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Automatic pupillary responses to pain perception in adults and children: The influence of race and autistic traits

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ABSTRACT

The ability to understand and share others' emotional states (e.g., feeling of pain) plays a fundamental role in survival and prosocial behavior. The current study utilized pupillometry to assess automatic psychophysiological responses to others' painful facial expressions in both adults and children ($N = 72$). Results revealed that pupil size significantly increased when perceiving painful versus neutral expressions, independent of low-level visual features. Notably, both adults and children exhibited a racial in-group bias, with pupil dilation effects observed only for same-race painful faces. Furthermore, individuals' Autism Spectrum Quotient scores were negatively correlated with pupil dilation effects toward painful expressions of same-race faces. These findings suggest that pupillary responses might reflect automatic empathic arousal to others' pain and are modulated by racial group membership and autistic traits, providing a potential physiological indicator, at least at the group level, for probing affective resonance in children or individuals with socio-cognitive disorders (e.g., autism spectrum disorder).

1. Introduction

Perceiving and understanding others' pain holds significant evolutionary value, serving as a cornerstone for survival and interpersonal interaction. Pain-related cues, such as facial expressions of pain and injured body parts, are biologically and socially salient stimuli that signal potential threats, draw attention, and prompt prosocial behaviors (Craig, Versloot, Goubert, Vervoort, & Crombez, 2010; Williams, 2002). Neuroimaging studies have consistently shown that observing others in painful situations activates the neural circuit consisting of the anterior cingulate cortex (ACC) and anterior insula (AI), suggesting automatic affective processing in response to others' suffering (Avenanti, Paluello, Bufalari, & Aglioti, 2006; Botvinick et al., 2005; Gu, Hof, Friston, & Fan, 2013; Saarela et al., 2007).

Pupillary responses, governed by the autonomic nervous system, are sensitive to both changes in ambient light and fluctuations in mental states (Joshi & Gold, 2020). Empirical evidence has shown pupil dilation in response to emotionally charged images (Bradley, Miccoli, Escrig, & Lang, 2008), reward cues (Bijleveld, Custers, & Aarts, 2009), biological motion (Cheng, Yuan, & Jiang, 2024), and social interaction (Cheng, Liu, Yuan, & Jiang, 2021). Given the inherent high salience of painful expressions, rooted in their biological and social relevance, observing others in pain likely triggers spontaneous pupillary changes through arousal mechanisms. In accordance with this, previous studies have found that witnessing physical pain and social exclusion elicits pupil dilation (Krach et al., 2015). Additionally, pupillometry is particularly valuable in research with young children and infants due to its convenient applicability and noninvasive nature. For instance, infants aged 6 and 12 months exhibited greater pupil dilation when watching videos of other infants crying or laughing compared to neutral babbling (Geangu, Hauf, Bhardwaj, & Bentz, 2011). Therefore, these findings suggest that pupillary response involved in the perception of bio-social information may serve as reliable quantitative markers of psychophysiological changes in both adults and children.

Furthermore, previous literature suggests that perceiving others' pain could generate empathy – defined as the capacity to understand and share others' emotional states (Decety & Jackson, 2004) – which provides a potential mechanism that motivates altruistic behaviors (Jackson, Meltzoff, & Decety, 2005; Preston & de Waal, 2002; Singer et al., 2004). Although empathy represents a multidimensional construct consisting mainly of affective and cognitive components (de Waal, 2008; Lamm, Batson, & Decety, 2007), pupillary responses may

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reflect its automatic affective resonance aspect, commonly referred to as emotional contagion or empathic arousal (Fan, Chen, Chen, Decety, & Cheng, 2014; Singer & Lamm, 2009). Moreover, social factors such as racial group membership modulate empathic responses, with pupillary changes correlating with activation in the left-AI during observation of others' hands being painfully penetrated (Azevedo et al., 2013). Despite evidence that affective sharing and empathic neural responses to others' pain can be observed very early in development (Cheng, Chen, & Decety, 2014; Decety & Holvoet, 2021), research on the developmental trajectory of racial in-group favoritism in perceiving others' pain has been limited to behavioral evidence, such as subjective reports (Dore, Hoffman, Lillard, & Trawalter, 2014; Spinrad et al., 2023). Consequently, the present study aimed to investigate whether the racial in-group bias in perceiving others' painful facial expressions can be reflected in pupil size in both adult and child populations.

While the aforementioned findings have demonstrated socio-cultural influences and developmental changes in responses to others' pain, inter-individual variation in neurobiological underpinnings is noteworthy, such as autistic traits or autism spectrum disorders (ASD) – a neurodevelopmental disorder characterized by difficulties in social interaction and communication, as well as restricted and repetitive behaviors (American Psychiatric Association, 2013). Individuals with ASD often show atypical affective understanding and altered behavioral or physiological responses to others' emotions (Fatima & Babu, 2023; Guo et al., 2024; Rieffe et al., 2021; van der Zee & Derksen, 2019). For example, children with ASD exhibit less efficient emotion recognition and show reduced automatic responses (e.g., electrodermal and pupillary responses) to others' emotional states (Hobson, 1986; Sepeta et al., 2012). Likewise, adults with ASD also showed atypical psychophysiological and brain responses during empathy for pain (Gu et al., 2015; Krach et al., 2015). However, it remains unclear whether individuals with autism or high autistic traits exhibit racial in-group bias in their automatic affective responses to others' pain. Considering social proficiency is suggested to be a continuum that varies widely even among neurotypical individuals and is viewed as a stable personality trait (Liu, Yuan, Chen, Jiang, & Zhou, 2018; Nummenmaa, Engell, von dem Hagen, Henson, & Calder, 2012), we wondered if the extent of racial bias in empathic arousal, indexed by automatic pupillary changes, would vary with individuals' autistic traits.

Taken together, the present study investigated several issues regarding the automatic physiological reactivity (i.e., pupillary responses) involved in racial bias in empathy for pain, and its relationship with one's intrinsic social proficiency. Specifically, we examined whether pupillary responses reflect racial in-group bias in automatic affective resonance when perceiving others' pain in adults and children, respectively. In line with this proposal, Azevedo et al. (2013) found racial in-group bias in pupillary changes when viewing one's hands being penetrated by a needle or touched by a Q-tip in adults. Given that both observing body injuries and painful faces could activate empathy-related neural circuits (Lamm, Decety, & Singer, 2011), we aimed to extend previous findings by assessing pupillary responses when perceiving others' painful facial expressions, and further exploring potential racial bias in such dilation effects and their association with autistic traits in both adults and children.

2. Method

2.1. Participants

A total of 72 Chinese participants were recruited from local universities and primary schools for the current study, with 24 subjects in each experiment (see Table 1 for participants' demographic characteristics). The sample size was determined based on the prior power analysis conducted by G*Power 3.1.9.7 (Faul, Erdfelder, Lang, & Buchner, 2007). It indicated that a sample size of 24 participants would afford 80 % power with alpha at 0.05 to detect a medium effect ($f = 0.25$) of three-way interaction (i.e., facial expression × racial group × AQ group) on pupillary responses. All participants had normal or corrected-to-normal vision and reported no abnormal neurological history. All participants provided written informed consent after the experimental procedure had been fully explained. They were informed of their right to withdraw at any time during the study and received monetary compensation after completing the study. The protocols of the research were approved by the institutional review board of the Anonymous Institution.

2.2. Apparatus and materials

The experiments were conducted in a dimly lit room. Participants were required to sit at a viewing distance of about 60 cm from a 23-in. Alienware LCD screen (refresh rate: 60 Hz, resolution: 1920 × 1080). A chin rest was used to stabilize their head position. The stimuli were displayed against a gray background (12.6 cd/m^2) and presented using MATLAB (The MathWorks Inc) together with Psychtoolbox (Brainard, 1997; Pelli, 1997). Participants' pupil sizes were recorded by an infrared Eyelink Portable Duo (SR Research Ltd) eye tracker placed under the screen. The sampling rate of the eye tracker was 1000 Hz.

Stimuli were adopted from a previous study (Sheng & Han, 2012) and consisted of digital photographs of adult faces with neutral or painful expressions that were taken from 16 Asian models (8 females) and 16 Caucasian models (8 females). Based on Prkachin's (1992) criteria for painful expressions (i.e., brow lowering, orbit tightening, nose wrinkling, and upper lip raising), one photograph of a pain expression and one of a neutral expression were selected for each model, yielding a total of 64 images (illustrated in Fig. 1). Luminance level, emotional intensity, and facial attractiveness were matched between Asian and Caucasian faces (see Sheng & Han, 2012 for details of the norming results based on measures of rating scores of two independent samples).

We adopted the Chinese version of the Autism Spectrum Quotient (AQ) which contains 50 items (e.g., "I prefer to do things with others rather than on my own"; "I find social situations easy") to measure the autistic traits of all participants. Individuals with higher AQ scores generally possess more autistic traits, which has been demonstrated to be reliable and consistent among Chinese samples at different ages (Lau et al., 2013; Zhang et al., 2016). In Experiment 1a and 1b, adults' responses were scored binarily, yielding a maximum score of 50. In

Table 1
Demographic characteristics of participants and AQ scores for each group in each experiment (Mean ± SD).

	Sample		Age (years)		AQ score	
	Female	Male	Female	Male	Low	High
Experiment 1a	14	10	Range 19–29 23.5 ± 2.5	Range 19–28 23.6 ± 2.9	Range 10–20 15.3 ± 3.1	Range 21–29 24.7 ± 3.2
Experiment 1b	16	8	Range 19–29 24.4 ± 3.1	Range 20–30 23.1 ± 3.2	Range 9–17 12.4 ± 2.4	Range 20–32 24.6 ± 3.8
Experiment 2	12	12	Range 6–11 8.7 ± 1.5	Range 6–12 9.2 ± 2.4	Range 37–60 52.6 ± 7.1	Range 62–77 69.5 ± 5.3

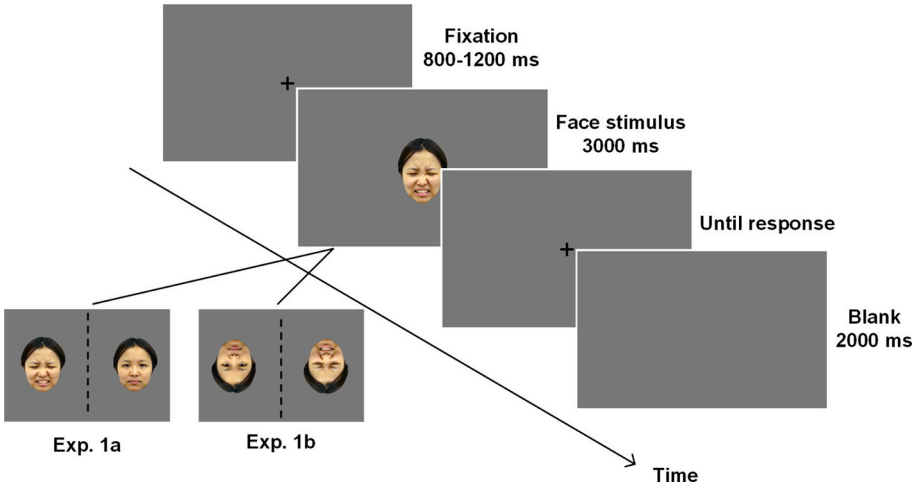

Fig. 1. The illustration of sample stimuli and example trial of the experiments.

Experiment 2, the items of the Autism Spectrum Quotient - Children's Version (AQ-Child) were kept as close to the adult version as possible but adopted a four-point Likert scale (0 = "definitely disagree" to 3 = "definitely agree"), resulting in a total score range of 0–150 (Auyeung, Baron-Cohen, Wheelwright, & Allison, 2008).

2.3. Procedure

In Experiment 1a, standard 9-point eye-tracker calibration and validation were routinely conducted at the beginning of each block. Each trial began with a central fixation with a varied duration (800–1200 ms), followed by a face displayed for 3000 ms at the center of the screen (approximately subtended 3.8° × 4.7°). Participants were instructed to respond as quickly as possible without time constraints by pressing one of two buttons to perform an expression judgment task (painful vs. neutral) after each face disappeared (Fig. 1). The relationship between response buttons and facial expressions was counterbalanced across blocks. Participants were also required to minimize blinking and maintain their gaze on the central fixation or stimuli at all times except during the inter-trial interval (2000 ms). Participant completed 2 blocks of 32 trials (64 trials in total, including 16 trials for each expression and racial group). Experiment 1b was identical in procedure to Experiment 1a, except that facial stimuli were presented inverted. Experiment 2 was similar to Experiment 1a in procedure, except that children completed 4 blocks of 16 trials to prevent fatigue. After the eye-tracking experiment, adult participants and the parents of child participants completed the AQ or AQ-Child.

2.4. Data analysis

Continuous pupil data were first segmented into epochs from −200 to 3000 ms, locked to the time when the stimuli were displayed (i.e., stimulus onset). The pupil size data in each trial were then visually inspected and preprocessed to remove eye-blinks (either replaced by linear interpolation or with this trial discarded) or other obvious artifacts. Trials with the pupil size out of ±3 SDs were also excluded, which resulted in rejection of 4.2 %, 3.4 % and 7.9 % of the trials on average in each experiment. The remaining artifact-free data were baseline-corrected for each trial by subtracting the mean pupil size of the 200 ms pre-stimulus period for further analyses.

To conduct time-series comparisons of pupil responses to faces of different expressions and racial groups, the pupil data were down-sampled to 20 Hz. Consecutive paired sample *t*-tests were conducted at each time point after the stimulus onset (i.e., 0–3000 ms) to examine whether the painful expressions evoked larger pupil sizes than the neutral expressions. The inflation of false positives after multiple comparisons was controlled using the false discovery rate (FDR) correction ($p < 0.05$). Furthermore, the mean pupil size across all time-points and all trials for each condition and each participant was calculated as a simpler index. The Kolmogorov-Smirnov test and Levene's tests confirmed that the data met the assumptions of normality and homogeneity of variances ($ps > 0.05$), and visual inspection of histogram and P—P plot supported the normal distribution of residuals. We conducted repeated-measures analysis of variance (ANOVA), with racial group (Caucasian, Asian) and facial expression (painful, neutral) as the within-subject variables. In addition, to statistically compare the pupillary responses to different expressions of Asian and Caucasian faces presented upright (Experiment 1a) and inverted (Experiment 1b), we conducted a repeated-measures ANOVA with racial group and facial expression as within-subject variables, and facial orientation (upright vs. inverted) as a between-subject variable. Note that all pupil data were analyzed and reported in arbitrary units (a.u.).

3. Results

3.1. Experiment 1

3.1.1. Behavioral results

All participants performed well in the facial expression discrimination task in both Experiments 1a and 1b, with mean accuracies of 99.3 % and 98.6 %, respectively. ANOVAs of their response accuracies and reaction times (RTs) did not show any significant differences between different facial expressions across racial groups ($ps > 0.07$), nor between experiments where faces were presented upright (Exp 1a) or inverted (Exp 1b) ($ps > 0.1$), indicating comparable task difficulty and attentional demand across conditions and experiments, thereby ruling out potential modulations of pupil responses by cognitive load (Alnaes et al., 2014; van der Wel & van Steenbergen, 2018).

3.1.2. Pupil size results

Pupillary responses to the stimuli in the Experiment 1a are shown in Fig. 2. The results of the consecutive paired-sample *t*-tests revealed that pupil size was significantly dilated in response to painful faces compared to neutral faces between 650 and 2150 ms ($ps < 0.05$, FDR-corrected; Fig. 2A). Separate paired-sample t-tests further showed significant pupil dilation between 600 and 3000 ms for Asian faces ($ps < 0.05$, FDR-corrected), but no such effect for Caucasian faces in any time window. Meanwhile, ANOVA of the mean pupil size across all time points showed a significant main effect of facial expression ($F(1,23) = 21.68$, $p < 0.001$, $\eta_p^2 = 0.485$), suggesting larger pupil size when viewing painful compared

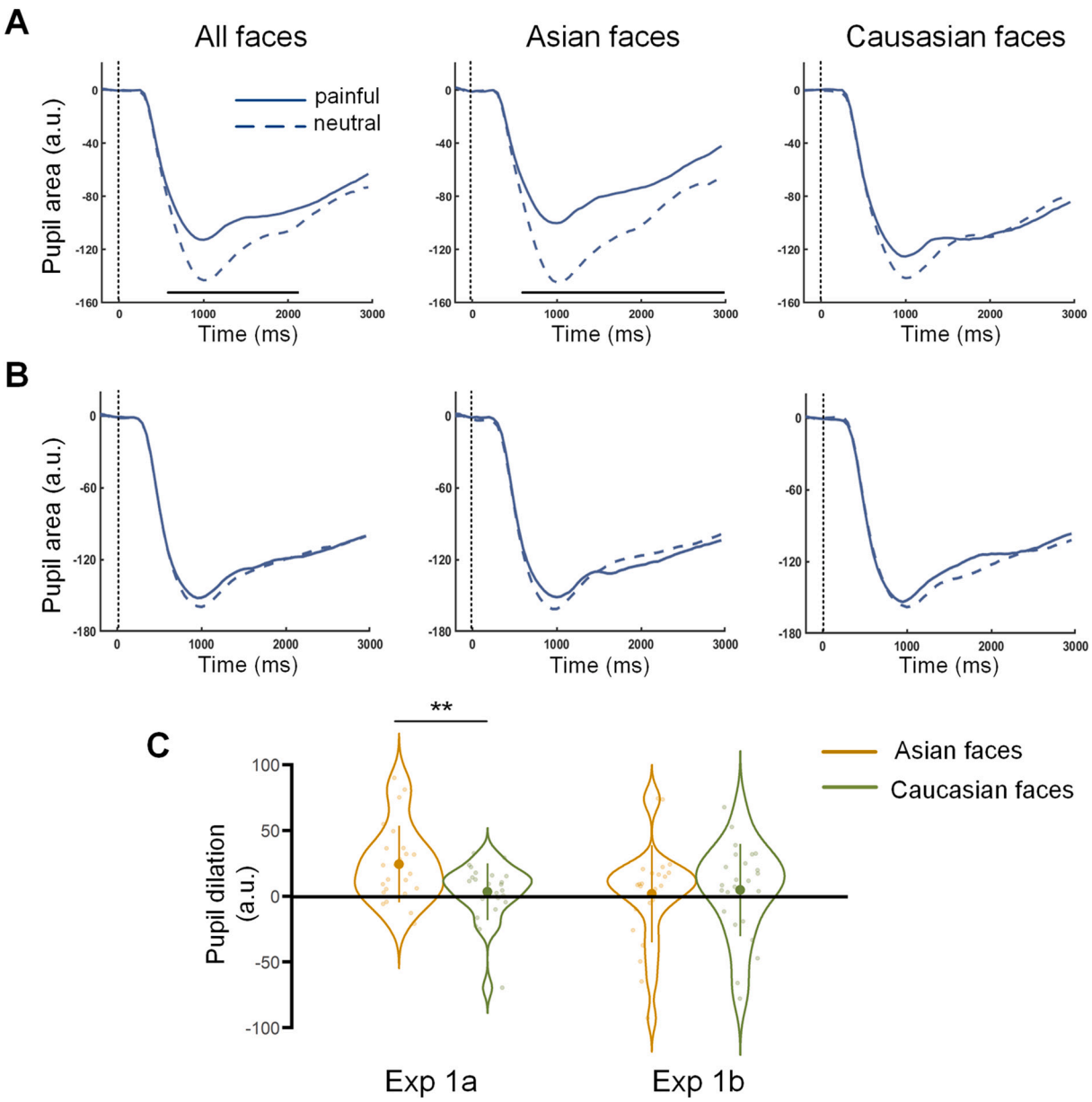

Fig. 2. Results of Experiment 1a and 1b. (A, B) The pupil time series induced by painful (solid line) and neutral expressions (dot line) of all models (left panel), Asian models (middle panel), and Caucasian models (right panel) in Experiment 1a (upright faces) and 1b (inverted faces), respectively. The horizontal black lines indicate significant differences after FDR-correction ($p < 0.05$). (C) Illustration of the group means (big dots), standard deviations (bars), measures of each subject (small dots), and distribution (violin shape) of the pupil dilation effect (pain > neutral). $^{**}p < 0.01$.

to neutral faces. Moreover, there was a significant interaction between facial expression and racial group ($F(1, 23) = 5.99$, $p = 0.022$, $\eta_p^2 = 0.207$). Simple effect analyses further confirmed significant pupil dilation for painful faces of Asian individuals ($F(1, 23) = 16.75$, $p < 0.001$, $\eta_p^2 = 0.421$), but not for Caucasian models ($F(1, 23) = 0.53$, $p = 0.474$, $\eta_p^2 = 0.023$), providing evidence for racial bias in pupillary responses to others' pain.

In Experiment 1b, consecutive paired-sample t-tests on the pupil time series did not show any significant difference between inverted painful and neutral faces (Fig. 2B). Specifically, neither the inverted painful faces of Asian nor Caucasian individuals induced significant pupil dilation. Similarly, ANOVA of the mean pupil size revealed no significant effect ($ps > 0.5$), providing no evidence for pupil dilation in response to inverted facial expressions.

Additionally, to further compare the pupillary responses to different expressions of Asian and Caucasian faces in upright and inverted orientations (Experiments 1a and 1b), we conducted a repeated-measures ANOVA with racial group and facial expression as within-subject variables, and facial orientation (upright vs. inverted) as a between-subject variable. As expected, the results showed a significant main effect of facial expression ($F(1, 46) = 5.78$, $p = 0.024$, $\eta_p^2 = 0.106$) and a significant three-way interaction of facial expression × racial group × facial orientation ($F(1, 46) = 5.15$, $p = 0.028$, $\eta_p^2 = 0.101$), indicating a racial in-group bias specific to upright painful faces (see Fig. 2C, for Asian: $F(1, 46) = 12.88$, $p = 0.001$, $\eta_p^2 = 0.219$; for Caucasian: $F(1, 46) = 0.38$, $p = 0.575$, $\eta_p^2 = 0.007$). These results suggest that pupil dilation in response to painful faces cannot be merely attributed to the differences in processing low-level features (e.g., furrowed brows, raised upper lip) between painful and neutral expressions.

3.1.3. Association between pupillary responses and AQ

A higher AQ score indicates a greater prevalence of autistic-like

traits, which have been suggested to be associated with reduced social-cognitive abilities and atypical neural responses to social stimuli (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001; Nummenmaa et al., 2012). To examine whether the individual differences in pupil dilation effect reflecting automatic physiological responses to others' pain were associated with autistic-like tendency, we conducted correlation analyses between the pupil dilation effects and participants' AQ scores. In Experiment 1a, there was a significant negative correlation between AQ scores and the pupil dilation effects (**Fig. 3A**, $r = -0.433$, $p = 0.034$). Particularly, separate correlation analyses revealed that individuals' AQ scores were significantly associated with the pupil dilation effects to painful expressions of Asian faces ($r = -0.575$, $p = 0.003$) but not to Caucasian faces ($r = 0.180$, $p = 0.399$). However, the results of correlation analyses in Experiment 1b revealed neither a significant correlation between the pupil dilation effect and autistic traits for inverted faces, nor significant correlations for Asian or Caucasian faces ($ps > 0.08$).

Moreover, to further explore potential differences in pupil dilation between individuals with low- and high-autistic traits, we split the participants into the low- ($N = 12$) and high-AQ group ($N = 12$) based on the median AQ score (20.5 and 18.5 in Experiment 1a and 1b, respectively; see Table 1), and conducted a 2 (facial expression) × 2 (racial group) × 2 (AQ group) ANOVA of the mean pupil size. Note that while AQ scores were significantly different between groups in both experiments ($ps < 0.001$), no significant difference found between participants in Experiment 1a and those in 1b ($ps > 0.1$), suggesting comparable degree of autistic traits of individuals across experiments. As expected, the ANOVA of Experiment 1a showed a significant interaction of facial expression × AQ group ($F(1,22) = 5.02$, $p = 0.036$, $\eta_p^2 = 0.186$), which further qualified by a significant three-way interaction ($F(1, 22) = 8.93$, $p = 0.011$, $\eta_p^2 = 0.289$). Interestingly, there was a significant interaction of facial expression and racial group only in the low-AQ group ($F(1,11) = 19.13$, $p = 0.001$, $\eta_p^2 = 0.635$) but not in the high-AQ group ($F(1, 11) = 0.02$, $p = 0.905$, $\eta_p^2 = 0.001$), demonstrating a significant racial ingroup bias in pupil dilation effect to painful faces specific for low-AQ individuals (Fig. 3B). In Experiment 1b, the ANOVA did not show any significant main effect or interaction ($ps > 0.08$), suggesting no evidence for differences in the absence of pupil dilation in response to inverted painful faces between the low- and high-AQ groups.

3.2. Experiment 2

3.2.1. Behavioral results

Child participants performed well in the facial expression judgment task with high response accuracy (mean accuracy = 98.2 %). Consistent with Experiment 1, ANOVAs of the response accuracies and RTs revealed no significant effect ($ps > 0.08$), indicating comparable task difficulty and attentional demand across conditions.

3.2.2. Pupil size results

Similar to Experiment 1a, the consecutive paired-sample *t*-tests of the pupil time series revealed that pupil size significantly dilated in response to painful faces compared to neutral faces between 300 and 2250 ms ($ps < 0.05$, FDR-corrected; Fig. 4A). Specifically, a significant pupil dilation effect was observed between 300 and 3000 ms for Asian faces ($ps < 0.05$, FDR-corrected), whereas no such effect was detected for Caucasian

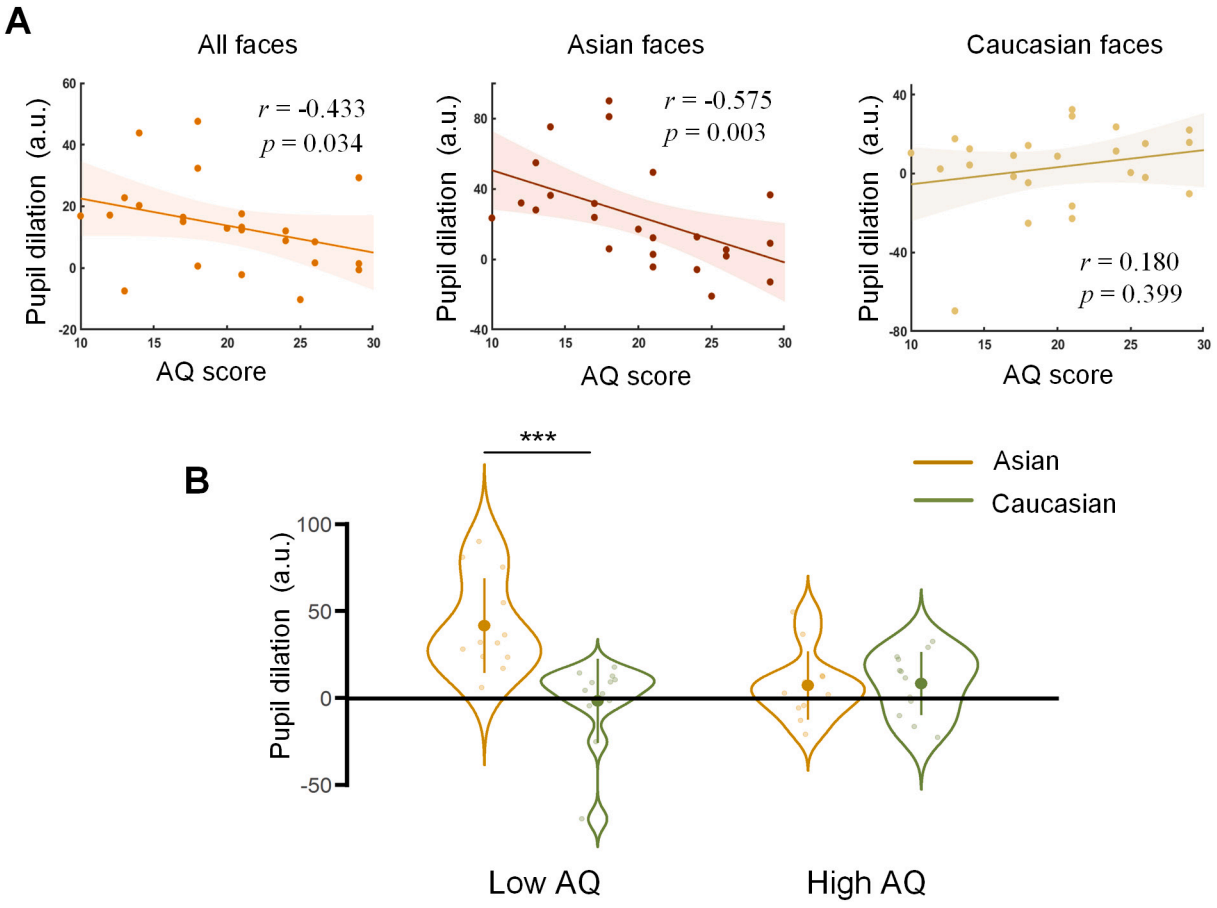

Fig. 3. Pupil dilation effect (pain > neutral) and its relationship with individual autistic trait (AQ score) in Experiment 1a. (A) The correlation of AQ and the pupil dilation effects for all models (left panel), Asian models (middle panel), and Caucasian models (right panel). (B) Illustration of the group means (big dots), standard deviations (bars), measures of each subject (small dots), and distribution (violin shape) of the pupil dilation effects to Asian and Caucasian faces in the low- and high-AQ groups. ***$p < 0.001$.

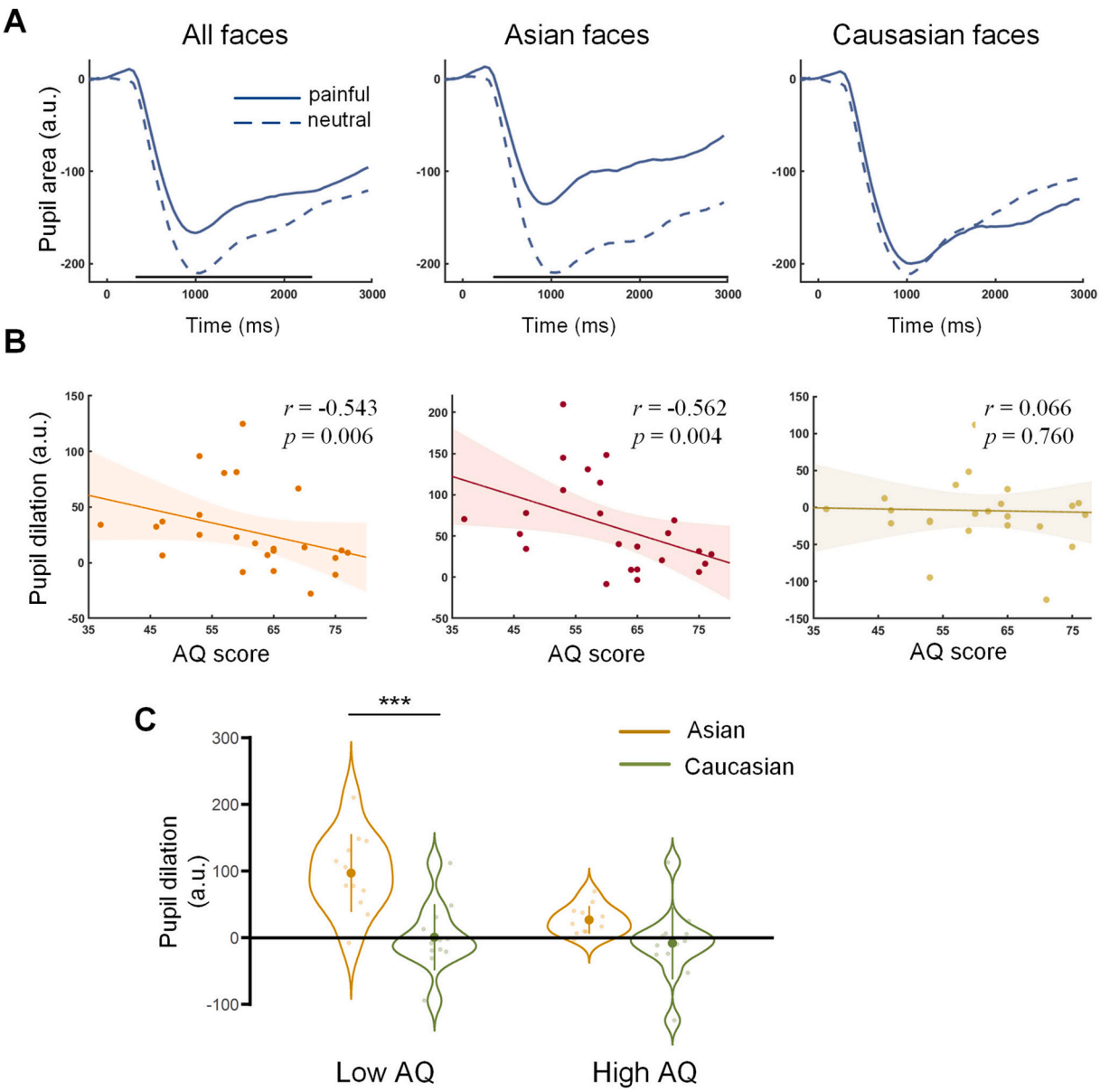

Fig. 4. Results of Experiment 2. (A) The pupil time series induced by painful (solid line) and neutral expressions (dot line) of all models (left panel), Asian models (middle panel), and Caucasian models (right panel). The horizontal black lines indicate significant differences after FDR-correction ($p < 0.05$). (B) The correlation between with individual autistic trait (AQ score) and the pupil dilation effects (pain > neutral) for all models (left panel), Asian models (middle panel), and Caucasian models (right panels). (C) Illustration of the group means (big dots), standard deviations (bars), measures of each subject (small dots), and distribution (violin shape) of the pupil dilation effects to Asian and Caucasian faces in the low- and high-AQ groups. ***$p < 0.001$.

faces. In addition, ANOVA of the mean pupil size showed a significant main effect of facial expression ($F(1, 23) = 14.08$, $p = 0.001$, $\eta_p^2 = 0.380$), which was further qualified by a significant interaction of facial expression and racial group ($F(1, 23) = 18.16$, $p < 0.001$, $\eta_p^2 = 0.441$). Simple effect analyses further confirmed a significant pupil dilation effect in response to painful expressions of Asian faces ($F(1, 23) = 28.95$, $p < 0.001$, $\eta_p^2 = 0.557$), but not to Caucasian faces ($F(1, 23) = 0.20$, $p = 0.657$, $\eta_p^2 = 0.009$), replicating the findings of Experiment 1a.

3.2.3. *Association between pupillary responses and AQ*

Likewise, we also examined whether pupil dilation to painful faces was associated with the degree of autism-like tendency in children. Results revealed a significantly negative correlation between AQ scores and the pupil dilation effects (Fig. 4**B**, $r = -0.543$, $p = 0.006$). Separate correlation analyses further showed that the association between AQ scores and the pupil dilation effects was significant for Asian faces ($r = -0.562$, $p = 0.004$) but not for Caucasian faces ($r = 0.066$, $p = 0.760$). Additionally, ANOVA with AQ group (defined by a median split at 61) as between-subject variable showed a significant three-way interaction of facial expression × racial group × AQ group ($F(1, 18) = 4.63$, $p = 0.043$, $\eta_p^2 = 0.174$). Specifically, separate analyses for each AQ group revealed a significant interaction between facial expression and racial group in the low-AQ group (Fig. 4**C**, $F(1, 11) = 21.81$, $p = 0.001$, $\eta_p^2 = 0.665$) but not in the high-AQ group ($F(1, 11) = 3.09$, $p = 0.107$, $\eta_p^2 = 0.219$). Simple effect analyses further confirm a significant pupil dilation to painful expressions specific to same-race faces ($F(1, 11) = 32.66$, $p < 0.001$, $\eta_p^2 = 0.748$), providing compelling evidence for a racial in-group bias in pupil dilation in response to others' pain only in low-AQ individuals.

4. Discussion

Pain perception is of great importance as it fundamentally supports

both survival and social functioning. In the current study, we investigated automatic pupillary responses evoked by others' painful facial expressions in both adult and child observers. We found that pupil size dilated more in response to painful faces than to neutral faces, particularly for same-racial group members compared to other-race individuals. Moreover, we provided evidence that attenuated pupil dilation in response to others' pain was associated with higher levels of autistic traits.

Previous studies have revealed that exposure to bio-social cues with high-salience induces pupillary changes, reflecting arousal states mainly modulated by the locus coeruleus norepinephrine (LC-NE) system (Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014). Specifically relevant to the current work, previous research has shown pupil dilation during observation noxious stimuli applied to body parts (Azevedo et al., 2013). In the present study, we extended these findings by demonstrating that painful expressions of faces elicited larger pupil sizes than neutral faces. Through a control experiment using inverted faces to rule out potential confounding factors, we further confirmed that such pupil dilation could not be merely attributed to the differences in perceptual features between painful and neutral expressions. Crucially, our results also indicated the pupil dilation effect to others' pain occurred specifically for same-race rather than other-race individuals in both adults and children, suggesting that painful faces of ingroup members may evoke stronger physiological arousal possibly due to their greater evolutionary and social relevance (Cosmides, Tooby, & Kurzban, 2003; Han, 2018; Hornsey, 2008; Tajfel, 1982; Xu, Zuo, Wang, & Han, 2009). As participants exhibited comparable performance in the explicit judgment task, the racial in-group bias in pupillary responses likely reflects the pupil-linked arousal mechanism (Joshi & Gold, 2020) rather than potential differences in expression identification between same- and other-race faces. Additionally, our findings of pupil dilation in response to painful expressions may reflect the automatic affective component of empathy – defined as the capability to understand and share others' emotional states – given that the perception of others' suffering inherently involves empathic responses (Decety & Jackson, 2004; Jackson et al., 2005; Singer & Lamm, 2009). And the observed pupil dilation effect specific for same-race painful faces aligns with previous findings on racial in-group bias in empathy for pain and its early emergence with psychophysiological evidence, providing more insights into the automatic aspects of empathic responses particularly in children (Avenanti, Sirigu, & Aglioti, 2010; Dore et al., 2014; Han, 2018).

Moreover, our findings demonstrated a significant negative correlation between pupillary responses to observed pain and autistic traits, which carry important implications for understanding individual differences in social-affective processing. It has been suggested that autistic individuals exhibit atypical empathic responses and altered social-emotional processing patterns, which represent core features among this population (Fatima & Babu, 2023; Frith & Happé, 2005; Minio-Paluello, Baron-Cohen, Avenanti, Walsh, & Aglioti, 2009; Rieffe et al., 2021). In our study involving neurotypical adults and children, pupillary responses to others' pain varied with AQ scores, providing supportive evidence for this notion. Contrary to our findings, some studies reported comparable or even overarousal in automatic responses and neural processing during the perception of others' pain in autistic relative to neurotypical individuals (Gu et al., 2015; Krach et al., 2015). We speculated that the discrepancy might be due to methodological variations in stimulus selection. In the aforementioned studies, participants viewed somatic pain stimuli depicting first-person perspective scenes that explicitly indicates specific types of noxious stimuli (e.g., scissors or knives) and painful events (e.g., injection or stabbing). It is possible that the perception of others' physical pain in the limbs may evoke embodied empathy of one's affective states in both neurotypical and autistic individuals. Meanwhile, the lower pain threshold reported in autistic individuals suggested that such hypersensitivity to first-hand pain may account for their vulnerability to empathic over-arousal for others' physical pain (Chen et al., 2017; Fan et al., 2014). In contrast, the static facial expressions of pain used in our study merely depicted others' subjective reactions in ambiguous painful situations, which may elicit empathic responses through distinct processes. Given that autistic individuals tend to rely on inflexible or stereotyped manners to learn social rules and conventions to compensate for differences in social intuition, it seems plausible that painful facial expressions may just serve as a particular signal within the social environment, resulting in attenuated automatic empathic arousal or emotional contagion (Baron-Cohen, Richler, Bisarya, Gurunathan, & Wheelwright, 2003; Klin, Jones, Schultz, & Volkmar, 2003). Therefore, future research should explore how pupillary changes in response to different types of painful stimuli (e.g., dynamic vs. static, somatic vs. facial) manifest in individuals with ASD or high autistic traits.

Notably, our results also revealed robust pupil dilation specific to same-race but not to other-race painful faces only in low-AQ individuals. This finding aligns with previous evidence of attenuated and even absent intergroup bias in both autistic individuals and non-autistic adults with high autistic traits (Qian et al., 2022; Vaucheret Paz et al., 2020). It is possible that individuals with high autistic traits may exhibit blurred intergroup boundaries in processing same-race and other-race members, and thus produce less racial in-group bias in response to others' pain. For example, research has shown lower sensitivity in discriminating same-race faces in a perceptually based task in autistic individuals, resulting in less advantage in processing same-race over other-race faces (Hadad, Schwartz, & Binur, 2019). In addition, previous literature has suggested that atypical social processing in autism may also be associated with the dysfunction in self-categorization — the process of classifying oneself as a member of a social category (Skorich et al., 2016; Turner, Hogg, Oakes, Reicher, & Wetherell, 1987). Behavioral evidence indicates that individuals with higher autistic traits show less in-group identification, suggesting social identification underlies the relationship between their autistic traits and in-group favoritism (Bertschy, Skorich, & Haslam, 2020). Therefore, our results extend previous findings by providing physiological evidence that individuals with more pronounced autistic traits exhibit attenuated intergroup bias in automatic empathic response for others' pain. Future research may benefit from exploring the underlying mechanism of the reduced in-group favoritism in autistic individuals.

Despite the strengths of our study, several limitations warrant consideration. First, the painful facial expressions represent both high evolutionary significance and social salience, raising the possibility that the observed pupillary dilation reflect general arousal rather than empathy-specific processes. Future studies should consider adopting salience-matched controls to disentangle empathy-related responses from nonspecific arousal effects, which could also clarify whether the observed effects are specific to pain expressions or generalizable to other negative expressions, such as sad or angry. Second, all participants viewed adults' facial expressions in the present study, leaving open the question of age-related differences in pupillary responses to painful expressions (Hauschild, Felsman, Keifer, & Lerner, 2020; Riddell, Nikolic, Dusseldorp, & Kret, 2024). Future studies could address this issue by comparing pupil dilation toward standardized emotional faces of both adults and children. Additionally, our findings on autistic traits were based on AQ scores within a neurotypical sample. Although it has been suggested that the degree of autistic traits in both autistic and neurotypical populations is associated with variations in behavioral performance and neural responses during social attention tasks (Bayliss & Tipper, 2005; Nummenmaa et al., 2012), our findings may have limited generalizability to individuals with clinically diagnosed ASD populations. Investigating such pupillary patterns in autistic individuals may offer valuable insights for clinical assessment and intervention (Aguillon-Hernandez et al., 2020; Nuske, Vivanti, & Dissanayake, 2016).

In summary, the present study demonstrates that pupil dilation reflects automatic physiological responses to others' pain and provides compelling evidence of racial in-group bias in both adults and children.

Intriguingly, we found that these effects were modulated by individual differences in autistic traits. These findings suggest that pupillometry may serve as a promising biomarker for automatic empathic responses in neurotypical individuals and offer an applicable approach for investigating socio-affective processing across developmental and neurodiverse populations.

CRediT authorship contribution statement

Ting Zhang: Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Writing – original draft. **Shujia Zhang:** Investigation, Writing – review & editing. **Yi Jiang:** Supervision, Software, Resources, Methodology, Funding acquisition, Conceptualization, Writing – review & editing.

Declaration of competing interest

All authors declare no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2025.106384.

Data availability

All organized data and analysis scripts of the current manuscript are accessible (https://doi.org/10.57760/sciencedb.psych.00351).

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