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Eye Avoidance in Young Children With Autism Spectrum Disorder Is Modulated by Emotional Facial Expressions

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Individuals with autism spectrum disorder (ASD) exhibit a reduced duration of eye contact compared with typically developing (TD) individuals. This reduced eye contact has been theorized to be a strategy to relieve discomfort elicited by direct eye contact (Tanaka & Sung, 2016). Looking at threatening facial expressions may elicit more discomfort and consequently more eye avoidance in ASD individuals than looking at nonthreatening expressions. We explored whether eye avoidance in children with ASD is modulated by the social threat level of emotional expressions. In this study, 2- to 5-year-old children with and without ASD viewed faces with happy, angry, sad, and neutral expressions, while their eye movements were recorded. We observed the following: (a) when confronted with angry faces, the children with ASD fixated less on the eyes than did TD children, persistently across time; (b) the group differences in the overall eye-looking time were rarely found for happy, neutral, and sad faces; (c) the ASD group showed eye avoidance for neutral faces between 1,000 ms and 2,900 ms after the stimulus onset. Additionally, both groups spent more time looking at the angry faces than the faces showing other emotions. Considering that the children with ASD spent less time looking at the eyes of the angry faces than other emotional faces, the results suggest a combination of vigilance to threatening faces and an avoidance of the eyes in children with ASD. Our study not only extends the gaze aversion hypothesis but also has implications for the treatment and screening of ASD.

General Scientific Summary
Previous studies have indicated that individuals with ASD exhibit an eye-avoidance pattern when scanning faces. This study observed that this pattern is modulated by facial expressions; the eye-avoidance pattern in young children with ASD is specific to threatening facial expressions, which suggests that eye avoidance may help children with ASD alleviate discomfort elicited by threatening facial expressions.

Keywords: autism spectrum disorder, face scanning, eye avoidance, eye movement, emotional expressions

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Autism spectrum disorder (ASD) is a pervasive neurodevelopmental disorder characterized by impairments in social interaction and communication, as well as by the presence of repetitive or stereotypical behaviors (American Psychiatric Association, 2013). Along with these social deficits, individuals with ASD have been found to have impairments in facial identity discrimination (Weigelt, Koldewyn, & Kanwisher, 2012) and emotion recognition (Rump, Giovannelli, Minshew, & Strauss, 2009; Uljarevic & Hamilton, 2013). People with ASD also exhibit atypical neural responses to faces (Dalton et al., 2005; Pierce, Müller, Ambrose, Allen, & Courchesne, 2001) and atypical face-scanning patterns (for a review, see Falck-Ytter & von Hofsten, 2011). Particularly, eye-tracking studies have repeatedly found that people with ASD spend less time looking at others' eyes than typically developing (TD) counterparts (e.g., Jones & Klin, 2013; Pelphrey et al., 2002; Yi et al., 2013). This is referred to as the "eye avoidance" looking pattern in ASD (Tanaka & Sung, 2016). These findings are consistent with clinical observations that individuals with ASD have limited eye contact with others (Adrien et al., 1993; however, see later).

The mechanisms underlying this atypical eye-gaze in ASD have attracted increased research interest in the past decade. Some researchers have proposed that individuals with ASD perceive direct eye contact as socially threatening, and thus actively avoid looking at others' eyes to relieve the uncomfortable feelings elicited by direct eye gaze (e.g., Hutt & Ounsted, 1966; Kliemann, Dziobek, Hatri, Steimke, & Heekeren, 2010; Tanaka & Sung, 2016). This gaze-aversion hypothesis has been supported by studies showing that faces, especially faces with a direct gaze, can elicit hyperarousal in individuals with ASD—an increased physiological response indicated by heightened skin conductance (Kaartinen et al., 2012; Kylliäinen & Hietanen, 2006) and amygdala activity (Dalton et al., 2005; Kleinhans et al., 2010). Several eye-tracking studies also support this hypothesis by showing that when adults with ASD were cued to look at the eyes, they actively gazed away from the eyes more frequently and faster than TD adults (e.g., Kliemann et al., 2010).

Based on these previous findings, the question arises whether the eye-avoidance pattern in children with ASD is modulated by different levels of social threat reflected by different facial expressions. The current study aimed to address this question by comparing the differences in eye-looking time of children with and without ASD when faces bore threatening facial expressions (e.g., anger) and nonthreatening facial expressions (e.g., joy). Emotional faces, especially those with threatening expressions, have been found to result in an overreaction of the amygdala (Adolphs, 2002). Individuals with ASD with higher levels of social anxiety were found to exhibit increased activation of the amygdala (Kleinhans et al., 2010) and reduced fixation on the eyes when processing faces with fearful expressions (Corden, Chilvers, & Skuse, 2008). This leads to the idea, in line with the gaze-aversion hypothesis, that in order to relieve discomfort and hyperarousal, individuals with ASD may be more likely to avoid looking at the eyes when viewing threatening facial expressions than they are when viewing nonthreatening ones.

However, previous empirical evidence based on eye-tracking technology and the bubble paradigm (Gosselin & Schyns, 2001) has been inconsistent on the point of the modulatory effect of the facial expression on eye avoidance in ASD. Several studies have confirmed the effect of facial expressions on eye-looking time in ASD. Individuals with ASD could indeed extract sufficient information from the eyes of others when viewing happy faces but not fearful faces (Song, Hakoda, & Sang, 2016; Song, Kawabe, Hakoda, & Du, 2012; Spezio, Adolphs, Hurley, & Piven, 2007); however, several other studies reported that individuals with ASD looked less at the eyes than control individuals, regardless of facial expressions (Corden et al., 2008; Pelphrey et al., 2002). Further, no scanning difference between ASD and TD groups for any expressions have been reported (Bal et al., 2010; De Wit, Falck-Ytter, & Hofsten, 2008; Falck-Ytter, Fernell, Gillberg, & von Hofsten, 2010; Matsuda, Minagawa, & Yamamoto, 2015). The discrepancies in previous research can be attributed to several factors—different tasks (passive vs. active viewing), differing stimuli (dynamic vs. static), duration of exposure to faces, and participants' age (children vs. adults). Particularly, the developmental literature on face processing suggests that facial emotion recognition and face-scanning patterns continue to change with age (Nakano et al., 2010; Rump et al., 2009). The present study focused on a group of 2- to 5-year-old children with ASD and their age-matched TD peers using a free-viewing task. As children with ASD are usually first diagnosed in this age range and as such have been exposed to limited intervention, investigations based on children at this age may provide valuable insights into the underlying mechanisms of diminished eye-gaze in ASD.

In this study, we aimed to test whether eye avoidance in young children with ASD is specific to threatening facial expressions (e.g., anger). To this end, we showed different expressions (happy, angry, sad, and neutral) to young children with ASD and TD children while their eye movements were recorded. Sad facial expressions were included to disentangle the possible confound between threat-relatedness and negativity of the displayed emotion; if children with ASD avoid eyes in response to a social threat, they should be more likely to exhibit eye avoidance when scanning angry faces than other expressions. On the other hand, if eye avoidance occurs to avoid negative expressions as a whole, then children with ASD should spent less time looking at both angry and sad faces, since both expressions are negative in valence.

Another focus of the current study was to examine when eye avoidance in ASD occurs, how it changes over time, and whether this temporal course of eye avoidance was modulated by the different facial expressions. This fine-grained temporal course of attention allocation to the eyes has rarely been evaluated in previous studies on ASD. The temporal-course analysis has been used in previous literature on people with social anxiety (e.g.,Holas, Krejtz, Cypryanska, & Nezlek, 2014; Wieser, Pauli, Weyers, Alpers, & Mühlberger, 2009), to examine whether abnormal eye/face processing in people with social anxiety was due to the avoidance of or vigilance to socially threatening information (Chen, Ehlers, Clark, & Mansell, 2002; Horley, Williams, Gonsalvez, & Gordon, 2003; Mogg, Garner, & Bradley, 2007), or the combination of vigilance and avoidance responses to the eyes or faces (Holas et al., 2014; Mogg & Bradley, 1998; Wieser, Pauli, Alpers, & Mühlberger, 2009). In our study, the ASD group was not expected to have a vigilance response to the eyes (enhanced eye-looking time) as some individuals with social anxiety do (Boll, Bartholomaeus, Peter, Lupke, & Gamer, 2016). Rather, we expected that children with ASD would avoid looking at the eyes persistently across time, or their eye avoidance might occur at the beginning and decline with time. The former would indicate a strong, consistent form of eye avoidance, suggesting that children with ASD cannot habituate to social threats, and thus continue to avoid looking at the eyes. The latter, on the other hand, would suggest a mild form of eye avoidance, perhaps representing their habituation to the threat over time. We expected to see different eye-avoidance patterns when children with ASD were processing faces with different facial expressions—more specifically, we expected stronger forms of eye avoidance in more threatening facial expressions (e.g., anger). The temporal-course analysis was intended to reveal the nuances in children's responses to different facial expressions over time, which is of importance to our understanding of emotional face processing in ASD. Such nuanced responses to different facial expressions could also distinguish ASD from other disorders (e.g., social anxiety), and might have implications for the development of training programs targeted at improving eye contact in individuals with ASD.

Method

Participants and Ethical Considerations

We recruited thirty 2- to 5-year-old Chinese children with ASD, who were diagnosed by pediatric psychiatrists according to the diagnostic criteria for ASD in the *Diagnostic and Statistical Manual of Mental Disorders (DSM-V*; American Psychiatric Association, 2013). Children with ASD were further assessed by using the Autism Diagnostic Observation Schedule (ADOS; Lord et al., 2000). Three children were excluded from the study as they did not meet diagnostic criteria based on the ADOS. Ultimately, 27 children with ASD (four girls, M_{age} = 40.3 months, SD_{age} = 10.3 months) participated in our study (see Table 1). We also recruited 31 age-matched TD children (five girls, M_{age} = 41.2 months, SD_{age} = 9.2 months). The TD children were recruited at their routine wellness examinations at local hospitals, and they did not exhibit any signs of ASD or other developmental issues. The present protocol (protocol number: 2016-03-03e) was approved by the Committee for Protecting Human and Animal Subjects at School of Psychological and Cognitive Sciences at Peking University, China. We obtained all children's verbal assent and their parents' written consent before commencing with the experiment.

Materials

The faces used in the present study included four neutral, four happy, four angry, and four sad female faces. We drew these face photos from the Chinese Facial Affective Picture System (CFAPS; Gong, Huang, Wang, & Luo, 2011; Wang & Luo, 2005) stimulus set. All facial images (width, 260 pixels; height, 300 pixels) were frontal views and were rendered in gray scale, with hair eliminated (see Figure 1). We used female faces as past studies indicated children are more familiar with female adult faces than male faces (Quinn, Yahr, Kuhn, Slater, & Pascalis, 2002).

Procedure

Children sat approximately 50 cm away from the screen. Parents were asked to sit behind them (out of view of the eye tracker) and to remain quiet. We used a Tobii T60 eye tracker (Tobiitech, Stockholm, Sweden), an integrated eye tracker and presentation desktop system with 60 Hz sample rate and 1,024 × 768 pixel resolution, to record the gaze data. The Tobii Studio 1.5 software (Tobiitech, Stockholm, Sweden) was used to control the stimulus presentation. We used the Tobii's five-point calibration method for every child. We accepted the calibration only if all five points for the two eyes were caught by the Tobii, with only small error vectors (smaller than 0.5 degree of visual angle).

A trial began with a black screen with a white cross at the center of the monitor (approximately at the nose region relative to the face) for 500 ms. One face was later displayed for 5,000 ms at the center of the computer screen, and the children were instructed to looked at it freely. The 16 pictures, four in each facial expression, were randomly presented (i.e., a new random order for each participant). The interstimulus interval between the face presentations was 500 ms with a white cross presented at the center of the monitor. After every two trials, a cartoon video was presented for 10 s to maintain the child's attention.

Data Analysis

We defined four areas of interest (AOIs) for each face: the right eye, the left eye, the mouth, and the whole face (see Figure 1). We defined the eye region as described in earlier studies (eyebrows not

Table 1
Mean (SD) Scores on the Autism Diagnostic Observation Schedule in Children With ASD

Module (Number of participants)	Domain	*M* (*SD*)
Module 1 (*N* = 16)	Communication	6.3 (2.4)
	Social interaction	8.9 (3.0)
	Communication & social interaction	15.2 (4.7)
	Play	2.1 (1.2)
	Stereotyped behaviors	2.3 (1.1)
Module 2 (*N* = 11)	Communication	5.8 (1.7)
	Social interaction	8.3 (2.1)
	Communication and social interaction	14.1 (3.5)
	Imagination/creativity	1.0 (.5)
	Stereotyped behaviors	1.5 (1.0)

Note. Sixteen out of 27 children with ASD with low-level language (no speech to simple phrases) were conducted with Module 1, and 11 out of 27 children with ASD with higher-level of language (use phrase speech but not yet achieve verbal fluency) were conducted with Module 2.

Figure 1. Sample faces (from left to right: neutral, happy, angry, and sad faces) and sample AOIs (the AOIs were not seen by the children during the experiment). The face images were taken from the Chinese Facial Affective Picture System (CFAPS; Gong et al., 2011; Wang & Luo, 2005), a research database for the stimuli for research purposes. See the online article for the color version of this figure.

included; e.g., Yi et al., 2013), and we combined the time spent at the left and right eyes and used that result as the time spent at the eyes, or eye-looking time. The "whole face" region included the area within the face contour. Because the current study primarily focused on the eyes, supplementary analysis of the nose and the nonfeatural face region (face areas excluding the eyes, nose, and mouth) can be found in the online supplementary material (Figure S1 and Table S1). We also computed the Eye-Mouth Index (the difference between eye-looking time and mouth-looking time), and have reported it in the online supplemental material (Table S2).

We used the gaze data (i.e., sample data) rather than the fixation data as an analytical unit. We first computed the total face-looking time by summing all gaze durations on the whole face for each expression. Next, we calculated the proportional looking time on the AOIs of the eyes and mouth, respectively, by dividing the total looking time on each AOI by the total looking time on the whole face for each expression. We excluded the trials in which participants spent no time looking at the face, to avoid invalid denominators; the average number of invalid trials is listed in Table 2. At least one valid trial for each expression was necessary to be admitted into the study. According to these exclusion criteria, one child with ASD did not have any valid trials when scanning the sad faces and thus was excluded from any analysis including sad faces. To examine whether there was a difference in the number of invalid trials across groups and expressions, we conducted a 2 (Group) × 4 (Expression) repeated measures ANOVA on the invalid trial number, and found a significant main effect of group, suggesting more invalid trials in the ASD than the TD groups, and an effect of expression (see Table 2).

Table 2
Average Number (SD) of Invalid Trials and the Corresponding ANOVA Results

Group	Angry	Neutral	Happy	Sad
ASD	0.26 (0.45)	0.52 (0.75)	0.56 (0.75)	0.56 (1.01)
TD	0.03 (0.18)	0.10 (0.30)	0.23 (0.50)	0.16 (0.45)
Effects	Group	Expression	Group × Expression	
F	8.83	3.24	0.51	
p	.004	.031	.646	
η_p^2	.14	.06	.01	

To test whether eye avoidance in ASD was modulated by different expressions, we used ANOVA and t tests (two-tailed) to test our hypothesis, and used false discovery rate (FDR) adjustment for multiple comparisons to control for Type I error.

We further adopted two temporal-course analyses to examine how the eye-avoidance pattern in ASD changed over time, and how the eye-looking time changed over time for each group. First, we examined the temporal course of the scanning pattern relating to the eyes by adopting a temporal-course analysis based on the moving-average approach (e.g., Dankner, Shalev, Carrasco, & Yuval-Greenberg, 2017). We segmented each set of trial data (300 sample data in total) into epochs of 500 ms (30 sample data), with 29 sample data overlap, resulting in 271 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.

Because adjacent time-pairs are likely to exhibit the same effect, we used a statistic test based on clustering of these adjacent time-pairs to do multiple comparisons. Thus, changes in the eye-avoidance pattern across time were statistically assessed by means of a cluster-level randomization procedure (Maris & Oostenveld, 2007; see online supplementary material for more detailed information).

Second, to further explore how eye-looking time changed over time for each group, we submitted time series signal of proportional eye-looking time to ball divergence change-point analysis (BDCP; Zhang, Pan, Chen, & Wang, 2018). Change-point analysis is the process of assessing distributional changes within time-ordered observations. Ball divergence (Pan, Tian, Wang, & Zhang, 2018) is a nonparametric two-sample test in separable Banach spaces with a remarkable feature—the ball divergence of two probabilities is zero if and only if these two probabilities are the same. BDCP extends ball divergence to weakly depend on Banach-valued sequences, which can detect the number of change-points automatically without any assumptions on the specific change-point type. BDCP is a divisive hierarchical algorithm performed as follows. First, for each sequence, BDCP detects the empirical ball divergence value location of the samples before and after its maximum. Second, moving-block bootstrap is used to test whether the maximum value is significant at the .05 significance level. If it is, then the location is a change-point, and the samples before and after the location belong to different clusters with different distributions. Third, the previous two steps are repeated for each cluster until none of the maximum values in any cluster is significant.

The two temporal-course analyses are described in more detail in the online supplementary material.

Results

Total Looking Time on the Whole Face

We first examined group differences regarding total looking time on the whole face using a 2 Group (ASD and TD groups) × 4 Expression (Angry, Neutral, Happy, and Sad) repeated-measures ANOVA. As shown in Figure 2 and Table S3, only the main effect of Expression was significant, $F(3, 165) = 31.99$, $p < .001$, $\eta_p^2 = .37$, 90% CI [.26, .44]. Post hoc pairwise *t* tests (after FDR correction) revealed that children looked longer at angry than neutral, happy, and sad faces, $t(57) = 4.43$, $p < .001$, Cohen's $d = 0.58$, 95% CI [0.30, 0.86]; $t(57) = 7.05$, $p < .001$, Cohen's $d = 0.93$, 95% CI [0.61, 1.23]; $t(56) = 7.48$, $p < .001$, Cohen's $d = 0.99$, 95% CI [0.67, 1.31], respectively. Children also looked longer at neutral faces than happy and sad faces, $t(57) = 3.51$, $p = .001$, Cohen's $d = 0.46$, 95% CI [0.19, 0.73]; $t(56) = 4.53$, $p < .001$, Cohen's $d = 0.60$, 95% CI [0.32, 0.88], respectively. The difference in face-looking time between happy and sad faces was not significant, $t(56) = 1.87$, $p = .067$, Cohen's $d = 0.25$, 95% CI [−0.02, 0.51]. There was no significant main effect of group, $F(1, 55) = 0.22$, $p = .64$, $\eta_p^2 < .01$, 90% CI [.00, .07], or the Group × Expression interaction, $F(3, 165) = 2.31$, $p = .087$, $\eta_p^2 = .04$, 90% CI [.00, .09], indicating a similar amount of time looking at the whole face for the two groups. The same analyses were applied to the total time spent looking at the screen, and results were very similar to those of total time spent looking at the whole face (see Table S3 and Figure S2 for more details).

Proportional Eye-Looking Time

We examined whether the ASD and TD groups showed different proportional looking time focused on the eyes for different facial expressions across total viewing time. A repeated-measures ANOVA was conducted on the proportional eye-looking time, with expression as the within-subject variable, and group as the between-subjects variable. The results are shown in Figure 3A and Table S4.

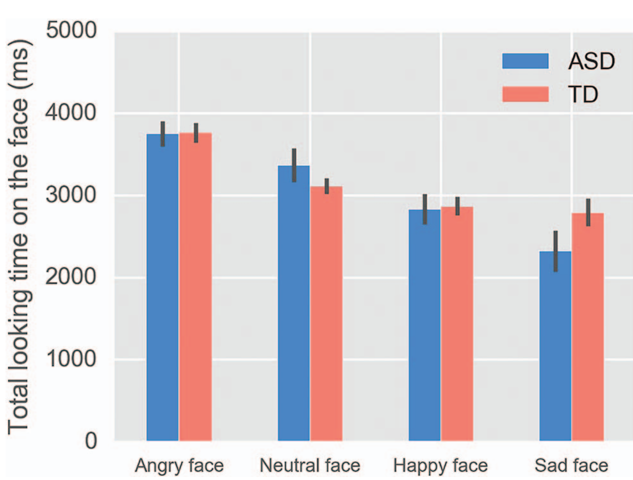

Figure 2. Group means of total looking time on the whole face (error bars denote standard errors). See the online article for the color version of this figure.

Both main effects of group and expression on the proportional eye-looking time were significant, $F(1, 55) = 5.09$, $p = .028$, $\eta_p^2 = .09$, 90% CI [.01, .21], and $F(3, 165) = 8.73$, $p < .001$, $\eta_p^2 = .14$, 90% CI [.06, .21], respectively; additionally, the Group × Expression interaction was found, $F(3, 165) = 4.25$, $p = .009$, $\eta_p^2 = .07$, 90% CI [.01, .13]. To ensure that the unbalanced trial numbers between the groups (see Table 2) would not affect our main findings, we conducted a 2 (Group) × 4 (Expression) ANCOVA on the proportional eye-looking time with the deleted trial number as the covariate; we still found a significant Group × Expression interaction, $F(3, 162) = 4.04$, $p = .008$, $\eta_p^2 = .07$, 90% CI [.01, .13]. Additionally, the main effect of expression was also significant, $F(3, 162) = 3.81$, $p = .01$, $\eta_p^2 = .07$, 90% CI [.01, .12], whereas the main effect of group was not significant, $F(1, 54) = 1.68$, $p = .20$, $\eta_p^2 = .03$, 90% CI [.00, .13].

We further performed simple effect analyses to test whether the differences of proportional eye-looking time between the two groups would be moderated by different facial expressions. The results indicated that the ASD group looked at the eyes less than the TD group only for the angry faces, $F(1, 55) = 15.81$, $p < .001$, $\eta_p^2 = .22$, 90% CI [.08, .36]. No group differences of the eye-looking time were found for the neutral, $F(1, 55) = 3.67$, $p = .06$, $\eta_p^2 = .06$, 90% CI [.00, .18]; happy, $F(1, 55) = 0.27$, $p = .61$, $\eta_p^2 < .01$, 90% CI [.00, .07]; and sad faces, $F(1, 55) = 0.65$, $p = .42$, $\eta_p^2 = .01$, 90% CI [.00, .10].

We also conducted simple effect analyses to test whether each group spent a different amount of time looking at the eyes for different expressions. For the ASD group, we found a significant main effect of expression on the proportional eye-looking time, $F(3, 165) = 8.81$, $p < .001$, $\eta_p^2 = .14$, 90% CI [.06, .21]. Post hoc paired-wise *t* tests (after FDR correction) revealed that the children with ASD looked at the eyes of the angry faces less than those of the happy, neutral, and sad faces, $t(26) = -3.36$, $p = .006$, Cohen's $d = 0.65$, 95% CI [0.23, 1.06]; $t(26) = -2.41$, $p = .035$, Cohen's $d = 0.46$, 95% CI [0.06, 0.86]; $t(25) = -5.14$, $p < .001$, Cohen's $d = 1.01$, 95% CI [0.53, 1.48], respectively. They also looked at the eyes of neutral and happy faces less than those of sad faces, $t(25) = -2.82$, $p = .018$, Cohen's $d = 0.55$, 95% CI [0.13, 0.96]; $t(25) = -2.30$, $p = .036$, Cohen's $d = 0.45$, 95% CI [0.04, 0.85], respectively. No difference was found between happy and neutral faces, $t(26) = 1.51$, $p = .14$, Cohen's $d = 0.29$, 95% CI [−0.10, 0.67]. For the TD group, the results also showed a main effect of expression, $F(3, 165) = 3.73$, $p = .012$, $\eta_p^2 = .06$, 90% CI [.01, .12]. Post hoc pairwise *t* tests (after FDR correction) revealed that the TD children looked at the eyes of happy faces less than the eyes of angry and sad faces, $t(30) = -2.60$, $p = .04$, Cohen's $d = 0.47$, 95% CI [0.09, 0.83]; $t(30) = -2.67$, $p = .04$, Cohen's $d = 0.48$, 95% CI [0.10, 0.85], respectively. No other significant differences were found for other expression pairs: angry versus neutral, $t(30) = 0.81$, $p = .42$, Cohen's $d = 0.15$, 95% CI [−0.21, 0.50]; angry versus sad, $t(30) = -1.09$, $p = .41$, Cohen's $d = 0.20$, 95% CI [−0.16, 0.55]; neutral versus happy, $t(30) = 0.97$, $p = .41$, Cohen's $d = 0.17$, 95% CI [−0.18, 0.53];

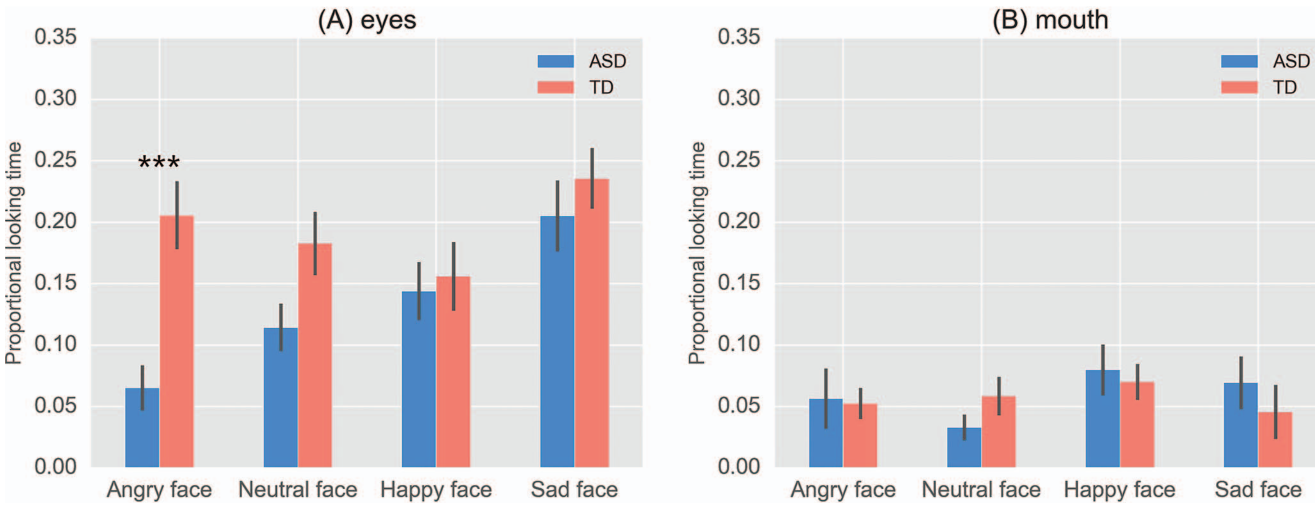

Figure 3. Proportional looking time on the eyes and mouth of different emotional faces of the ASD and the TD groups (error bars denote standard errors; *** denotes $p < .001$). See the online article for the color version of this figure.

and neutral versus sad, $t(30) = -2.20$, $p = .07$, Cohen's $d = 0.40$, 95% CI [0.03, 0.76].

Temporal-Course Analysis

Aside from the analyses that collapsed all time spent looking at the eyes across the total viewing time, we further examined the temporal course of the eye-looking time to determine when the eye avoidance appeared and how it changed over time. The results are presented in Figure 4. For the angry faces, the ASD group spent less time looking at the eyes than the TD group in almost all epochs. For the neutral faces, significant group differences in eye-looking time existed between about 1,000 ms and 2,900 ms after the face appeared, and the two groups looked at the eyes similarly in other epochs. For happy faces, the two groups displayed similar eye-looking time in almost all epochs with the exception of a short interval, 616 ms–682 ms, after the face appeared. For sad faces, the two groups spent similar time on the eyes in all epochs.

Additionally, we examined how eye-looking time changed over time for each group and expression respectively. Change-points found by the BDCP analysis are illustrated in Figure 5. For angry faces, only one change-point was found for the ASD group, and no change-points were found for the TD group. For other expressions, multiple change-points were found, suggesting that proportional eye-looking time for both groups oscillated across time—they increased their attention to the eyes gradually and then gradually decreased their attention to the eyes, and repeated this procedure across time. The oscillation amplitudes, however, changed across time.

Combining these two temporal-course approaches, we reached the following conclusions. (a) For angry faces, the ASD group displayed consistently shorter proportional eye-looking time across time relative to the TD group. (b) For neutral faces, the eye-avoidance pattern of ASD occurred around 1,000 ms after the onset of the face, and lasted for around 2,000 ms (see Figure 4). Due to both the increased proportional eye-looking time of the ASD group and the decreased proportional eye-looking time of the TD group between 1,500 ms and 3,000 ms (see Figure 5), the group difference disappeared after 2,900 ms. (c) For the happy and the sad faces, the proportional eye-looking time was very similar in the two groups across time.

Proportional Mouth-Looking Time

A 4 (Expression) × 2 (Group) repeated-measures ANOVA on the proportional mouth-looking time found no significant main effect of group, $F(1, 55) = 0.05$, $p = .83$, $\eta_p^2 < .01$, 90% CI [.00, .04]; expression, $F(3, 165) = 2.03$, $p = .11$, $\eta_p^2 = .04$, 90% CI [.00, .08]; or their interaction, $F(3, 165) = 1.35$, $p = .26$, $\eta_p^2 = .02$, 90% CI [.00, .06]. That is, the two groups looked at the mouth similarly for all four expressions (Figure 3B and Table S4).

Discussion

In the present study, we employed eye-tracking to examine eye avoidance in young children with ASD when processing facial expressions. We observed that the hypothesized eye avoidance in ASD was most prominent for threatening facial expressions (i.e., angry faces), which is consistent with the gaze aversion hypothesis that considers eye avoidance as a strategy to relieve discomfort elicited by social threat (Hutt & Ounsted, 1966; Kliemann et al., 2010; Tanaka & Sung, 2016). The results of the within-group comparisons further revealed that the children with ASD looked at the eyes of the angry faces less than the neutral, happy, and sad faces, while TD children looked at the eyes of angry and sad faces more than happy faces. Furthermore, our temporal-course analysis revealed for angry faces, children with ASD showed the eye-avoidance pattern relative to the TD children in almost all time epochs; for neutral faces, the eye avoidance in children with ASD began about 1,000 ms after the onset of the face, and lasted to 2,900 ms. For the happy and sad faces, group differences were rarely found at any time. These findings could not be explained by the group differences in the overall attention distribution, given the similar face-looking time between the two groups.

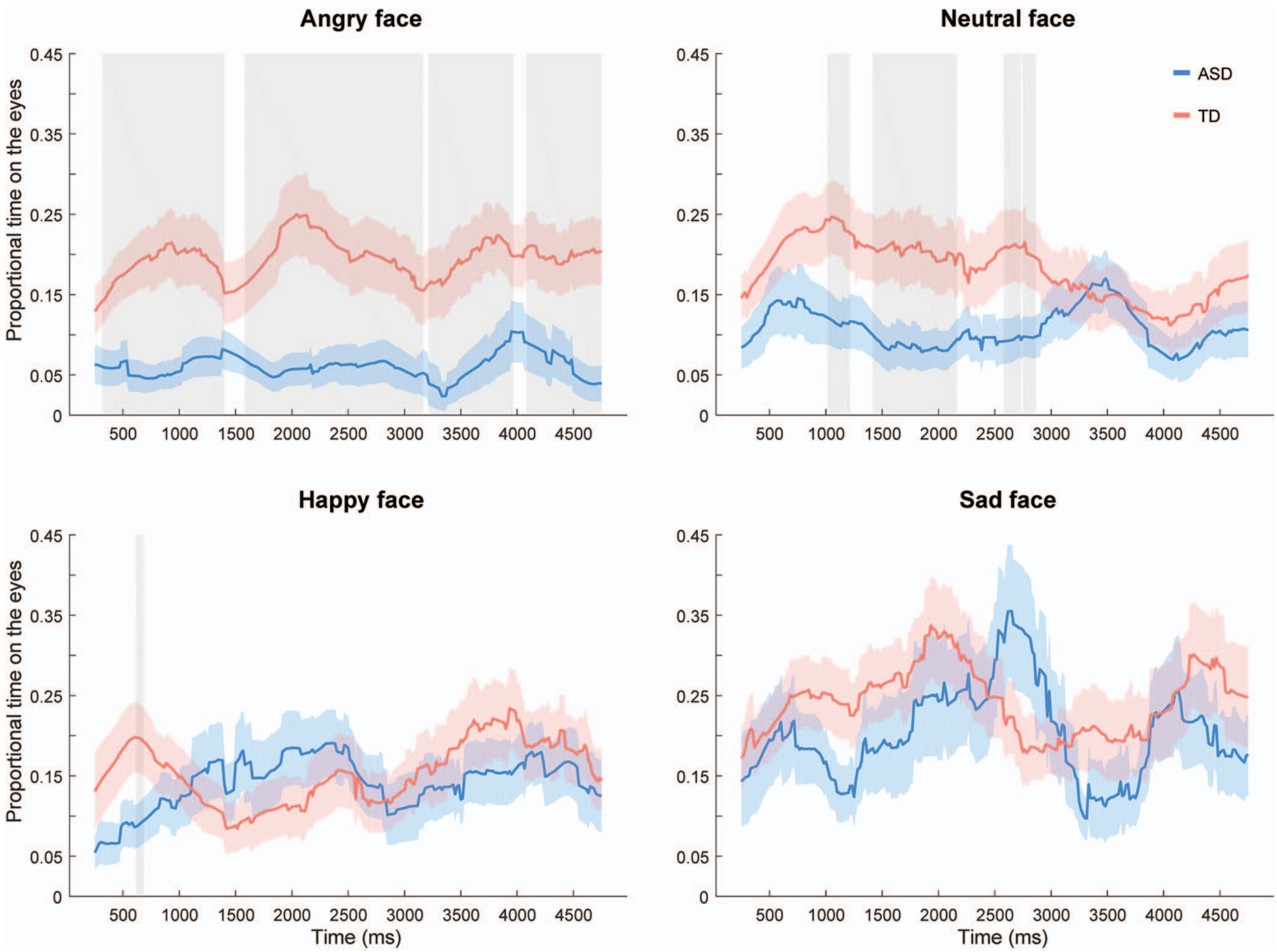

Figure 4. Proportional eye-looking time of the ASD and the TD groups for different expressions over time (shaded area indicates standard errors). Gray shade illustrates the cluster of time epochs when the group differences of eye-looking time are significant. See the online article for the color version of this figure.

Our comparative findings, in which the ASD group showed reduced proportional eye-looking time of angry faces, but not of sad faces, suggest that the eye avoidance of ASD has a greater likelihood of being associated with more socially threatening stimuli, rather than with negativity as a whole. Further evidence came from the analyses that compared the face-scanning patterns between different expressions for each group. The TD children looked at the eyes of the angry and sad faces more than those of the happy faces. Considering that expressive information of negative expressions is, for the most part, conveyed by the upper half of the face (Eisenbarth & Alpers, 2011; Schurgin et al., 2014; Smith, Cottrell, Gosselin, & Schyns, 2005), our finding suggests that TD children are very sensitive to this nuance among expressions. However, such sensitivity was absent in the children with ASD, who looked at the eyes of the angry faces less than the neutral, happy, and sad faces, further suggesting that eye avoidance in ASD is specific to socially threatening expressions. These interexpression comparisons also suggest that the decreased eye-looking time of children with ASD for angry faces is due to their atypical face processing, but not to their decreased physical salience for the eyes of angry faces, given that the TD children spent the most time looking at the eyes of angry faces.

Despite their eye avoidance responses toward angry faces, the children with ASD, similar to TD children, looked more at the whole faces with threatening emotional expressions than those with nonthreatening expressions, which is consistent with several previous studies (Hall, Hutton, & Morgan, 2012; Perez-Edgar et al., 2017). Faces displaying threatening emotional expressions, such as anger and fear, have been described to evoke vigilance responses from individuals (Green, Williams, & Davidson, 2003), leading to longer looking time for these faces. In fact, infants as young as 7 months already show difficulty in disengaging from threatening faces (Peltola, Leppänen, Vogel-Farley, Hietanen, & Nelson, 2009). It should be noted that although the children with ASD paid more attention to the angry faces than to the nonthreatening faces, they looked less at the inner features of the faces (especially the eyes). That is, the children with ASD did not concentrate on the eyes, nose, and mouth of the angry faces, but distributed their gaze to a greater extent (more than half of the time), over the nonfeatural face region (Table S1), strongly indi-

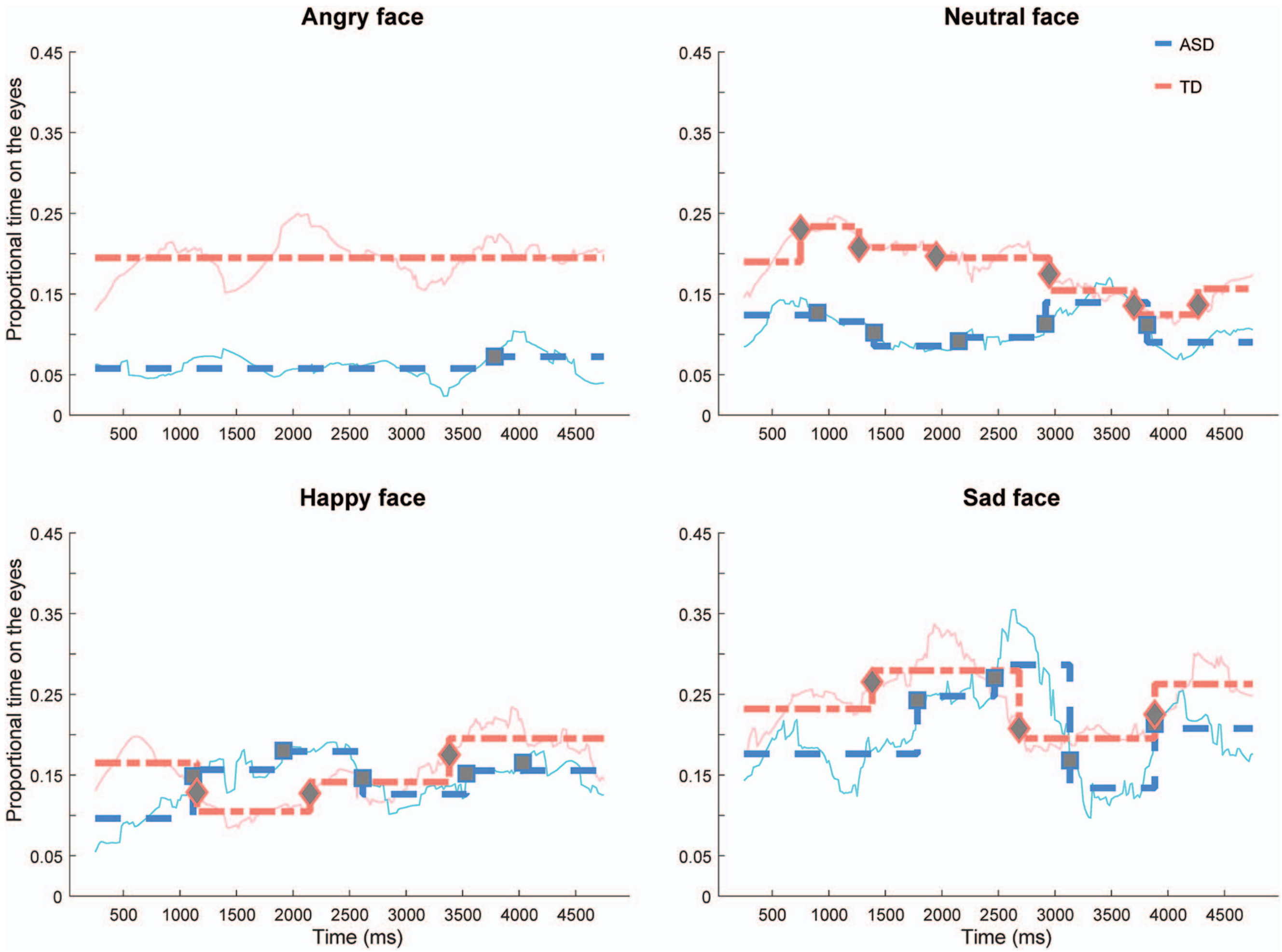

Figure 5. Change-point analysis. Change-points are marked by square for the ASD group and diamond for the TD group. Average proportional eye-looking time before, after, or between change points are marked by dash line for the ASD group and dot line for the TD group. The solid lines represent proportional eye-looking time across time. See the online article for the color version of this figure.

cating a complete avoidance of the core facial features specific to angry faces. This looking style might be a combination of vigilance to threatening faces and avoidance to the core features of such faces, especially the eyes, which convey the most social and threatening information (Eisenbarth & Alpers, 2011; Farabee, Holcom, Ramsey, & Cole, 1993; Smith et al., 2005; Wieser, Pauli, Alpers, et al., 2009). While further research is certainly needed, such a special attentional style is obviously meaningful to people with ASD. For example, being more vigilant to threatening faces can help people with ASD detect important social cues; also, avoiding eye contact can alleviate discomfort elicited by threatening facial expressions. Notably, this looking pattern reflects a *spatial* distribution of visual attention, and is different from the vigilance-avoidance looking pattern found in people with social anxiety (Holas et al., 2014; Wieser, Pauli, Weyers, et al., 2009), which, revealed by the temporal-course analyses, represents a *temporal* change of looking pattern toward social threat (initially enhanced and then subsequently reduced looking time).

With regard to the temporal-course analysis, as expected, the children with ASD demonstrated a strong form of eye avoidance by showing eye avoidance for the threatening facial expression (anger) persistently over the presentation time. For the neutral faces, although the group difference of the overall eye-looking time was not significant, the temporal-course analysis revealed that eye avoidance did appear between 1,000 ms and 2,900 ms after the face onset. After that, the group difference disappeared, due to both increased eye-looking time of the ASD group and decreased eye-looking time of the TD group. This eye-avoidance pattern confirms the mild form of eye avoidance in line with our hypothesis. Neutral expressions are often found to be confused with negative and threatening faces by both TD participants and participants with ASD (Eack, Mazefsky, & Minshew, 2015; Juth, Lundqvist, Karlsson, & Ohman, 2005; Lee, Kang, Park, Kim, & An, 2008). Thus, the decreased eye-looking with neutral faces in children with ASD may still reflect their tendency to avoid the threat-elicited discomfort posed by the eyes of neutral facial expressions. Given the lower degree of threat of neutral faces relative to angry faces, children with ASD showed a mild form of the eye-avoidance pattern that eclipsed over time. This can be attributed to their habituation or their reduced perception of the threat of neutral faces over time.

Our temporal-course analysis has additional implications. First, most previous research measured gazing behavior across the whole stimulus-presenting time without evaluating the exact temporal course of attention allocation to the eyes (e.g., De Wit et al., 2008; Yi et al., 2013). Our results suggest that attention allocation may depend on the length of the stimulus presentation time. Thus, it may provide insights into the inconsistent findings in previous studies regarding emotional face-scanning in ASD. Second, this temporal-course measure may help disentangle the abnormal attentional processes in different psychiatric disorders. It has been shown that people with social anxiety avoid looking at the eyes as well (Horley et al., 2003; Wang, Hu, Short, & Fu, 2012); however, they also show an initial vigilance (e.g., enhanced eye-looking time) followed by avoidance of social threat (e.g., reduced eye-looking time), which has been interpreted as evidence of a vigilant-avoidant attentional bias (Boll et al., 2016; Wieser, Pauli, Weyers, et al., 2009). In contrast, in our study children with ASD did not show enhanced eye-looking time toward the threatening expressions. Our findings suggest the feasibility of developing an algorithm to classify individuals with ASD and those with social anxiety simply based on their nuanced temporal courses of eye-looking patterns.

We failed to demonstrate the longer mouth-looking time in the ASD group relative to the TD group found by previous eye-tracking studies using dynamic videos (Jones, Carr, & Klin, 2008; Klin, Jones, Schultz, Volkmar, & Cohen, 2002). It is possible that when presented with a dynamic stimulus and in a communicative situation, individuals with ASD may be more attracted by the movements of the mouth, which is compatible with their preserved ability to use visual information from the mouth for speech-related processing (Klin et al., 2002). Previous studies using static faces have found similar results as the current study by showing comparable or even reduced mouth-looking time in ASD as compared with TD children (e.g., Fedor et al., 2017; Yi et al., 2013). The similar mouth-looking time in ASD and TD groups found in our study has ruled out the possibility that eye avoidance in ASD is driven by increased attention to, or interest in, the visual and communicative information conveyed by the mouth.

Several main considerations emerge from these findings. First, similar to most previous studies on face processing in ASD, we used static photos of emotional expressions. The generalization of our conclusions should be examined in future studies using more ecologically valid stimuli, perhaps even live stimuli (e.g., interpersonal interactions between the participants and an experimenter) using head-mounted eye-tracking equipment. Second, the lack of measurement of IQ or developmental level of the current sample is another limitation of the current study. Although a recent meta-analysis indicated no impact of IQ on gaze abnormalities in ASD (Frazier et al., 2017), from a scientific point of view it is crucial to match this variable between groups to ensure that the observed group differences were due to the diagnostic status rather than to developmental levels. To better illustrate the relationship between IQ and the eye-avoidance pattern in ASD, future work could study the gaze patterns of children with ASD with a broad range of IQ. Third, future investigations could explore the link between eye contact and arousal in young children with ASD by recording skin conductance and eye movements simultaneously. Future studies could also use the eye-tracking technique combined with questionnaires about anxiety and neuroimaging techniques to further explore the relationships between anxiety and eye avoidance in ASD. Fourth, future studies should examine the effects of other types of threatening facial features (e.g., aggressiveness and gender, Carré, McCormick, & Mondloch, 2009; Renzi, Tagliaferri, & Boehringer, 2014) on eye-looking patterns in ASD. For example, our study only used female faces, and it is unclear whether male faces, which could be perceived as more threatening than female faces (Renzi et al., 2014), elicit a stronger eye-avoidance pattern. Additionally, we could cue children's attention to the eyes, as Moriuchi, Klin, and Jones (2017) did, but with faces of different expressions to test whether facial expressions would modulate the extent of "flight from the eyes" in ASD (Moriuchi, Klin, & Jones, 2017). Fifth, the atypical face-scanning pattern was used as a potential marker for screening infants and children with ASD in previous studies (e.g., Jones & Klin, 2013; Liu, Li, & Yi, 2016). The findings of the present study imply that angry faces may be a more powerful marker than other expressions for the purpose of screening and identifying ASD. Future studies can consider the likelihood of using the scanning pattern for angry faces, combined with machine-learning algorithms, to support an ASD diagnosis and improve the accuracy of detecting infants at risk of ASD. Additionally, we need to consider the specificity of markers for ASD. For example, we should tease apart the distinct looking patterns of children with ASD and children with an inhibited or shy temperament in future investigations. An interesting alternative explanation that has been proposed is that eye avoidance of angry faces in children with ASD could be associated with the indirect impact of their greater disorganization of scan patterns caused by emotional arousal. However, this possibility is not testable in our current paradigm. We believe this interesting speculation is a valuable topic for further research and theoretical development.

In conclusion, we observed that 2- to 5-year-old children with ASD tend to look less at others' eyes, especially the eyes of threat-related expressions. We speculate that the diminished eye-looking time for socially threatening expressions may help relieve the threat-elicited hyperarousal caused by direct eye contact. This eye avoidance in ASD could not be explained by reduced face-looking time or enhanced attention or interest to the month. Instead, our findings suggest a combination of vigilance to, and avoidance of the core features of threatening faces. Our study also has important implications for the clinical interventions for ASD. Particularly, it suggests that interventions that address social impairments in young children with ASD should incorporate methods of alleviating discomfort elicited by the threatening information of faces. Moreover, the scanning patterns for socially threatening facial expressions can also serve as a potential early marker in developing a computer-aided system to support the diagnosis and early detection of ASD in future investigations.

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