, this account has been recently challenged by the argument that relatively low levels of eye contact in ASDs did not necessarily reflect their lack of social motivation (Jaswal & Akhtar, 2018). Similar eye avoidance has been found in East Asians when viewing faces compared to the Caucasian observers (Blais, Jack, Scheepers, Fiset, & Caldara, 2008), but they are not attributed to reduced social motivation. In Chinese culture, direct eye contact is considered to be 'rude and arrogant' (Zhang, Wheeler, & Richey, 2006), so that Chinese people are found to use a compensatory strategy to avoid direct eye contact by fixating at nose to process the gaze information (Caldara, Zhou, & Miellet, 2010). In this way, they could still process the information from the eyes through peripheral vision, without experiencing the discomfort elicited by direct eye contact. Similarly, individuals with ASD also find the direct eye contact uncomfortable and threatening (e.g. Hutt & Ounsted, 1966; Tanaka & Sung, 2013), and may also use the similar compensatory strategy to obtain the information of eyes through peripheral vision and to avoid looking at the eyes directly. In fact, individuals with ASD have been suggested to tend to rely more frequently on their peripheral vision than TD individuals according to clinical report (Basilio, Jacqueline, Mandy, Nouchine, & Aude, 2012; Laurent et al., 2007). If this alternative explanation is true, it is problematic to explain the abnormal face scanning found in children with ASD under the framework of social motivation hypothesis.

Previous eye tracking studies always used full-view face (i.e. clear face, Pelphrey et al., 2002; Yi et al., 2013) to study face scanning in ASD, and compared it with TD children. A major pitfall of these eye-tracking studies is that it merely measures the focal vision and therefore cannot account for attention allotted to the periphery of the visual field (Grynszpan & Nadel, 2015). Researchers have suggested that fixation to one region of face (e.g. nose) does not necessarily preclude the other region (e.g. eyes) from being processed simultaneously, without the need to reorient gaze (Cuve, Gao, & Fuse, 2018). Therefore, any conclusions regarding 'reduced eye-looking time' or 'eye-avoidance' in ASD, derived from observations of decreased gaze to eyes based on full-view face need to be treated with caution.

The current study was designed to examine this alternative hypothesis that children with ASD use the compensatory strategy to obtain the information of the eyes from peripheral vision. If so, their eye avoidance is accounted for by the atypical face scanning strategy instead of lack of motivation. What is more, it can even lead to the conclusion that children with ASD do not avoid looking at eyes compared to TD children. To this end, we compared the face scanning pattern of children with ASD in a full-view condition, as previous studies did, with a gaze-contingent condition (Caldara et al., 2010; Grynszpan & Nadel, 2015; Grynszpan, Nadel, et al., 2012; Grynszpan, Simonin, Martin, & Nadel, 2012), in which the whole face was blurred except for a small region being fixated at. In this blurred condition, viewers, who could not rely on the peripheral information, need to seek out and process information by their focal attention (Grynszpan & Nadel, 2015). Such a paradigm has been used in several previous studies (Caldara et al., 2010; Grynszpan & Nadel, 2015; Grynszpan, Nadel, et al., 2012; Grynszpan, Nadel, et al., 2012), one of which demonstrated that compared with Caucasian participants, East Asian participants who spent less time looking at the eyes but more time looking at the nose when scanning full-view faces, spent similar looking time at the eyes as Caucasian participants in the gaze-contingent condition (Caldara et al., 2010). This finding suggests a unique face scanning strategy in Easterners: although they do process the information in the eyes, they actually obtain this information through peripheral vision (fixating at the nose) in order to avoid direct eye contact. Children with ASD could also use the similar strategy given their anxiety and discomfort elicited by direct eye contact (Tanaka & Sung, 2013). If this alternative explanation is true, children with ASD in our study would show increased eye-looking time in the blur (gaze-contingent) condition over the clear (full-view) condition since they could not obtain eye information through peripheral vision in the blur condition.

We further used a fine-grained temporal-course analysis to explore the nuanced differences across time between conditions, which might be obscured by the analysis based on the overall looking time. Given that physical saliency of eyes was weakened in the blur condition compared to full-view condition, children might be attracted to the eyes of clear faces at the beginning due to the physical saliency of the clear eyes. The longer fixation of the blurred eyes would emerge later guided by children's motivation to process the information from the eyes.

**Research Highlights**

- We examined whether children with autism spectrum disorder (ASD) might use peripheral vision to avoid direct eye contact.
- The abnormal face scanning pattern in ASD could not be explained by their compensatory strategy to process the eyes through peripheral vision.
- Children with ASD scan faces more randomly than TD children, implying an atypical face scanning strategy in children with ASD.
- These results advance our understanding of the mechanisms underlying abnormal face scanning in children with ASD.

Finally, to further understand face scanning strategy in children with ASD, we calculated eye movement entropy based on the participants' gaze data to measure the statistical randomness of the eye movements (Gu, Jin, Dong, & Chang, 2018; Kennedy et al., 2017). It is assumed that participants' eye movement entropy decreased when the environment is perceived as meaningful (Jordan & Slater, 2009). We expected that children with ASD would display a more random and less strategical face scanning pattern, reflected in their higher eye movement entropy than that of TD children.

## 2 | METHOD

### 2.1 | Participants

Twenty-five high-functioning children with ASD (23 boys) and 20 TD children (19 boys) from China participated in our study. Six children with ASD were excluded from analysis due to their poor eye movement data quality (see "Data Analysis" section for details), resulting in 19 children with ASD (17 boys) in the final sample. The children with ASD were all previously diagnosed by professional pediatricians in licensed hospitals according to the criteria of ASD in DSM-V (American Psychiatric Association, 2013), and were further confirmed by using the Autism Diagnostic Observation Schedule (ADOS; Lord, Risi, Cook, Leventhal, & DiLavore, 2000) and the Autism Diagnostic Interview-Revised (ADI-R; Lord, Rutter, & Le, 1994). The two groups were matched by chronological age and IQ (Table 1). Detailed descriptions of participant characteristics can be found in Table 1.

**TABLE 1** Characteristics of the participants

| | ASD (*N* = 19) | | TD (*N* = 20) | | |
|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | *t* |
| Age | 6.97 | 1.54 | 7.43 | 0.70 | −1.21 |
| Full scale IQ[a] | 105.0 | 15.73 | 98.10 | 9.49 | 1.67 |
| ADOS total severity | 16.16 | 2.41 | – | – | – |
| SA severity[b] | 8.26 | 1.49 | – | – | – |
| RRB severity[c] | 7.89 | 1.15 | – | – | – |
| ADI-R | | | – | – | – |
| Social interaction | 21.79 | 6.16 | – | – | – |
| Communication | 17.58 | 4.73 | – | – | – |
| RRB | 8.26 | 2.10 | – | – | – |
| D Scale[d] | 3.32 | 1.16 | | | |

Abbreviations: ADI-R, autism diagnostic interview-revised; ADOS, autism diagnostic observation schedule; ASD, autism spectrum disorder; TD, typically developing.
[a]IQ was measured using the Chinese abbreviated version of Wechsler Intelligence Scale for Preschool and Primary Children-Forth Edition (Wechsler, 2014b), for children younger than 6-year-olds, and Chinese abbreviated version of Wechsler Intelligence Scale for Children-Forth Edition (Wechsler, 2014a), for children older than 6-year-olds.
[b]SA Severity = ADOS Social Affect Severity.
[c]RRB Severity = ADOS Restricted, Repetitive Behavior Severity; SA and RRB Severity were calculated according to Gotham, Pickles, and Lord (2009) (Gotham et al., 2009).
[d]D Scale is abnormality of development evident at/before 36 months.

### 2.2 | Ethical considerations

This research was conducted according to the ethical standards laid down in the 1964 Declaration of Helsinki and was approved by the Ethical Committee of sponsoring university. We obtained all of the children's and their parents' written consents before the onset of the experiment.

### 2.3 | Materials

Forty photos of Chinese faces (half female) were used as stimuli. All images were standardized to be the same shape and size (width: 660 pixels, 13° visual angle; height: 920 pixels, 18° visual angle). The position of key face feature (eyes, nose and mouth) for each face was standardized to the same locations. All face images were shown in a forward-facing view with a neutral expression and were presented in grey-scale. To control the impact of the contour (e.g. hairstyle), all face images were cropped in an oval shape (Figure 1a). The 40 face images were randomly assigned to either the clear (full-view) or the blur (gaze-contingent) condition (half were males for each condition) for each child. In the clear condition, the face was completely visible (Figure 1a). In the blur condition, the whole face was blurred using a Gaussian spatial filter with a standard deviation equals to 50 pixels, corresponding to approximately 1° visual angel. The children's gaze position was linked to a two-dimensional Gaussian window with a standard deviation equals to 1.4° visual angel. The window, moving in conjunction with the children's gaze, removed the blur by revealing clear facial information within the window (see the Video S1 in the supplementary material). The size of this window was determined so that it was large enough to see the face stimuli's one eye or mouth (Figure 1b,c, and the Video S1).

Eye movement data were recorded by a Tobii Pro X3-120 eye tracker (sampling rate: 120 Hz). The Psychtoolbox and Tobii Analytics Software Development Kit on the Matlab platform were used to control stimulus presentation and data recording.

### 2.4 | Procedure

Children sat approximately 60 cm away from a 21.5 inch LCD monitor (1,920 × 1,080 pixels resolution) to complete a gender-judgement task. Each trial was preceded by an attention-getter (a cartoon character) on the center of the monitor to attract children's attention. The experimenter started each trial by pressing a space key when children attended at the screen. One face, either clear or blurred, was then displayed for 5,000 ms on the centre of the monitor. Children were asked to scan the face freely and to judge its gender. Following the offset of each face, a black screen with 'male or female' text was

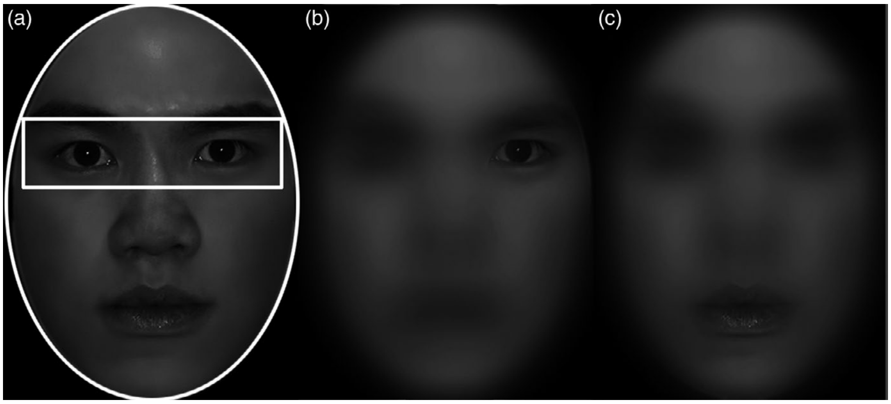



**FIGURE 1** Sample face for the clear condition (a) with the sample areas of interest (AOIs, determined in the data analysis), and the blur condition (the whole face is blurred except for the region being fixated at: (b) and (c) are examples for looking at the right eye and the mouth). AOIs, Areas of interests

presented until the children gave their verbal responses of the face gender. The experimenter recorded the verbal answer by pressing one of the two keyboard buttons (i.e., '1' for 'male' and '2' for 'female'). The 40 experimental trials, with 20 trials for each condition, were randomly presented with the constraint that same stimulus type could not occur more than three in a row. Before the formal experiment, four practice trials with similar settings as formal experiment but with different face images were first administered to the children to familiarize them with the task. In the practice trials, children were told that they can reveal different parts of the blurred face by moving their gaze.

Before the data collection, children's eye movements were calibrated by using a five-point calibration procedure. During the calibration, an animated cartoon character paired with an engaging sound sequentially appeared in the centre and four 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).

## 2.5 | Behavioural data analysis

Discriminating ability *d'* and criterion *c* were calculated for each condition according to the signal detection theory (Stanislaw & Todorov, 1999). When computing hit rate and false alarm rate, 0 was replaced with 1/(2*N*) and 1 was replaced with 1−1/(2*N*) (Macmillan & Kaplan, 1985), where *N* (i.e. 10) is the number of signal (i.e. male faces here) or the number of noise (i.e. female faces). To test effects of groups and conditions on the *d'* and *c*, we used an ANOVA with Condition as the within-subject variable, and Group as the between-subject variable.

## 2.6 | Eye movement data analysis

### 2.6.1 | Data preprocessing

Trials with more than 30% missing gaze data were considered unreliable and excluded from the analysis. Missing gaze data in the other trials were filled in using linear interpolation, with a maximum gap length of 75 ms, which was regarded as an eye blink (Olsen, 2012). Average gaze position of the left and right eyes was used as an analytical unit.

Areas of interest (AOIs) for the eyes and whole face were illustrated in Figure 1a. We computed the whole face-looking time by summing all gaze durations on the whole face. Trials with the total face-looking time <2000 ms were excluded from the analysis. Finally, six children (all in the ASD group) with fewer than 10 valid trials for each condition after trial rejection were excluded from further analyses.

### 2.6.2 | Overall proportional eye-looking time

We calculated the proportional looking time on the AOI of the eyes by dividing the total looking time on this AOI by the total looking time on the whole face. To test whether the proportional eye-looking time varied for different groups and conditions, we used an ANOVA with Condition as the within-subject variable, and Group as the between-subject variable.

### 2.6.3 | Eye-looking time across time

To examine how the eye-looking time changed over time, we proposed a novel data-driven method based on a moving-average approach (Dankner, Shalev, Carrasco, & Yuvalgreenberg, 2017; Wang, Hu, et al., 2018; Wang, Lu, et al., 2018) with a cluster-based permutation test to control the family-wise error rate (Maris & Oostenveld, 2007). Specifically, we segmented each set of trial data (600 sample data in total) into epochs of 250 ms (30 sample data), with 29 sample data overlap, resulting in 571 epochs for each trial. The proportional eye-looking time was calculated in each epoch as the dependent variable, which effectively created a time series signal of the proportional eye-looking time. We examined the difference of eye-looking time across time between the two conditions for each group to test our hypothesis, as well as the difference between the two groups for each condition (see the supplementary material). Since adjacent time-pairs are likely to exhibit the same effect, we used a cluster-based permutation test which was widely used in the neuroscience studies (Groppe, Urbach, & Kutas, 2011; Maris & Oostenveld, 2007) to control the family-wise error rate. We explained this method in detail in the supplementary material. This fine-grained data-driven based temporal-course analysis has revealed many interesting results in the current study (see the Results Section), which could not be revealed by the analysis just based on the overall proportional eye-looking time.

#### 2.6.4 | Gaze difference map

The AOI approach is based on the prior hypothesis, that is, the group difference of the eye-looking time. For full presentation of difference on any part of the face (in pixel space) without the restriction of the AOI between group and condition, we used a data-driven approach based on iMap4 (Lao, Miellet, Pernet, Sokhn, & Caldara, 2017). See detailed method in the supplementary material.

#### 2.6.5 | Eye movement entropy

We further calculated the eye movement entropy as an index to quantify how strategical children with ASD was to process human faces compared to TD children. First, each valid trial duration heatmap was produced by smoothing gaze data using a 2° full width at half maximum (FWHM) Gaussian kernel spatial filter (Kennedy et al., 2017). For each child, their all valid trial smoothed duration heatmaps were averaged together to produce two mean heatmaps (one for each condition). Then, Shannon entropy was calculated on the mean heatmaps (Gu et al., 2018; Kennedy et al., 2017). Entropy provides a measure of statistical randomness or agglomeration of the participants' eye movements, such that spatially diffused gaze would result in higher entropy values, and spatially tightly focused gaze would result in lower entropy values (Figures S1 and S2 in the supplementary material). Thus, if participants used more similar face scanning strategies across the trials, their eye movement entropy value would be lower. Detailed calculation method for Shannon entropy is described in the supplementary material.

Temporal-course of eye movement entropy was also calculated by segmenting the whole trial data (600 sample data in total) into 10 no-overlap time-bins (500 ms or 60 sample data for each bin). Then, eye movement entropy was calculated for each time-bin. Between group comparisons were done by using *t* test (two-tailed) with FDR adjustment for multiple comparisons to control for type I error.

## 3 | RESULTS

### 3.1 | Behavioural results

The results were shown in Figure 2. Discriminating ability *d'* was lower in the ASD group than the TD group, $F(1, 37) = 27.39$, $p < 0.001$, $\eta_p^2 = 0.425$. In fact, in the ASD group, the *d'* is at the chance level (not significantly different from the zero). Neither the main effect of Condition nor the Group × Condition interaction was significant, *ps* > 0.05. For the criterion *c*, no significant effects were found, *ps* > 0.05.

### 3.2 | Eye movement results

As shown in Figure 3, only the main effect of Group was significant on the overall proportional eye-looking time, $F(1, 37) = 9.40$, $p = 0.004$, $\eta_p^2 = 0.203$. Children with ASD looked less at the eyes than TD children. Other effects were not found, all *ps* > 0.05. Thus, both the TD and ASD groups spent similar eye-looking time for the clear and blurred faces based on the overall proportional eye-looking time. However, the temporal-course analysis revealed the nuanced differences between conditions (Figure 3, right panel): Both groups showed longer eye-looking time in the clear condition than in the blur condition within 1,000 ms after the face onset. After 1,000 ms, the difference disappeared in the ASD group, but the TD children gradually looked more at the eyes of the blurred face relative to the clear face. The difference between the two groups for each condition was also examined in the supplementary material (Figure S3).

iMap results were similar with AOI-based results. We found main effects for both Group and Condition (Figure 4a). The interaction did

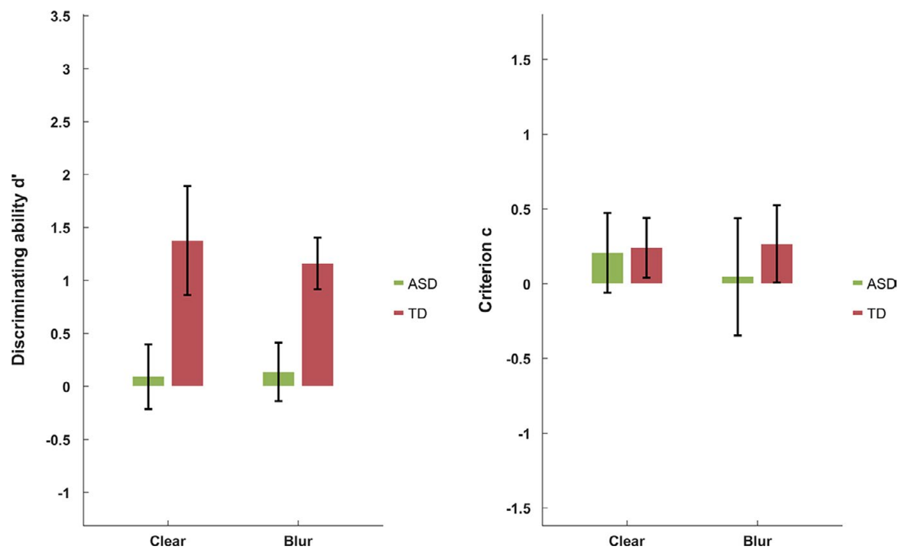



**FIGURE 2** Bar plot of discriminating ability *d'* and criterion *c* of the gender-judgement task (error bar represents standard error)

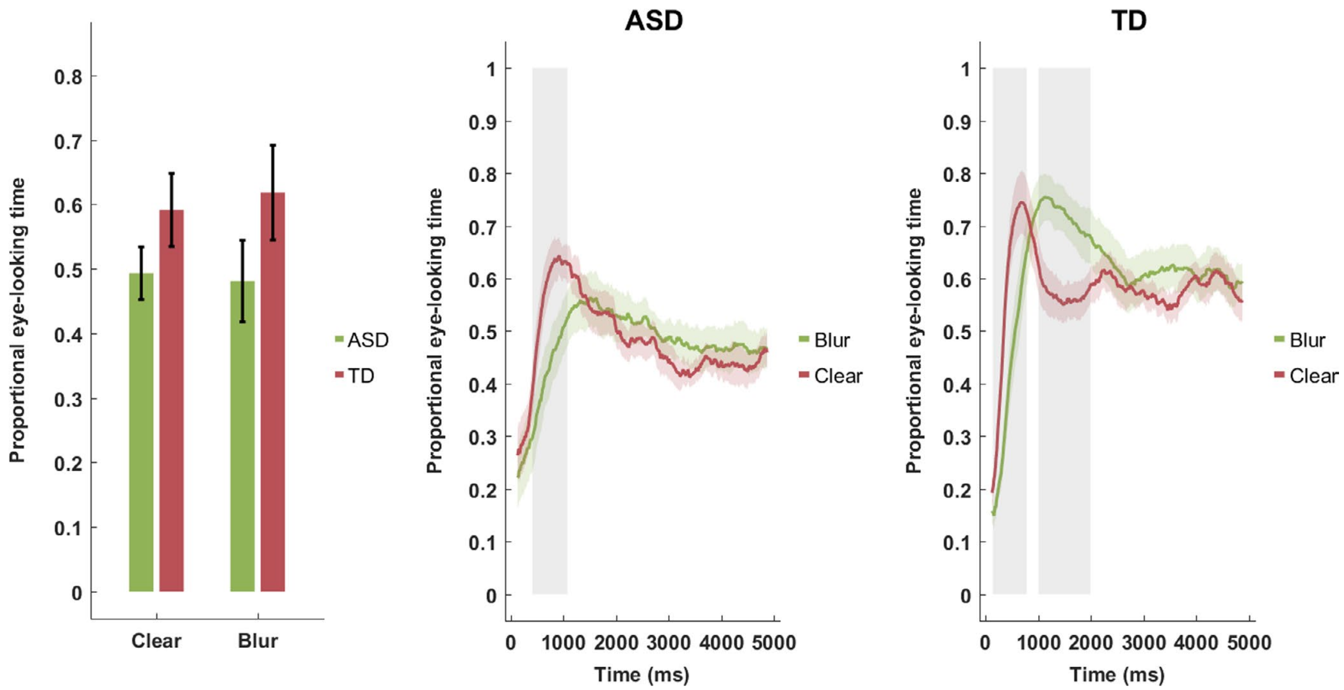



**FIGURE 3** Proportional eye-looking time. Left panel: Bar plot of overall eye-looking time (error bar represents standard error). Right panel: eye-looking time across time (shaded area indicates standard error). Grey shade illustrates the cluster of time epochs when the condition differences of eye-looking time are significant

not reach significance. Specifically, the main effect of the Group was shown around the eye and eyebrow regions, and the main effect of the Condition was shown around the eyes, nose and mouth regions. By comparing the group differences directly, we found that children with ASD looked less at the eyes (especially regions around pupils) but more at the eyebrow than TD children (Figure 4b) for both conditions. By comparing the condition differences directly, we found that children with ASD looked more at the eyes and mouth but less at the nose in the clear condition than the blur condition (Figure 4b). For TD children, however, the spatial distributions of proportional looking time were similar for both conditions.

For the eye movement entropy, as shown in Figure 5, we found significant main effects of Condition and Group on the overall eye movement entropy, $F(1, 37) = 26.99$, $p < 0.001$, $\eta_p^2 = 0.422$, and $F(1, 37) = 42.25$, $p < 0.001$, $\eta_p^2 = 0.533$, respectively, but no interaction between them, $p > 0.05$. These results implied that eye movement entropy was higher in the clear condition than that in the blur condition, and higher in the ASD group than the TD group. The temporal-course analysis revealed that the group differences appeared in the second time-bin (501–1000 ms), and lasted to the last time-bin for both the clear and blur conditions (Figure 5).

## 4 | DISCUSSION

Consistent with many previous studies (Jones & Klin, 2013; Moriuchi et al., 2017; Yi et al., 2013), we found that children with ASD look less at the eyes than TD children. Using a gaze-contingent paradigm (Caldara et al., 2010; Grynszpan & Nadel, 2015; Grynszpan, Nadel, et al., 2012; Grynszpan, Nadel, et al., 2012), we further examined whether this abnormal face scanning pattern was accounted for by their compensatory strategy to process the eyes through peripheral vision. Our finding of the similar reduced eye-looking time in ASDs in the blur condition has helped rule out this hypothesis. The temporal-course analysis further revealed the possible motivation-based guidance of attention to process the eyes in the TD group but not in the ASD group. Finally, the analysis based on Shannon entropy revealed that children with ASD scanned faces more randomly and less strategically than TD children.

The social motivation theory that children with ASD may find faces and eyes less meaningful, and thus have less motivation to process them (Chevallier et al., 2012) has a considerable influence on our understanding of the deficits in social cognition and social skills of individuals with ASD. However, this theory was challenged by Jaswal and Akhtar (2018) recently, who argued that the ‘abnormal’ social deficits of ASD do not necessarily reflect lack of social motivation, and other alternative explanations should be considered. Evaluating these alternative explanations is important considering the great impacts of the social motivation theory on the field of autism research. Our study tested one of the alternative explanations for reduced eye contact in ASDs: children with ASD may use a compensatory strategy to avoid direct eye contact by fixating at other regions to process the gaze. This compensatory strategy has been found in previous literature to be used by Easterners, who also avoid direct eye contact by fixating at nose to process the information from the eyes, compared with Westerners (Caldara et al., 2010). Such an alternative hypothesis is difficult to assess using the traditional eye movement paradigms including clear faces: considering that the visual system

**FIGURE 4** iMap results. (a) Main effects of Group and Condition. (b) Smoothed proportional gaze duration heatmaps and estimated coefficient ($\beta$) difference maps. For the third column of faces, hot colours (i.e. red) denote greater proportional looking time by children with ASD than TD children and cold colors (i.e. blue) denote greater proportional looking time by TD children than children with ASD. For the third row of faces, hot colors (i.e. red) denote greater proportional looking time in the clear condition than the blur condition and cold colors (i.e. blue) denote greater proportional looking time in the blur condition than the clear condition. Significant regions are outlined with black lines. ASD, autism spectrum disorder; TD, typically developing

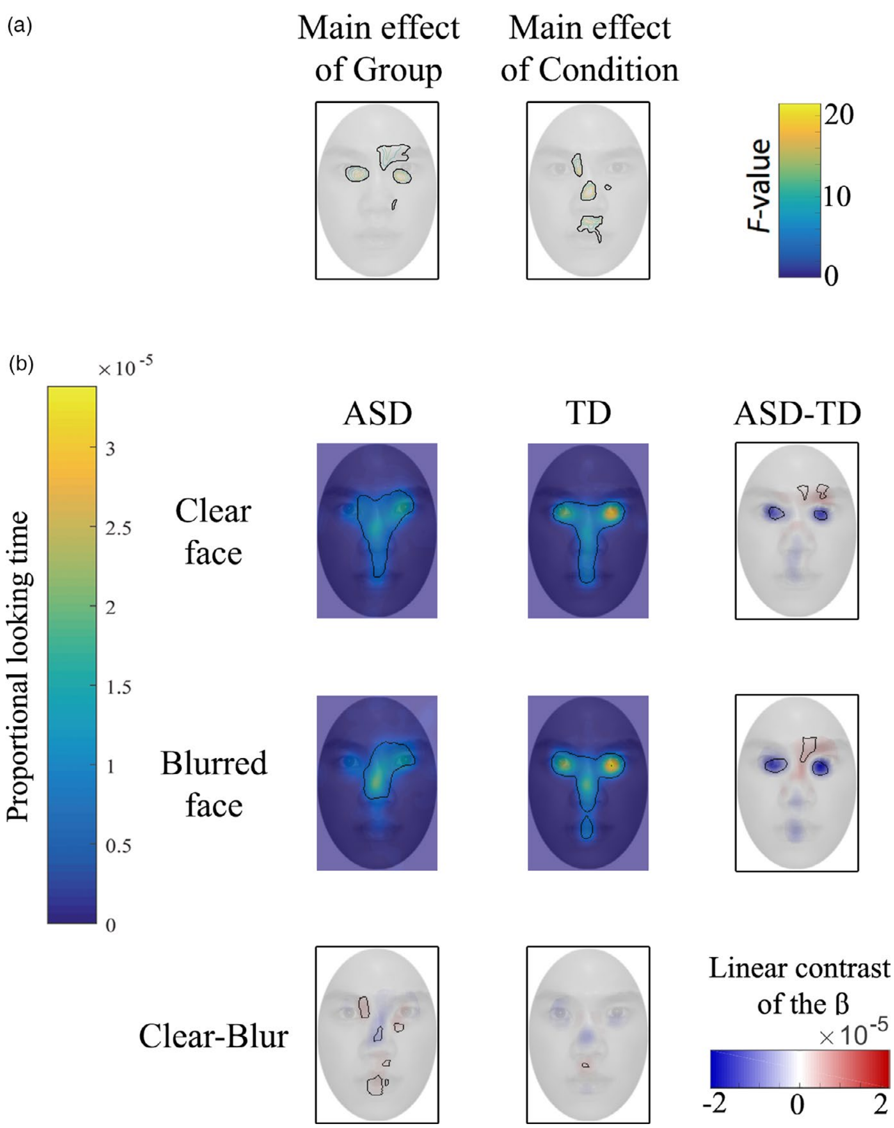
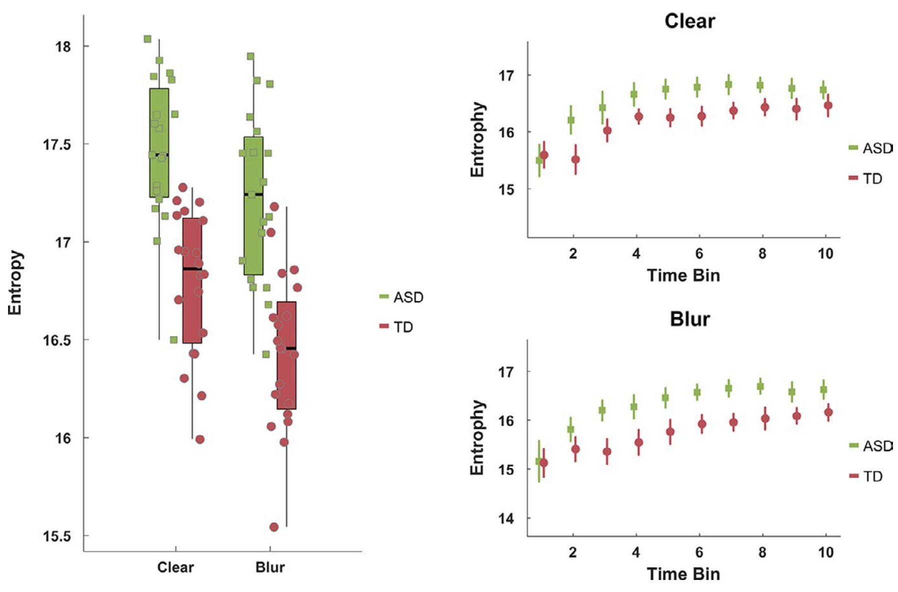



**FIGURE 5** Eye movement entropy. Left panel: box plot of overall eye movement entropy (each point represents one individual data). Right panel: eye movement entropy across time (error bar indicates standard error)



could ubiquitously extract diagnostic extra-foveal information, the visual information actually processed by individuals with ASD is still unknown. With the gaze-contingent paradigm (Grynszpan & Nadel, 2015; Grynszpan, Nadel, et al., 2012; Grynszpan, Nadel, et al., 2012), in which the whole face is blurred except for a small region being fixated at, we were able to investigate the exact information processed by participants. We found that children with ASD still spent less time looking at the eyes than TD children when scanning blurred faces; children with ASD even looked less at the eyes when faces were blurred compared to clear faces, especially at the beginning. Thus, our results are inconsistent with the prediction from the compensatory strategy hypothesis. However, our results did not provide sufficient evidence to evaluate the social motivation theory since we could not rule out other alternative explanations of social motivation theory proposed by Jaswal and Akhtar (2018), such as the gaze aversion hypothesis (Hutt & Ounsted, 1966; Tanaka & Sung, 2013) that individuals with ASD actively avoid the eyes to relieve the uncomfortable feelings elicited by the direct eye gaze. All these alternative accounts are worth testing in further investigations to evaluate the social motivation theory.

When we compared children's eye movements between when scanning blurred and clear faces based on the temporal-course analysis, we discovered that both groups showed longer eye-looking time when viewing clear than blurred faces within 1,000 ms after the face onset. The clear eyes, with a sclera surrounding the highly contrasted iris (Kobayashi & Kohshima, 1997), are certainly more physically salient than the blurred eyes. Thus, it is possible that the physical saliency of the clear eyes could automatically capture attention of both groups of children initially. This could also explain why we did not find group difference of eye-looking time in the early phase when viewing clear faces (Figure S3). After 1,000 ms, TD children gradually looked more at the eyes of the blurred faces relative to the clear faces, possible due to their motivation-based guidance of attention to process the eyes. The children with ASD, however, did not show such modulation of the motivation, and their looking time at the blurred face after 1,000 ms were very similar to the clear face.

Additionally, we found that the ASD group had higher eye movement entropy than TD group when scanning faces, suggesting that their face scanning pattern is more random and less strategical than TD children. A recent study found that eye movements of viewers became less similar to each other when they cannot develop a schematic understanding of the unfolding video (Kirkorian & Anderson, 2008). Furthermore, it was assumed that participants' eye movement entropy decreased when the environment was perceived as meaningful (Jordan & Slater, 2009). Similarly, higher eye movement entropy might reflect less prior knowledge of where and when to process the social information and thus lack of strategy to efficiently scan the face. Temporal course analysis revealed that the group difference in eye movement entropy appeared early after the face onset (before 1,000 ms, Figure 5). This result together with the findings from the eye-looking time across time, which revealed the group difference in eye-looking time appeared within 1,000 ms after the face onset (especially for the blurred faces, Figure S3), suggested that atypical face scanning emerged early after the face onset in children with ASD. Furthermore, we found that both groups showed higher eye movement entropy in the clear condition than that in the blur condition, suggesting the important role of physical saliency in guiding attention in the clear condition.

It is worth noting that although our findings provide evidence against the compensatory strategy hypothesis, they do not provide the direct evidence for the social motivation theory. Social motivation is associated with expecting responses from the social partner. Thus, social motivation might be less likely to manifest during recognition of static face's gender than interacting in real social scene and watching dynamic faces. To this end, more complex experimental designs with real and interactive faces are recommended, and neuroimaging techniques should also be used to test whether reward system (Chevallier et al., 2012) would be active in children with ASD. Also, other alternative hypotheses of the social motivation theory, as suggested by Jaswal and Akhtar (2018) still need to be tested.

As shown by the iMap results, we failed to demonstrate the longer mouth-looking time in children with ASD relative to TD children found by some previous studies (Jones, Carr, & Klin, 2008; Klin, Jones, Schultz, Volkmar, & Cohen, 2002). However, the longer mouth-looking time in ASD is far from conclusive based on the existing evidence: one recent meta-analysis reveals that group (individuals with ASD vs. TD individuals) difference in mouth-looking time is not as stable as the group difference in eye-looking time, evidenced by larger effect sizes in the latter (Frazier et al., 2017). In fact, some previous studies have also found comparable or even reduced mouth-looking time in ASD as compared with TD children (e.g. Fedor et al., 2017; Yi et al., 2013). Future studies should explore what factors (e.g. types of stimuli, types of tasks, participant characteristics, etc.) may influence the group difference in mouth-looking time.

In the current study, we proposed a data-driven temporal-course analysis method to reveal when group/condition difference appeared. Until now, most eye-tracking studies have used hypothesis-based analyses that amalgamate all fixation/gaze points that fall into a particular predetermined area of interest (AOI) and then perform statistical tests on the total looking time across whole stimulus-presenting time. Such analyses could detect the presence of an effect but do not take full advantage of the wealth of information contained in the eye-tracking data, therefore it can only provide relatively crude information as to 'when' and 'where' an effect occurs. Recently, a data-driven method—iMap (Lao et al., 2017), also used by the current study, was developed to allow for statistical testing of condition differences on any part of a stimulus without the restriction of the AOIs in the pixel level, which solved the 'where' problem. Here, we proposed a data-driven method based on a moving-average approach with a cluster-based permutation test to control the family-wise error rate to solve the 'when' problem. This fine-grained data-driven based temporal-course analysis has revealed many interesting results in the current study, which could not be found by the analysis just based on the overall looking time. For example, the analysis based on the overall proportional eye-looking time found no differences between when scanning clear and blurred faces in both groups. The temporal-course analysis, however, revealed the nuanced differences across time between conditions.

One limitation of the current study was that the gender judgment task was rather challenging for children with ASD, reflected by their poorer discriminating ability in judging the gender of faces compared to TD children. This result is in line with numerous previous observations suggesting that individuals with ASD have lower sensitivity to many facial characteristics, including gaze direction, facial identities and expressions (Forgeot et al., 2016; Pellicano, Rhodes, & Calder, 2013; Uljarevic & Hamilton, 2013; Weigelt, Koldewyn, & Kanwisher, 2012). However, the result that the discriminating ability *d'* of the ASD group is actually at the chance level is unexpected. The purpose of setting up this task, instead of free viewing, was to keep children's attention to the faces, otherwise they might feel bored and lost their attention when viewing the faces freely for 5 s. In our task, all face images were cropped in an oval shape to eliminate the external clues such as the hairstyle, which could be particularly important for gender judgement. This manipulation has been used by many previous studies (e.g. Spezio, Adolphs, Hurley, & Piven, 2007; Yi et al., 2013), to fully control the impact of the external facial features on face scanning, but also created more challenges for children with ASD. Thus, our finding could imply that in daily life, children with ASD rely heavily on the external clues (e.g. the hairstyle, the clothes or the human voice) to judge the gender of people, and once these factors are unavailable, they experience tremendous difficulty to judge the gender based merely on the face features. Future studies could replicate our results with less challenging tasks. Moreover, the gender judgment task could influence the face scanning pattern. For example, a machine learning study has showed that eyebrow features can be used to classify gender (Dong & Woodard, 2011). This is evidenced by our iMap results showing that children with ASD, who tended to avoid looking at eyes, looked more at eyebrow during gender recognition task. Considering the potential influence of the type of task on eye movements (e.g. Falck-Ytter & Von Hofsten, 2011), other tasks should also be used to evaluate the generalizability of the current findings to other contexts.

In sum, we examined one of the alternative explanations of the eye avoidance in ASD that children with ASD may use compensatory strategy to obtain information of the eyes from peripheral vision. We found that the abnormal face scanning pattern in ASD could not be accounted for by their compensatory strategy to process eyes through peripheral vision. However, our findings do not provide direct evidence for the social motivation theory, which needs to be further evaluated in future investigations.

## ACKNOWLEDGEMENTS

This study was supported by National Natural Science Foundation of China (31871116, 31571135) and Beijing Municipal Science & Technology Commission (Z171100000117015). The authors are grateful to children and parents who participated in our study.

## CONFLICT OF INTEREST

The authors report no biomedical financial interests or potential conflicts of interest.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author (Li Yi) upon reasonable request.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**How to cite this article:** Wang Q, Hoi SP, Wang Y, et al. Out of mind, out of sight? Investigating abnormal face scanning in autism spectrum disorder using gaze-contingent paradigm. *Dev Sci*. 2020;23:e12856. https://doi.org/10.1111/desc.12856