Journal of Anxiety Disorders 104 (2024) 102871

Contents lists available at ScienceDirect

Journal of Anxiety Disorders

journal homepage: www.elsevier.com/locate/janxdis

Distinct patterns of monocular advantage for facial emotions in social anxiety

Mengyuan Gong [a], Chaoya Pan [a], Ruibo Pan [b], Xiaohua Wang [b], Jiafeng Wang [b], Han Xu [c], Yuzheng Hu [a], Jun Wang [c], Ke Jia [d,e,f,*], Qiaozhen Chen [b,g,**]

[a] *Department of Psychology and Behavioral Sciences, Zhejiang University, Hangzhou, China*
[b] *Department of Psychiatry, The Second Affiliated Hospital, Zhejiang University School of Medicine, Hangzhou, China*
[c] *Department of Neurobiology and Department of Psychiatry of the Second Affiliated Hospital, Zhejiang University School of Medicine, Hangzhou, China*
[d] *Department of Neurobiology, Affiliated Mental Health Center & Hangzhou Seventh People's Hospital, Zhejiang University, School of Medicine, Hangzhou, China*
[e] *Liangzhu Laboratory, MOE Frontier Science Center for Brain Science and Brain-Machine Integration, State Key Laboratory of Brain-Machine Intelligence, Zhejiang University, Hangzhou, China*
[f] *NHC and CAMS Key Laboratory of Medical Neurobiology, Zhejiang University, Hangzhou, China*
[g] *Key Laboratory of Medical Molecular Imaging of Zhejiang Province, Hangzhou, China*

ARTICLE INFO

Keywords:
Social anxiety
Monocular advantage
Facial emotions
Subcortical structures

ABSTRACT

Individuals with social anxiety often exhibit atypical processing of facial expressions. Previous research in social anxiety has primarily emphasized cognitive bias associated with face processing and the corresponding abnormalities in cortico-limbic circuitry, yet whether social anxiety influences early perceptual processing of emotional faces remains largely unknown. We used a psychophysical method to investigate the monocular advantage for face perception (i.e., face stimuli are better recognized when presented to the same eye compared to different eyes), an effect that is indicative of early, subcortical processing of face stimuli. We compared the monocular advantage for different emotional expressions (neutral, angry and sad) in three groups ($N = 24$ per group): individuals clinically diagnosed with social anxiety disorder (SAD), individuals with high social anxiety in subclinical populations (SSA), and a healthy control (HC) group of individuals matched for age and gender. Compared to SSA and HC groups, we found that individuals with SAD exhibited a greater monocular advantage when processing neutral and sad faces. While the magnitudes of monocular advantages were similar across three groups when processing angry faces, individuals with SAD performed better in this condition when the faces were presented to different eye. The former findings suggest that social anxiety leads to an enhanced role of subcortical structures in processing nonthreatening expressions. The latter findings, on the other hand, likely reflect an enhanced cortical processing of threatening expressions in SAD group. These distinct patterns of monocular advantage indicate that social anxiety altered representation of emotional faces at various stages of information processing, starting at an early stage of the visual system.

1. Introduction

Social anxiety disorder (SAD) is a common class of anxiety disorder characterized by fear and avoidance of the scrutiny of others (American Psychiatric Association, 2013; Stein & Stein, 2008). According to a cross-national epidemiological study (Stein et al., 2017), the lifetime prevalence of SAD is approximately 5%, along with an increasing trend of individuals reporting social anxiety symptoms in general populations (Xiong et al., 2022). Cognitive theories suggest that information processing biases play a pivotal role in the development of social anxiety (Heinrichs & Hofmann, 2001; Hirsch & Clark, 2004), particularly during face perception (Gentili et al., 2016; Pei et al., 2023). For instance, socially anxious individuals consistently exhibited attentional bias toward emotional faces, particularly those conveying threat-related information (Mogg et al., 2004; Staugaard, 2010; Günther et al., 2021; Rozen & Aderka, 2023). They tend to interpret neutral faces in a negative manner

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* Corresponding author at: Department of Neurobiology, Affiliated Mental Health Center & Hangzhou Seventh People's Hospital, Zhejiang University, School of Medicine, Hangzhou, China.

** Corresponding author at: Department of Psychiatry, The Second Affiliated Hospital, Zhejiang University School of Medicine, Hangzhou, China.

E-mail addresses: kjia@zju.edu.cn (K. Jia), crazil@zju.edu.cn (Q. Chen).

https://doi.org/10.1016/j.janxdis.2024.102871
Received 18 October 2023; Received in revised form 11 April 2024; Accepted 29 April 2024

(Yoon & Zinbarg, 2008) and exhibit a stronger memory for negative expressions compared to neutral faces (Foa et al., 2000), although some studies reported mixed findings regarding the memory bias (Pérez-López & Woody, 2001). While previous studies have predominantly focused on cognitive bias during emotional face processing, whether social anxiety influences early, perceptual processing of emotional faces remains largely unknown.

A protocol based on the monocular segregation provides a useful tool to investigate this possibility (Gabay et al., 2014a, 2014b). Because visual information is propagated in an eye-specific manner during early visual processing, this monocular segregation persists up to layer IV of primary visual cortex (Baker et al., 1974; Menon et al., 1997). Previous studies manipulated the eye-of-origin to isolate monocular versus binocular processing of face perception in healthy adults, by sequentially presenting two face stimuli to the same eye (monocularly) or to different eyes (interocularly). The recognition of face stimuli was better when presented to the same eye than to different eyes. This monocular advantage suggests the involvement of early, monocular portion of the visual pathway in face perception, likely depending on subcortical structures (e.g., superior colliculus, pulvinar, lateral geniculate nucleus) (Gabay et al., 2014a, 2014b; Almasi & Behrmann, 2021). Given the role of subcortical pathways in face perception, it is reasonable to examine if atypical face processing in socially anxious individuals occurs at an early stage of information processing.

To test this hypothesis, we adopted a similar psychophysical method, as established in previous studies (Gabay et al., 2014a, 2014b). In a face identity discrimination task, we sequentially presented two face stimuli either to the same eye or to different eyes via a stereoscope. Each pair of face stimuli had one of the expressions (neutral, angry, or sad face). Angry expression was used because it is thought to be a prominent example of threatening expressions (Stauggard, 2010), sad expression was included to disentangle the possible differences between threat-relatedness and negativity of the displayed emotion. To examine the potential continuum between healthy and social anxiety levels, we compared individuals with subclinical social anxiety (SSA), clinically diagnosed social anxiety disorder (SAD), and matched healthy controls (HC). As individuals with SSA and those diagnosed with SAD may exhibit similar symptoms, incorporating both populations may provide early diagnostic indicators beyond the scale-based questionnaires. The study aimed to investigate whether and how social anxiety affects the monocular advantage for different facial emotions. Specifically, we hypothesized that socially anxious individuals would show larger monocular advantages compared to HC group. Furthermore, we hypothesized socially anxious individuals to demonstrate differences in processing threatening versus non-threatening facial emotions. While the specific patterns across experimental conditions require further exploration, we expected to observe a gradual shift in monocular advantage patterns from HC to SSA to SAD. Our findings revealed distinct patterns of monocular advantage in the processing of facial emotions among individuals with social anxiety.

2. Method

2.1. Participants

We recruited seventy-two participants in this study. We used a sample size that is comparable to studies using the stereoscopic presentation to examine the monocular processing of information in healthy participants (Gabay et al., 2014a, 15 participants; Gabay et al., 2014b, 19–22 participants) and in special populations (Peskin et al., 2020, 13 patients; Peskin et al., 2024, 20 patients). Furthermore, a power analysis using MorePower 6.04 (Campbell and Thompson, 2012) indicated that a total sample size of 72 (24 per group) is sufficient to detect a medium-sized effect ($\eta_p^2 = 0.08$) with a power of 0.8 and an alpha level of 0.05 for our primary effect of interest: a four-way interaction in a 2 (stimulus presentation) × 2 (image match) × 3 (facial expression) × 3 (group) mixed analysis of variance (ANOVA).

Specifically, twenty-four treatment-seeking participants (16 females and 8 males; age: M = 28.46 years, SD = 8.59) were diagnosed by clinical psychiatrists using the Structured Clinical Interview for Diagnostic and Statistical Manual of Mental Disorders (DSM-5; American Psychiatric Association, 2015). They also met the criteria based on Liebowitz Social Anxiety Scale (LSAS) cutoff-value ($\geq$30; Liebowitz, 1987) and Beck Depression Inventory (BDI-II) cutoff-value ($<$16; Beck et al., 1996). The majority of clinical patients (N = 15, 62.5%) received pharmacological treatment for varying durations before participating the study (ranging from 2 weeks to 15 months), four were prescribed serotonin–norepinephrine reuptake inhibitors (SNRIs), eleven were prescribed selective serotonin-reuptake inhibitors (SSRIs). The remaining patients (N = 9, 37.5%) did not use medications. None of these patients underwent psychological interventions. Based on the cut-off values of LSAS and BDI-II scales, we classified twenty-four participants (11 females and 13 males; age: M = 26.25, SD = 8.54) into the SSA group (LSAS score$\geq$ 30 and BDI-II score $<$ 16). The HC group consisted of twenty-four participants (16 females and 8 males; age: M = 26.25, SD = 7.83; LSAS score $<$ 30; BDI-II score $<$ 16). Note that none of the participants in SSA or HC group reported a history of psychological or psychiatric treatment.

Detailed demographic and diagnostic information for each group of participants is shown in Table 1. No differences across groups were found for age, gender and education level (*ps* $>$ 0.161). Participants' social anxiety scores were significantly different between each pair of groups (*ps* $<$ 0.045). The reduction in social anxiety ratings in SAD group as compared to SSA group could likely be attributed to medical interventions, as indicated by a negative correlation between treatment duration and LSAS scores in SAD group ($r = -0.418$, $p = 0.042$). Despite of our prior intention to minimize the impact of depression (one-sample t-test against the BDI cutoff: *ps* $<$ 0.001 across all groups), there was a gradual increase in BDI scores from HC to SSA to SAD group (*ps* $<$ 0.005). All participants had normal or corrected-to-normal vision and were right-handed. All participants provided written informed consent approved by the Institutional Review Board at Department of Behavioral Sciences and Psychology, Zhejiang University (protocol number: 2022–06-063).

2.2. Stimuli and apparatus

30 male and 30 female face images obtained from the Chinese Facial Affective Picture System (Gong et al., 2011) were used in the experiment. All images displayed front views of faces with neutral, angry or sad expressions. The averaged recognition rate were comparable across different facial expressions (neutral: 82.4%; angry: 81.0%; sad: 84.6%; one-way repeated-measures ANOVA: $F(2,38) = 0.545$, $p = 0.584$, $\eta_p^2 = 0.028$). The face images were cropped to remove hair cues and were displayed in grayscale against a black background. Face stimuli were 8°

Table 1
Demographic information and questionnaire (Values are mean ± SD).

Measure	HC (*N* = 24)	SSA (*N* = 24)	SAD (*N* = 24)	Group Effect
Female (%)	66.7%	45.8%	66.7%	$\chi^2(2) = 2.89$, $p = 0.236$
Age (years)	26.25 (7.83)	26.25 (8.54)	28.46 (8.59)	$F(2,69) = 0.56$, $p = 0.572$
College graduate (%)	91.7%	95.8%	79.2%	$\chi^2(2) = 3.66$, $p = 0.161$
LSAS	21.88 (7.01)	62.17 (17.64)	52.88 (19.54)	$F(2,69) = 43.18$, $p < 0.001$
BDI-II	3.17 (3.14)	6.75 (4.60)	10.75 (4.23)	$F(2,69) = 21.16$, $p < 0.001$

Note. HC = Healthy Controls; SSA = Subclinical Social Anxiety; SAD = Social Anxiety Disorder; BDI-II = Beck Depression Inventory – II; LSAS = Liebowitz Social Anxiety Scale – Self Report Version.

in height and 6° in width. Two images were presented in two separate squares (10° in height and 10° in width 5° to the left and right of the center). The images were presented in the front view on a 23.8-inch LCD monitor (resolution: 1024 × 768, refresh rate: 60 Hz). Participants viewed the images at an approximate distance of 60 cm.

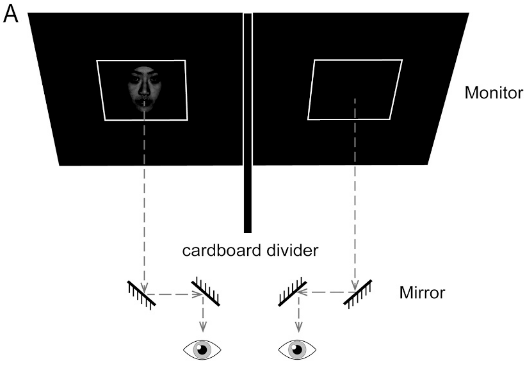
The stimuli were viewed with a mirror stereoscope placed in front of the participants. Two mirrors were positioned separately near one eye at a 45° angle to that eye's line of viewing (Fig. 1A). Another two mirrors were placed on either side of each of the first two mirrors, facing the stimuli at a 45° angle. To block the line of vision to the other eye's stimulus, a sheet of cardboard divider was placed between the participants' eyes, extending from the midline of the stereoscope toward the center of the display. This arrangement could enable eye-specific stimulus presentation. The mirrors can be rotated to enhance the adjustability to each participant's eyes, inducing a single, fused image. Participants were not aware of the eye to which the visual image was presented in either the same-eye or different-eye condition.

2.3. Procedure and tasks

At the beginning of each trial (Fig. 1B), a central fixation and two squares on the left and right side (5° from the center) were shown for 1 s. Participants were instructed to maintain fixation throughout the experiment. Two face images were then sequentially shown, each for 1 s, separated by an interstimulus interval of 1 s. Each trial consisted of two face images with one of the three expressions (neutral, angry and sad). Participants were asked to respond whether the identity of two faces were the same or different after the second image appeared, following the original studies (Gabay et al., 2014a). Half of the trials contained two identical images, whereas the remaining half containing two different images. Two face images were presented to the same eye (monocular: both left or both right) or to the different eyes (interocular: left and right). All trial types (2 stimulus presentation × 2 image match × 3 facial expression) were of equal probability and randomly interleaved across trials. Each participant completed 20 practice trials and 5 blocks of trials (72 trials per block). In this task, the facial expression was irrelevant to the discrimination of face identity. Note that we did not use a task explicitly requiring participants to focus on emotional content for three reasons. First, prior neuroimaging studies indicated elevated brain responses to threatening faces when facial expression is task-irrelevant (Straube et al., 2004). Second, discriminating between different pairs of emotion may not be equivalent, for instance, discriminating between expressions with the same negative valence (i.e., angry-sad) might be more difficult than discriminating those with different valences (e.g., neutral-angry). Third, the image bank does not have all expressions taken from the same group of models, making it difficult to precisely match of facial properties across emotions.

2.4. Statistical analysis

Correct responses were defined as appropriate keypresses within 0.2 - 1.5 s after the onset of the second image (on average 0.75% of the trials were excluded). Because the experimental manipulation can influence measures of both RT and accuracy (see Supplementary Materials), we used an inverse efficiency (IE) score that combines both measures as the dependent variable (IE = correctly responded RTs divided by the proportion of correct responses), similar to previous studies (Gabay et al., 2014a, 2014b). To examine group differences in demographic and questionnaire data, we used Chi-square tests (for measures of proportions) or one-way ANOVA. To examine how face discrimination performance varied across experimental conditions and groups, a mixed ANOVA (stimulus presentation × image match × facial expression × group) was applied on IEs, with stimulus presentation, image match and facial expression as the within-subject factors, and group as the between-subject factor (HC, SSA, SAD). To rule out the overall group difference, we further subtracted IEs in the same-eye condition from that



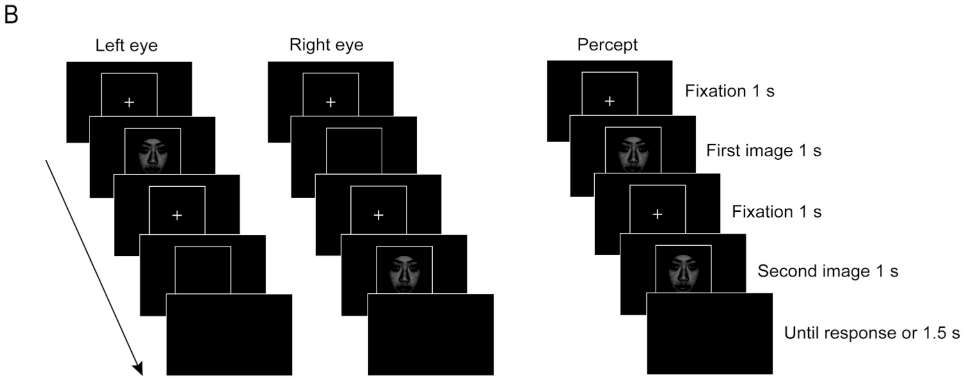


Fig. 1. Experimental task. An example trial with neutral expressions presented to different eyes. In the example, the first image is presented to the left eye and the second image is presented to the right eye. The right panel represents participants' perception of the fused images. Participants were not aware of the eye-of-origin.

in the different-eye condition (*IE difference*). Mixed ANOVAs (image match × facial expression × group) were then applied on IE differences. To examine whether the monocular advantages were comparable between two negative expressions, planned t-tests were used to compare IE differences between angry and sad expressions, separately for each group. Lastly, to explore whether gender and depression (BDI scores) influences the monocular advantage in different groups, we conducted additional analyses on IE differences (see Supplementary Materials). Data were analyzed using MATLAB, Version 2020b (The MathWorks, Natick, MA) and JASP Version 0.16.3 (JASP Team, 2022). All reported *p* values were Holm-Bonferroni-corrected for multiple comparisons. To evaluate the strength of evidence for the lack of significant effects, we conducted Bayesian analyses (Wagenmakers, 2007) using standard priors as implemented in JASP Version 0.16.3 (JASP Team, 2022).

3. Results

To examine whether and how social anxiety alters the monocular advantage for different facial emotions, we conducted a mixed four-way ANOVA, with stimulus presentation, image match and facial expression as the within-subject factors, and group as the between-subject factor (HC, SSA, SAD). The analysis revealed a main effect of stimulus presentation ($F(1,69) = 81.62$, $p < 0.001$, $\eta_p^2 = 0.542$) and image match ($F(1,69) = 12.40$, $p < 0.001$, $\eta_p^2 = 0.152$), as well as the two-way stimulus presentation × image match interaction ($F(1,69) = 126.56$, $p < 0.001$, $\eta_p^2 = 0.647$). These results showed superior performance in the same-eye condition than in the different-eye condition, particularly when the two images were identical than when the two images were different. These results replicated previous findings of monocular advantage in face perception (Gabay et al., 2014a, 2014b) and confirmed the validity of our manipulation. We also observed a significant main effect of facial expression ($F(2,138) = 71.61$, $p < 0.001$, $\eta_p^2 = 0.509$), showing that negative expressions (angry and sad) facilitated face discrimination performance compared to neutral expressions ($ps < 0.001$).

Particularly relevant to our focus on social anxiety, we found a main effect of group ($F(2,69) = 5.71$, $p = 0.005$, $\eta_p^2 = 0.142$), demonstrating poorer discrimination of faces in SAD compared to HC ($p = 0.013$) and SSA groups ($p = 0.013$). No difference was observed between HC and SSA group ($p = 0.965$). More importantly, we observed a significant four-way interaction ($F(4,138) = 3.02$, $p = 0.020$, $\eta_p^2 = 0.080$), suggesting a cross-group differences in the monocular advantage when processing different emotional expressions. To further elucidate the interaction effects, we examined how the monocular advantage varied as a function of emotional expressions, separately for each group.

Healthy control. A three-way repeated-measures ANOVA on IEs revealed main effects of stimulus presentation ($F(1,23) = 33.32$, $p < 0.001$, $\eta_p^2 = 0.592$) and image match ($F(1,23) = 12.54$, $p = 0.002$, $\eta_p^2 = 0.353$), as well as the two-way interaction between stimulus presentation and image match ($F(1,23) = 39.71$, $p < 0.001$, $\eta_p^2 = 0.633$). Simple effect analysis revealed superior performance in the same-eye condition than in the different-eye condition when the two images were identical ($ps < 0.001$), but not when the two images were different ($p = 0.372$). We also observed a significant main effect of facial expression ($F(2,46) = 22.57$, $p < 0.001$, $\eta_p^2 = 0.495$), demonstrating superior face discrimination for negative expressions (angry and sad) than neutral expressions ($ps < 0.001$). No difference was observed between angry and sad expressions ($p = 0.235$). There was no interaction between facial expression and other factors ($ps > 0.156$).

Subclinical social anxiety. The same analysis applied to IEs revealed similar patterns of results as that observed in HC group. In brief, we found main effects of stimulus presentation ($F(1,23) = 37.03$, $p < 0.001$, $\eta_p^2 = 0.617$), image match ($F(1,23) = 25.14$, $p < 0.001$, $\eta_p^2 = 0.522$), facial expression ($F(2,46) = 21.87$, $p < 0.001$, $\eta_p^2 = 0.487$). The two-way interaction between stimulus presentation and image match was also significant ($F(1,23) = 47.95$, $p < 0.001$, $\eta_p^2 = 0.676$). Simple effect analysis revealed superior performance in the same-eye condition than in the different-eye condition when two images were the same ($p < 0.001$), but not when two images were different ($p = 0.087$). No interaction effect was found between facial expressions and any of the other factors ($ps > 0.262$).

Social anxiety disorder. Different from the results in HC and SSA groups, the same analysis applied to IEs in SAD group revealed a significant three-way interaction effect (facial expression × stimulus presentation × image match: $F(2,46) = 8.89$, $p < 0.001$, $\eta_p^2 = 0.279$), suggesting that facial expressions modulated the monocular advantage in this group. In particular, for the same-image condition, we observed a significant two-way interaction between facial expression and stimulus presentation ($F(2,46) = 11.27$, $p < 0.001$, $\eta_p^2 = 0.329$). Simple effect analysis revealed a significant modulation of facial expressions when identical images were presented to different eyes ($p < 0.001$), but not when the identical images were presented to the same eye ($p = 0.302$). The results revealed two differences when compared to those observed in both HC and SSA groups. First, in the different-eye condition, apart from the superior performance for negative expressions (sad and angry) than neutral expression ($ps < 0.001$), we also observed a better performance for angry than sad expression ($p = 0.023$), suggesting an elevated specificity towards threatening expressions in individuals with SAD. Second, the emotional modulation was absent for the same-eye condition in this group, as further confirmed by moderate evidence in favor of the null model in Bayesian repeated-measure ANOVA ($BF_{01} = 3.22$). This result also differed from the observed emotion-driven facilitation in both HC and SSA groups, which leads us to speculate about possible impairment in subcortical processing of emotional contents. However, because the performance in the same-eye condition alone could not differentiate between monocular and binocular processing, we thus derived insights into these potential abnormalities by subsequent analysis of monocular advantage (as indexed by IE difference). For the different-image condition, facial expression facilitated discrimination performance ($F(2,46) = 11.64$, $p < 0.001$, $\eta_p^2 = 0.336$). Neither a main effect of stimulus presentation nor two-way interaction were observed ($ps > 0.184$).

Cross-group comparison of monocular advantage. To rule out the overall performance difference across groups before examining how social anxiety modulates the magnitude of monocular advantage, we subtracted IEs in the same-eye condition from that in the different-eye condition, separately for each facial expression and match type (Fig. 3). The larger IE difference indicates stronger monocular advantage. Because the monocular advantage was only evident in the same-image condition, consistent with previous findings (Gabay et al., 2014a, 2014b), we thus performed one-way ANOVAs to analyze the IE differences for the same-image condition, separately for each facial expression. The results showed a main effect of group for neutral expression ($F(2,69) = 7.16$, $p = 0.001$, $\eta_p^2 = 0.172$), demonstrating a more pronounced monocular advantage in SAD group than in SSA ($p = 0.005$) and HC groups ($p = 0.003$). Similar results were observed for sad expression ($F(2,69) = 3.25$, $p = 0.045$, $\eta_p^2 = 0.086$), with a greater monocular advantage in SAD than in HC group ($p = 0.042$). Despite the numerically larger monocular advantage in SAD than SSA group, the comparison did not reach the significance level ($p = 0.233$). No group differences were found between SSA and HC group for neutral or sad expressions ($ps > 0.355$). These results suggest that clinically diagnosed social anxiety exhibited increased monocular advantage when processing nonthreatening expressions, which is indicative of stronger involvement of subcortical structures.

To our surprise, we observed no group difference in monocular advantage for angry faces ($F(2,69) = 0.17$, $p = 0.846$, $\eta_p^2 = 0.005$), which was further confirmed by moderate evidence in favor of the null model in Bayesian ANOVA ($BF_{01} = 7.47$). This result suggests that social anxiety had little impact on the subcortical processing of angry faces. It is worth noting that the monocular advantage for angry face was reduced as compared to other expressions in SAD group. Given that the performance in the same-eye condition remained unaltered in response

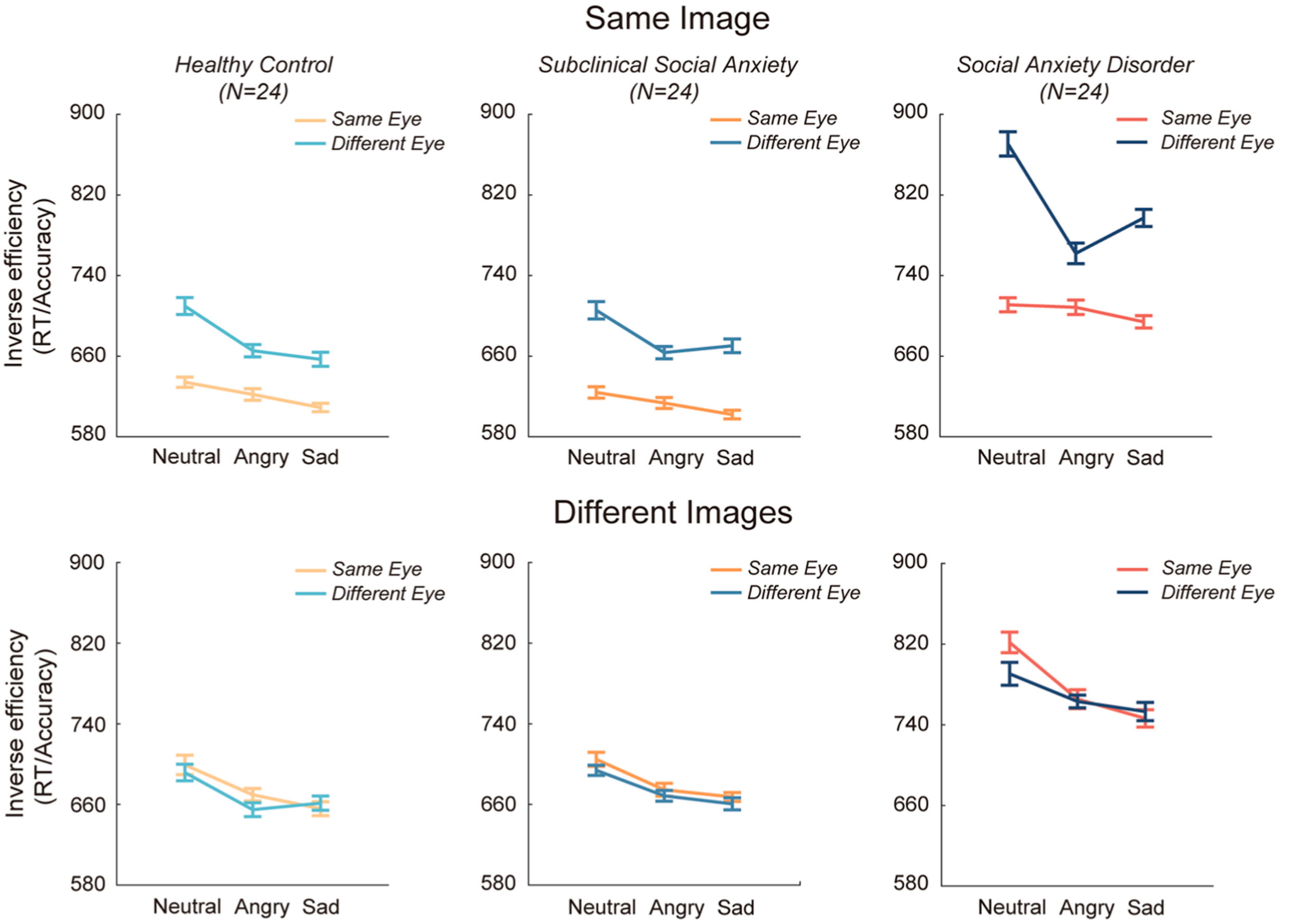


Fig. 2. Experimental results. Inverse efficiency (RT/accuracy) for the same image (top row) and different images (bottom row) conditions as a function of stimulus presentation (same-eye vs. different-eye) and facial expressions (neutral, angry, sad), separately for individuals from HC (left panel), SSA (middle panel) and SAD groups (right panel).

to facial expressions in SAD group, the reduced monocular advantage for angry expressions was primarily driven by an enhanced facilitation for angry expressions in the different-eye condition. These results likely reflect an enhanced cortical processing of threatening expressions in SAD group (Fig. 2, right panel), in line with previous findings of hyperactivity of cortico-limbic circuitry when processing threat-related expressions in individuals with SAD (Freitas-Ferrari et al., 2010; Brühl et al., 2014).

Finally, to examine whether the monocular advantages were comparable between two negative expressions (sad and angry), or showed specificity to threatening expressions (angry), we conducted planned t-tests to compare IE differences between sad and angry faces in the same-image condition, separately for each group. The results revealed a significant difference only in SAD group ($t(23) = -2.27$, $p = 0.033$), in contrast to a lack of difference in HC group ($t(23) = -0.37$, $p = 0.712$), as confirmed by Bayesian analysis supporting the null effect ($BF_{01} = 4.37$). The same analysis provided ambiguous evidence for a difference in SSA group ($t(23) = -1.43$, $p = 0.166$; $BF_{01} = 1.89$). The increased discrepancy between two negative emotions may corresponds to an elevated selectivity to threatening expressions, progressing from HC to SSA to SAD group.

4. Discussion

In the present study, we examined the influence of social anxiety on the monocular processing of facial expressions. In a face identity discrimination task, participants viewed two sequentially presented emotional face stimuli to the same eye or to different eyes. We chose a facial expression from three categories (neutral, angry, or sad). Discrimination performance was better when the same face images were presented to the same eye than to different eyes, replicating previous findings of a monocular advantage for face perception (Gabay et al., 2014a; Gabay et al., 2014b). Importantly, compared to SSA and HC group, SAD individuals exhibited a greater monocular advantage when processing neutral and sad expressions, suggesting an increased involvement of subcortex for processing nonthreatening expressions in SAD group. In contrast, individuals with SAD showed similar monocular advantage for angry expression as compared to other groups, despite a superior performance for angry expression in the different-eye condition, suggesting that SAD likely influenced the cortical processing of threatening expressions. In addition, we observed an increasing difference in the response to angry versus sad expressions, progressing from HC to SSA to SAD group. This trend suggests that social anxiety may mediate the selectivity to threatening expressions. Lastly, additional analyses did not reveal significant influences of gender and depression symptoms on the results (see Supplementary Materials), suggesting these factors had little impact on the observed monocular advantage. In particular, the increased BDI scores from HC to SAD group was not correlated with changes of monocular advantage, suggesting little impact of depression on the results. Taken together, our findings highlight an interplay between subcortical and cortical pathways in face perception for individuals with SAD. The distinct patterns of monocular

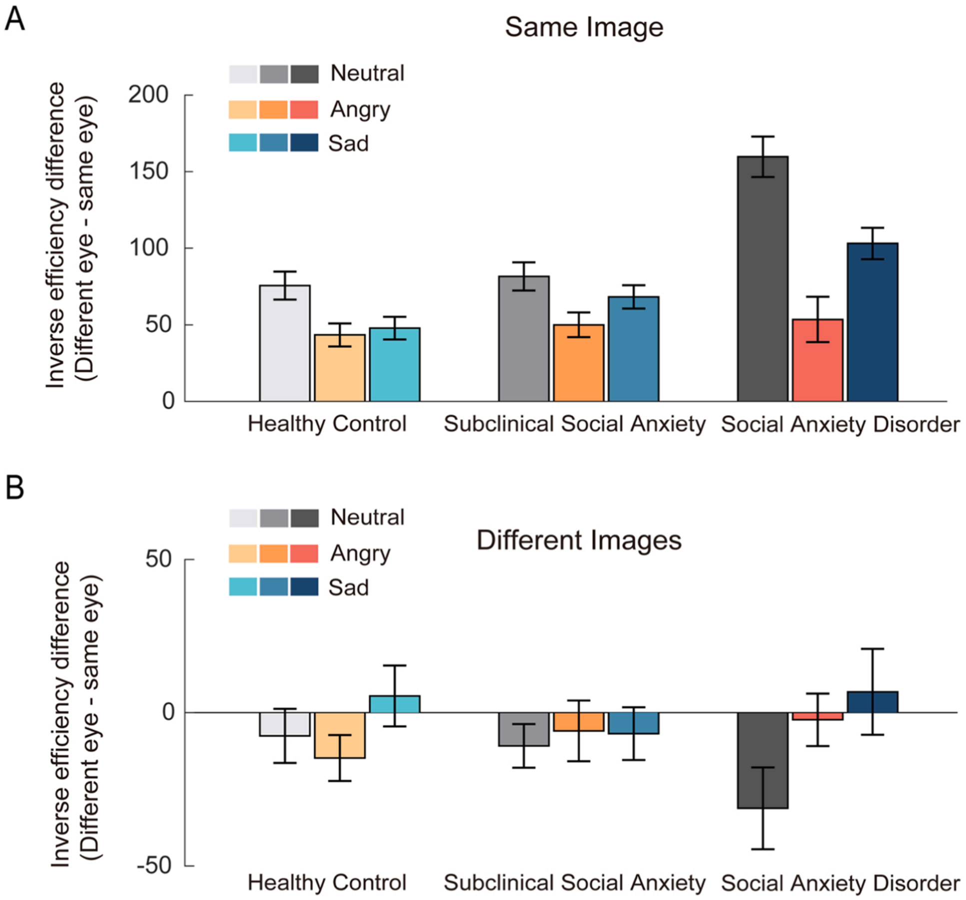


Fig. 3. Cross-group differences. (A) Inverse efficiency difference (different eyes – same eye) for the same image and (B) different image conditions as a function of facial expressions (neutral, angry, sad), separately for HC, SSA and SAD groups.

advantage observed across different facial emotions suggest that social anxiety altered facial processing at various stages of information processing, starting at an early stage of the visual system.

The increased monocular advantage in SAD group while processing nonthreatening expressions (neutral and sad) suggests that social anxiety increases reliance on subcortical pathways during face processing. The subcortical pathways are predominantly engaged in processing low spatial frequency content (Ohman, 2005), providing a coarser but rapidly processed information to the amygdala (Vuilleumier et al., 2003; Méndez-Bértolo et al., 2016). Previous studies suggest that socially anxious individuals exhibited higher sensitivity for low spatial frequency expressions (Langner et al., 2015; Novara et al., 2019). Our findings of increased monocular advantage in SAD group may thus be explained by a preferred processing of low spatial frequency information, which may correspond to higher responses in subcortical pathways. Although we are unable to identify which specific subcortical structures were involved in this process, we posit that potential candidates may include the superior colliculus, pulvinar and amygdala, as previous studies have indicated the role of colliculus-pulvinar-amygdala pathways in face processing (Johnson et al., 2015; McFadyen et al., 2017; Kragel et al., 2021). Some studies have indicated that processing in this subcortical pathway was independent of emotional valence (Garvert et al., 2014; McFadyen et al., 2017), which could potentially explain the increase of monocular advantage for both neutral and sad expressions in individuals with SAD.

The observation of a similar monocular advantage for angry expressions across three groups appears counterintuitive, as socially anxious individuals are typically expected to exhibit heightened sensitivity to threatening expressions (Mogg et al., 2004; Günther et al., 2021). When comparing the discrimination performance separately for the same-eye and different-eye conditions, two distinctive patterns were revealed across three groups. First, in the same-eye condition, SAD group exhibited a lack of sensitivity to facial emotions, in contrast to the emotion-driven facilitation observed in HC and SSA groups. Second, in the different-eye condition, the SAD group showed greater sensitivity for angry than sad faces, which contrasted with the comparable performance between these two negative emotions in HC and SSA groups. While it is difficult to discern whether the same-eye condition hinted at the possibility of abnormal subcortical processing of emotional information, the results from the different-eye condition likely suggest an elevated responses to threatening expressions along the cortical pathway in SAD group. This inference is consistent with neuroimaging findings of increased activity in cortico-limbic circuitry in SAD when processing threatening expressions (Freitas-Ferrari et al., 2010; Brühl et al., 2014), it also dovetails with the theoretical notion that cortex plays a more important role in the detection of ecologically relevant information (Pessoa & Adolphs, 2010). Given the established role of the cortico-limbic connection in transmitting high spatial frequency information (Vuilleumier et al., 2003), our findings suggest that individuals with social anxiety may prioritize the processing of high spatial frequency information when perceiving the threatening expressions. However, previous studies on subclinical social anxiety have yielded different results (Langner et al., 2009, 2015). According to their findings, all participants processed high spatial frequency information in the eye region to distinguish between neutral and angry expressions, regardless of social anxiety levels. Only individuals with high levels of social anxiety additionally extracted low spatial frequency information to assist discrimination between emotions. The discrepancy may be associated with the debates regarding whether the processing of threat-related contents depends on low or high spatial frequency information (Stein et al., 2014; Méndez-Bértolo et al., 2016), as well as task relevance of facial expressions, the characteristics of tested populations (subclinical vs. clinical), and additional factors influencing the extraction of spatial frequency during face perception (Jeantet et al., 2018). Future studies are needed to clarify the influence of spatial frequency on the processing of facial emotions in individuals with SAD.

Previous neuroimaging studies in individuals with SAD have predominantly focused on abnormalities in cortical processing of face stimuli (Brühl et al., 2014; Gentili et al., 2016), revealing alterations in neural response within distributed cortical networks and emotional structures (e.g., amygdala). Current understanding of whether subcortical structures contribute to atypical face perception in SAD remains limited. This gap may be attributed, in part, to the inherent challenges associated with investigating subcortical structures, which are relatively small, located deep, and have a low signal-to-noise ratio in neuroimaging studies. Our findings from SAD group provide insights into the potential deficits in the subcortical processing of nonthreatening expressions. While the processing of threatening expressions in SAD group appears to reflect alterations in cortical pathways, we cannot exclude the possibility of an intricate interplay between subcortical and cortical pathways, due to the group-level differences in both the same-eye and different-eye conditions. Therefore, the distinctive patterns of monocular advantage mediated by social anxiety and emotional contents suggest atypical processing of facial emotions that start from the early stage of the visual system. Future studies combining high resolution 7 T fMRI should be used to directly detect signals changes in subcortical structures while performing psychophysical tasks (Jia et al., 2021, 2023).

The present study has several limitations. First, individuals with SAD were classified into subclinical and clinical groups based on whether they sought treatment or not. The larger difference observed between HC and SAD group, as opposed to HC and SSA group, implies a higher severity of social anxiety symptoms in SAD group. However, the self-reported levels of social anxiety revealed opposite results, showing higher scores for SSA than SAD group. The reduced ratings of social anxiety levels in SAD group may be influenced by pharmacological treatments, as indicated by a negative correlation between treatment duration and LSAS scores. The cause of this inconsistency between self-reported social anxiety and atypical face perception in individuals with SAD remains unclear. Second, despite our initial goal to minimize the influence of depression by enrolling participants with scores below the BDI cutoff (< 16), we observed an increase in BDI scores from HC to SSA to SAD groups. Although our correlation analyses indicate that this increase in BDI scores had little impact on our findings of monocular advantage, we are cautious with this interpretation based on limited sample size. Future study should directly examine the influence of depression on the monocular advantage for face perception, particularly among clinical patients primarily diagnosed with depression. Third, the selection of emotional expressions in this study was limited, primarily due to the constrained time available for clinical patients. It is crucial to recognize that using "angry" as an example of a threatening expression does not necessarily mean that the level of threat is the only distinguishing factor between angry and sad expressions. Other elements, such as emotional intensity, may also play a role in differentiating between them. Future studies will be essential to test more emotional expressions and more precisely characterize the patterns of monocular advantage as a function of different types of emotions.

In conclusion, we observed distinct patterns of monocular advantage in the perception of facial expressions across HC, SSA and SAD groups. The group differences indicate that social anxiety altered the perception of facial emotions at various stages of information processing, starting at an early stage that likely relies on subcortical structures. It is worth noting that our findings have the potential to provide clinical insights into the diagnoses and treatments of SAD. First, we propose that the monocular advantage as a function of emotions may serve as a potential early indicator for the diagnosis and detection of social anxiety symptoms. More importantly, it provides insight into the potential of implementing prospective treatments based on perceptual training in SAD (Seitz et al., 2023), expanding upon the prevalent use of attention bias modification for reducing social anxiety levels (Heeren et al., 2015). Second, our results highlight a relation between social anxiety and aberrant activity in subcortical structures, extending beyond the conventional focus on cortico-limbic circuitry (Freitas-Ferrari et al., 2010). These results provide preliminary support for future clinical assessments utilizing neuroimaging technique to directly investigate signals changes in subcortical structures among individuals with SAD.

Author Note

This work was supported by a National Natural Science Foundation of China (3200784, 82090030), National Science and Technology Innovation 2030—Major Project 2021ZD0200409, Fundamental Research Funds for the Central Universities (2021FZZX001–06), and a grant from the MOE Frontiers Science Center for Brain Science & Brain-Machine Integration at Zhejiang University. We thank Miss. Mengzhen Yu for her contribution to the pilot experiment.

CRediT authorship contribution statement

Ruibo Pan: Investigation. **Xiaohua Wang:** Investigation. **Mengyuan Gong:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Chaoya Pan:** Investigation, Formal analysis. **Qiaozhen Chen:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Jun Wang:** Conceptualization. **Ke Jia:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Han Xu:** Conceptualization. **Yuzheng Hu:** Conceptualization. **Jiafeng Wang:** Investigation.

Declaration of Competing Interest

All authors declare no conflict of interest.

Data availability

All data have been made publicly available via the Open Science Framework at https://osf.io/93kaz/

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.janxdis.2024.102871.

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