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Understanding visual attention to face emotions in social anxiety using hidden Markov models

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Abstract

Theoretical models propose that attentional biases might account for the maintenance of social anxiety symptoms. However, previous eye-tracking studies have yielded mixed results. One explanation is that existing studies quantify eye-movements using arbitrary, experimenter-defined criteria such as time segments and regions of interests that do not capture the dynamic nature of overt visual attention. The current study adopted the Eye Movement analysis with Hidden Markov Models (EMHMM) approach for eye-movement analysis, a machine-learning, data-driven approach that can cluster people's eye-movements into different strategy groups. Sixty participants high and low in self-reported social anxiety symptoms viewed angry and neutral faces in a free-viewing task while their eye-movements were recorded. EMHMM analyses revealed novel associations between eye-movement patterns and social anxiety symptoms that were not evident with standard analytical approaches. Participants who adopted the same face-viewing strategy when viewing both angry and neutral faces showed higher social anxiety symptoms than those who transitioned between strategies when viewing angry versus neutral faces. EMHMM can offer novel insights into psychopathology-related attention processes.

Keywords: social anxiety, attentional bias, hidden Markov model, eye tracking

Introduction

Social anxiety (SA) is characterised by a persistent fear of social situations in which an individual might be scrutinised by others (American Psychiatric Association, 2013). As such, information that could signal negative social evaluation (e.g., angry expressions) is likely to be perceived as threatening amongst those with higher SA symptoms and so they may attend to these stimuli differently than people with lower levels of SA (Heimberg, Brozovich, & Rapee, 2014). Given the pivotal role of the eye-region in the recognition of facial expressions (Guarnera, Hichy, Cascio, Carrubba, & Buccheri, 2017) as well as its greater threat value compared to other facial features in the context of SA (Schneier, Rodebaugh, Blanco, Lewin, & Liebowitz, 2011), individuals with elevated SA symptoms are expected to exhibit attentional biases (AB) for this feature region when viewing others' faces, especially when negative emotions such as anger are perceived. Nevertheless, a recent review of eye-tracking studies found mixed results regarding this hypothesis, with some studies suggesting gaze avoidance in people with SA, and some others suggesting the opposite (Chen & Clarke, 2017).

One potential explanation for this inconsistency is that within-group inter-subject variabilities in eye movements (EM) have been largely neglected. Put otherwise, AB research typically treats all people within a given diagnostic category as though they are a homogeneous set of people who all adhere to the same attentional preference. However, it is possible that some people with SA express one preference (e.g., vigilance) whilst others exhibit another (e.g., avoidance). Conventional group-based aggregate statistics may have masked these subgroup differences. Therefore, complementing traditional EM analysis techniques with more advanced approaches that better capture individual and subgroup EM differences may provide novel insight into this field.

In the present study, we tested the associations between participants' SA symptoms and their EMs on angry and neutral expressions in a free-viewing task. We adopted a machine-learning data-driven method (i.e., Eye Movement analysis with Hidden Markov Models [EMHMM]) to operationalise EMs (Chuk, Chan, & Hsiao, 2014). This technique previously discovered two distinct EM patterns in the participants: an "eye-centred" pattern subgroup where participants focused primarily on the eyes, and a "nose-centred" pattern subgroup where participants allocated most fixations to the face centre (Chan, Suen, Hsiao, Chan, & Barry, 2020). In the context of SA, these two patterns may represent AB towards or away from threatening stimuli (i.e., the eye-region) as participants either stay vigilant to monitor the potential social threat or avoid eye contact to downregulate the negative affect it evokes. We hypothesised that SA may be characterised by both of these patterns.

Methodology

Participants

The inclusion criteria were: (1) Hong Kong local undergraduate students, and (2) able to read and understand Traditional Chinese. Participants were excluded if (1) they had visual or physical impairments that prevent them from completing the experiments, or (2) they self-reported a history of mental disorders. The current study recruited 67 undergraduate students in total. Four participants (3 females) were excluded due to failure of eye-tracker calibration. Three participants (1 female) were excluded due to fatigue during the experiments. The final sample consisted of 60 Asian undergraduate students (32 females, 53.3%) who were local to Hong Kong. The mean age was 19.42 (*SD* = 1.58). The study was approved by the Human Research Ethics Committee of the University of Hong Kong (reference number: EA1705030). Participants were given course credit or were entered into a lucky draw upon completion.

Self-report questionnaires

The Liebowitz Social Anxiety Scale (LSAS) was used to assess SA symptoms (Liebowitz, 1987). Participants rate from 0 to 3 the extent to which each of the 24 social situations evoke fear/anxiety (0 = none, 3 = severe) and the extent to which they would avoid them (0 = never, 3 = usually). Cronbach's alpha was .97 for the LSAS, and was .95 and .94 for the fear/anxiety and avoidance subscales, respectively. Based on a cut-off value of 35 for the self-reported version of LSAS (von Glischinski, et al., 2018), participants with a total score of 35 or above were assigned to the high SA symptoms group (HSA) while others were assigned to the low SA symptoms group (LSA). We also measured participants' depressive symptoms using the 14-item Depression subscale of the 42-item Depression Anxiety and Stress Scale (DASS) (Lovibond & Lovibond, 1995). Participants were asked to read each of the statements and indicate how much the statements applied to them over the past week. The Cronbach's alpha of DASS-Depression was .92.

Materials and apparatus

Thirty-two frontal view Asian face images were used as stimuli in the experiment (Zhang, Chan, Lau, & Hsiao, 2017). All face photos were taken under a consistent lighting condition and the interpupil distances were the same across faces. The image set comprised 16 angry and 16 neutral faces. The neutral faces were different people from those with angry expressions but all other factors such as gender and age group were matched between face emotions. The face sizes were adjusted to subtend 8 degrees of visual angle horizontally (317 pixels), which was similar to viewing faces in a conversation (Hsiao & Cottrell, 2008).

EMs were recorded by an EyeLink 1000 eye-tracker (SR Research). Participants sat 60cm in front of a 22" CRT monitor with a resolution of 1024 × 768 pixels. The tracking mode was pupil and corneal reflection, with a sampling rate of 1000Hz. Nine-point calibration was implemented at the beginning of the task and was repeated if the drift correction error was larger than one degree of visual angle during the task. A chin rest was used to reduce participants' head movements. In data acquisition, saccade motion threshold was 0.1 degree of visual angle, saccade acceleration threshold was 8000 degree/square second, and saccade velocity threshold was 30 degree/s, which were the EyeLink defaults for cognitive research.

Procedure

The study was advertised through bulk emails sent to students. Interested participants were assessed for eligibility. Only eligible participants were invited to the experiment. After providing informed consent participants completed the LSAS and DASS-Depression. The free-viewing task commenced after calibration and validation of EMs. Each trial began with a drift correction check (i.e., a dot at the screen centre). After confirming the participants gazed at the dot, a fixation cross replaced the dot for 500ms after which one of the faces was presented for 5000ms. Following an inter-trial interval of 500ms, the next trial started again with the drift check. The 32 faces were shown to the participants one at a time in a randomised order. Each face was only presented once. We presented each face image at one of the four quadrants of the screen in order to capture participants' first fixations when they saccade to a target face, which is an important indicator of their information processing strategy (Hsiao & Cottrell, 2008). The location and sequence of the stimuli were counterbalanced. No response was required during this task.

Data preparation and analysis

To analyse EMs by EMHMM, a MATLAB toolbox was employed (for a more detailed description of the EMHMM approach, see Supplementary Methods and Analyses). The EM data for angry faces and neutral faces were run separately in the toolbox. First, each individual's HMM of EM pattern was trained, during which the properties of regions of interest (ROI) were automatically decided by the program (Chuk, Chan, & Hsiao, 2014). We then clustered the HMMs into two subgroups using the variational hierarchical estimation maximization (VHEM) algorithm (Coviello, Chan, & Lanckriet, 2014), which generated two representative HMMs that summarised each subgroup. In the current study, we identified an “eye-centred” and a “nose-centred” pattern subgroup for both angry and neutral faces, replicating previous EMHMM studies (Chan, Suen, Hsiao, Chan, & Barry, 2020). Illustrations and descriptions for each EM pattern are available in supplementary materials (see Supplementary Methods and Analyses and Figures S1-S6).

Following a previous study (Chan, Chan, Lee, & Hsiao, 2018), we then quantified participants’ EM patterns using a unified measure called the Eye-Nose (E-N) Scale value (see Supplementary Methods and Analyses). A more positive E-N Scale value indicated a pattern that is more eye-centred and less nose-centred. Each individual had one E-N Scale value for angry-face-viewing, and another such value for neutral-face-viewing. The E-N Scale values were then used as continuous variables in data analyses. The toolbox also generated the group memberships indicating the pattern subgroup a participant belonged to when viewing angry and neutral faces. These data were used as categorical variables in data analyses. In addition, the EMHMM approach was compared to three traditional EM indices: (1) the proportion of first fixations that occurred on the eyes, (2) time spent to first fixate on the eyes, and (3) total dwell time on the eyes (relative to total dwell time on the face). For these three indices we predefined a rectangular ROI that covered both eyes and the interocular space.

We utilised both continuous (E-N scale) and categorical (group membership) measures of EM in our analyses. Since depressive symptoms have been associated with EMs according to previous studies (Armstrong & Olatunji, 2012), we ran all statistical tests with DASS-Depression as a covariate. First, 2 (angry vs. neutral) × 2 (HSA vs. LSA) ANCOVAs were run for E-N scale values as well as the three traditional EM indices, with depressive symptoms as a covariate. The statistical power for detecting a significant group effect ($p < .05$) was .59 for medium ($\eta^2 = .25$) and .94 for large ($\eta^2 = .40$) effects (G*Power 3.1.9.4);

the statistical power for detecting a significant moderate interaction effect was .97 (Faul, Erdfelder, Lang, & Buchner, 2007). We also performed 2 (eye-centred vs. nose-centred groups for angry faces) × 2 (eye-centred vs. nose-centred groups for neutral faces) ANCOVAs with LSAS and its subscales (i.e., LSAS-Fear/Anxiety, LSAS-Avoidance) as the dependent variables, and depressive symptoms as a covariate. The power for detecting a significant effect was .48 for medium and .86 for large effects. If any significant main effect or interaction was found, we followed up with other comparisons to examine the findings in more detail.

Results

The means, standard deviations and ranges of questionnaire responses and age of each group were summarised in Table 1. Preliminary analyses of participant characteristics are available in Supplementary Methods and Analyses.

First, a 2 (angry vs. neutral) × 2 (HSA vs. LSA) ANCOVA was performed with E-N Scale as the dependent variable. Results revealed a main effect of group, $F(1, 57) = 5.86$, $p = .019$, $\eta^2 = .09$, 90% CI [.01, .22]. However, there was no main effect of face emotion, $F(1, 57) = 0.02$, $p = .877$, $\eta^2 = .00$, 90% CI [.00, .01], or interaction between group and face emotion, $F(1, 57) = 0.07$, $p = .787$, $\eta^2 = .001$, 90% CI [.00, .05]. Pairwise comparisons showed that participants in the HSA group ($M = 0.004$, $SE = 0.002$) were more eye-centred compared to participants in the LSA group ($M = -0.004$, $SE = 0.002$). Participants with higher SA symptoms adopted a strategy that was more similar to the eye-centred pattern when viewing angry and neutral faces than participants with lower social anxiety symptoms, even when controlling for depressive symptoms.

We then performed a 2 (eye-centred vs. nose-centred groups for angry faces) × 2 (eye-centred vs. nose-centred groups for neutral faces) ANCOVA with LSAS as the dependent variable, which revealed no main effect of group membership for angry faces, *F*(1,

55) = 0.79, p = .377, η^2 = .01, 90% CI [.00, .10], or main effect of group membership for neutral faces, $F(1, 55)$ = 0.65, p = .423, η^2 = .01, 90% CI [.00, .10]. However, an interaction was found between the two factors, $F(1, 55)$ = 8.27, p = .006, η^2 = .13, 90% CI [.02, .27].

To follow up this interaction, we then compared social anxiety symptoms between different strategy groups (eye-centred vs. nose-centred) for one emotion at each level of the strategy groups for the other emotion. Results showed that people who were eye-centred for both face emotions (n = 15; M = 55.07, SE = 5.79) were more socially anxious than those who were eye-centred for neutral and nose-centred for angry faces (n = 13; M = 30.91, SE = 5.47), $F(1, 25)$ = 8.63, p = .007, η^2 = .26, 90% CI [.05, .45], and those who were nose-centred for neutral and eye-centred for angry faces (n = 10; M = 33.19, SE = 7.11), $F(1, 22)$ = 5.62, p = .027, η^2 = .20, 90% CI [.01, .41] (see Figure 1). However, there was no significant difference in social anxiety symptoms between those who were eye-centred for both emotions (M = 52.72, SE = 6.25) and those who were nose-centred for both emotions (n = 22; M = 42.65, SE = 5.16), $F(1, 34)$ = 1.54, p = .223, η^2 = .04, 90% CI [.00, .19]. Also, no significant difference in LSAS scores was observed between people who used eye-centred strategy for one emotion and nose-centred strategy for another and those who did the opposite, $F(1, 20)$ = 0.00, p = .984, η^2 = .00, 90% CI [.00, .00]. Participants who were nose-centred for both emotions did not differ in social anxiety symptom levels from those who were eye-centred for neutral and nose-centred for angry faces, $F(1, 32)$ = 2.54, p = .121, η^2 = .07, 90% CI [.00, .24], or those who were nose-centred for neutral and eye-centred for angry faces, $F(1, 29)$ = 1.48, p = .234, η^2 = .05, 90% CI [.00, .21].

It appeared that people who focused more on the eyes or focused more on the nose for both face emotions had higher LSAS scores than those who switched strategy between emotions. To further explore this finding, participants were separated into groups for those who consistently used one strategy and those who switched. Results showed that people who consistently used the same strategy across face emotions were more socially anxious than people who changed their viewing strategy between different faces emotions, $F(1, 57) = 7.64$, $p = .008$, $\eta^2 = .12$, 90% CI [.02, .25] (see Figure 1). Similar findings were also revealed when SA symptoms were quantified in terms of LSAS-Fear/Anxiety and LSAS-Avoidance separately (see Supplementary Methods and Analyses).

To compare the EMHMM approach to traditional EM analysis approaches, three 2 (angry vs. neutral) × 2 (HSA vs. LSA) ANCOVAs were performed for the three traditional EM indices (see Supplementary Methods and Analyses and Table S1). However, there was no significant finding.

Discussion

To our knowledge, this is the first study to adopt the EMHMM approach to investigating the relations between attentional processing of emotional faces and SA symptoms. In contrast to previous studies in which spatial ROIs and temporal segments were predefined, the present study summarises personalised face-viewing patterns directly from participants' EM using HMMs. As such, this study expands on past work by providing a novel account of overt attention in socially anxious individuals. Specifically, hypervigilance to and avoidance for the eye-region of faces might both be evident in SA, and the reduced tendency to transit between strategies across different face emotions seems to be associated with elevated SA symptoms.

Our data showed that participants in the HSA group focused more on the eye-regions than those in the LSA group. This finding was supported by subsequent analyses which revealed that people who were eye-centred for both face emotions had the highest mean LSAS score, while people who were eye-centred for one emotion and nose-centred for the other emotion had significantly lower LSAS scores compared to the former. For people with higher SA symptoms who showed eye-centred patterns for both emotions, the extensive monitoring of the eye-region might enable them help them quickly detect situations where negative evaluation and scrutiny are more likely. However, such vigilant scanning results in excessive processing of negative stimuli and makes it less likely for individuals with elevated SA symptoms to avoid or downregulate the affect evoked by negative information, which sustains the intensity of negative self-evaluative cognitions and exaggerated autonomic reactions (Norton & Abbott, 2016). In contrast, people with the lowest LSAS scores, though adopting a similar strategy for neutral faces (i.e., eye-centred) to identify the upcoming emotions, would avoid looking at the eye-region of angry faces so as to minimise the possibility of conflicts or judgements (Moukheiber, et al., 2010). If one is unable to shift gaze away from the eye-region when anger is perceived, one continues to be hypervigilant towards this region that contains the most threats, which might then reinforce the presumptions that other people are critical and social situations are threatening.

Though SA symptoms were the highest in people who were eye-centred for both emotions, being nose-centred for both emotions did not result in significantly lower SA symptoms than the former. One explanation for this is that being consistently nose-centred for different face emotions may prevent people from direct confrontations which is essential for learning to cope with social situations, and may make people ignore positive information which might alleviate one's anxiety, and thus might not be an optimal strategy in social situations. Collapsing across these groups, another interesting finding showed that people who used the same strategy for both face emotions were more socially anxious than those who switched strategy. This suggests that the flexibility in attentional strategy that one adopts when viewing faces of different emotions might be optimal in social situations. While being consistently eye-centred irrespective of face emotions may expose people to more negative information, being consistently nose-centred may limit one's chance of direct confrontation and receiving positive information. However, these findings should be interpreted with caution as there was no statistically significant difference in SA symptoms between those who were consistently nose-centred and the two groups who switched strategies. The significant difference between those who used the same strategy and those who switched seems to be mainly driven by the high LSAS scores in those who were consistently eye-centred. Nevertheless, the data presented in Figure 1 suggest that the consistently nose-centred group had higher SA symptoms compared to the two groups that switched strategy, and that the mean LSAS score of this group exceeded the cut-off point of 35. Despite the non-significant result, it suggests that hypervigilance and avoidance of the eye-region may both characterise individual with heightened SA symptoms.

Several limitations are evident. First, although the LSAS cut-off point adopted by the current study (von Glischinski, et al., 2018) might have convergence with clinical diagnoses, it remains unclear if similar effects would be observed amongst clinical populations. Second, only using angry and neutral faces without the inclusion of positive expressions limits our conclusions in the current investigation because it remains to be determined whether the observed effects are specifically due to threat processing or it reflects a more general emotion effect. A third limitation is that the current study recruited a relatively small sample, precluding us from detecting small effect sizes. Also, although we added depressive symptoms as a covariate in all our analyses, we were unable to control for general anxiety symptoms. Therefore, it is not clear whether the observed effects were specifically due to fear of negative evaluation or were instead related to broader anxiety symptoms. In addition, the EMHMM analysis in this study was based on the sequence of fixation locations only, without incorporating other important EM variables such as fixation duration, saccade length, and pupil diameter. Future work should examine whether these indices differ between EM patterns. Finally, in the current study, face identity was not counterbalanced across emotions and therefore the observed effects may be driven by identity rather than emotion. This was a key limitation of our software program. The results of the current study should therefore be interpreted and generalised with caution. Nevertheless, our results showed that face emotion did not affect the main findings and the consistency of EM strategy across emotions was a more important factor that differentiated the sample. Future replication studies that examine this hypothesis are warranted.

In conclusion, by using the EMHMM approach, our study shows that SA symptoms might be associated with both hypervigilance to and avoidance of the eye-region, arguing against the traditional assumptions that socially anxious individuals do not differ between each other in their threat-related attentional processes. This study also suggests that what distinguishes people with elevated SA symptoms from those with lower symptoms might be the inflexibility with which they utilise face-viewing strategies, whether that is in terms of a fixed eye-centred strategy or a nose-centred strategy. These results reinforce the importance of taking within-group individual differences in EMs into account in studies examining attentional biases.

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Table 1. *Demographics and questionnaire responses of each group*

	HSA (n = 33, 17 females)		LSA (n = 27, 14 females)	
Measure	Mean (SD)	Range	Mean (SD)	Range
Age	19.55 (1.79)	17-24	19.26 (1.29)	17-22
DASS-Depression	12.64 (7.42)	3-33	5.78 (4.67)	0-17
LSAS	60.33 (17.09)	35-106	18.11 (10.45)	0-33

Note. SD = Standard Deviation.

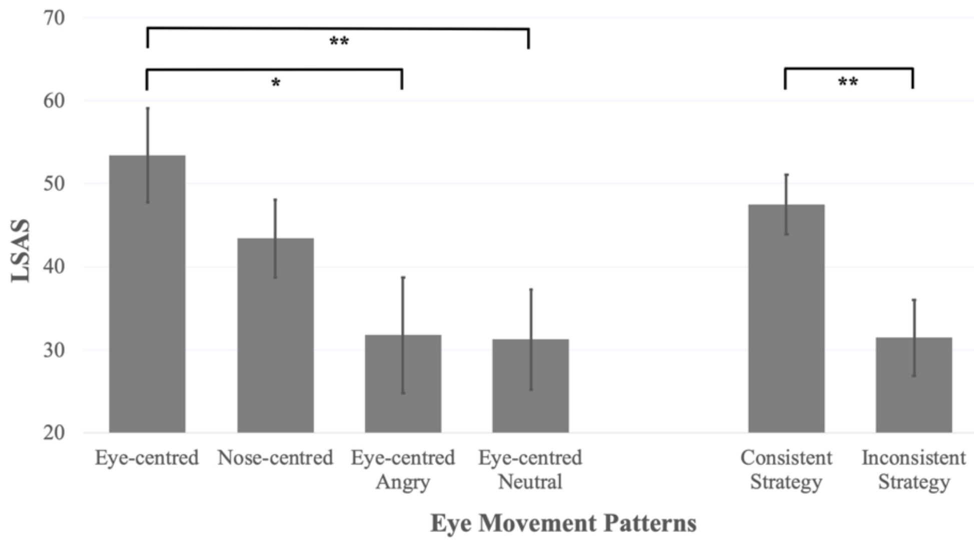

Figure 1 Mean LSAS scores of participants with different eye movement patterns on angry and neutral faces (controlling for DASS-Depression). Eye-centred = Eye-centred pattern for both emotions; Nose-centred = Nose-centred patterns for both emotions; Eye-centred Angry = Eye-centred for angry faces and nose-centred for neutral faces; Eye-centred Neutral = Eye-centred for neutral faces and nose-centred for angry faces; Consistent strategy = eye-centred for both emotions or nose-centred for both emotions.
Note. Error bars display standard errors. *$p < .05$. **$p < .01$.

Supplementary Methods and Analyses

Overview of the EMHMM approach

The EMHMM method is a data-driven machine-learning approach that accounts for individual differences in both spatial (i.e., fixation location) and temporal dimensions (i.e., transitions among fixation locations) of eye movements (EM) (Chuk, Chan, & Hsiao, 2014). A hidden Markov model (HMM) is a type of machine-learning model for modelling time-series data, which considers that the observed data (in this case, eye fixation locations) arises from an underlying dynamic process (in this case, the sequence of regions of interest [ROI] viewed). Within the context of eye-tracking research, an HMM contains a number of hidden states and each hidden state corresponds to an ROI on the stimuli. This approach assumes that the ROI of the current fixation is only dependent on the previously viewed ROI; therefore EMs could be considered as a Markovian stochastic process (Chan, Chan, Lee, & Hsiao, 2018). The EMHMM approach directly uses HMMs to model a person's gaze behaviour without predefining temporal segments or spatial ROIs. Using this approach, the properties of ROIs are automatically estimated for each individual based on the assumption that the fixation density of each ROI is a two-dimensional normal (Gaussian) distribution. According to this assumption, the fixation density would be the highest at the centre of each ROI and lowest near the border. Given the sequences of fixation points on the stimuli, the HMM then uses a probabilistic model to estimate the locations and sizes of the ROIs, as well as the probability of starting in a particular ROI and the probability of the fixations moving between two ROIs (Chuk, Chan, & Hsiao, 2014).

After each participant's EM pattern is summarised with personalised ROIs and transition probabilities among the ROIs, EMHMM enables participants to be clustered into groups based on similarities and differences among their HMMs. The extent to which an individual's EM pattern is similar to a common pattern can be calculated as the log-likelihood of the individual's eye fixations being from the common pattern, which reflects individual differences on a continuum (Chuk, Chan, & Hsiao, 2014). Through clustering participants' EMs during face recognition into two groups, previous studies discovered two face-viewing patterns: people with an "eye-centred" viewing pattern who focused more on the eye-region, in comparison to people with a "nose-centred" pattern who had most fixations located at the face centre (Chan, Suen, Hsiao, Chan, & Barry, 2020).

Analysing EM data with EMHMM

To analyse eye movements by EMHMM, a MATLAB toolbox was employed (http://visal.cs.cityu.edu.hk/research/emhmm/). The EM data were split into two sets based on the face emotions (fixations on angry faces and fixations on neutral faces) and were run separately in the toolbox. Participants completed 16 trials for angry faces, with an average of 12.58 fixations per trial (SD = 2.44), as well as 16 trials for neutral faces, with 12.13 fixations per trial (SD = 2.44). Based on a simulation study (Chan & Hsiao, n.d.), a minimum of 150 total fixations with at least 10 trials for each participant is recommended to estimate an HMM with 80% overlap with the participant's true HMM. Therefore, our data are sufficient to provide a reliable estimation of individuals' EM patterns.

First, each individual's HMM of EM pattern was trained based on the assumptions that the fixations in an ROI are distributed according to a two-dimensional normal distribution and that the target ROI of next fixation depends completely on the current ROI (Chuk, Chan, & Hsiao, 2014). All the hyperparameters of the HMM, including the number of ROIs (number of hidden states) were automatically estimated from a participant's data using a Bayesian method. In particular, for each individual, six candidate HMMs were trained with numbers of ROIs ranging from one to six. Each candidate HMM was trained for 200 times with different random initialisations[1], and the run with the largest marginal likelihood was kept. Then, for each individual, the number of ROIs of the HMM was automatically determined by selecting the candidate HMM with the largest marginal likelihood of the data. During the training procedure, the shape, size, location and number of ROIs, as well as the transition probabilities between ROIs, were estimated from the data. Since we trained HMMs separately for fixations on angry faces and fixations on neutral faces, each individual had two unique HMMs, one for angry faces and one for neutral faces, resulting in 60 individual HMMs for angry faces and 60 individual HMMs for neutral faces in total. As the individual HMMs were decided by the data itself, the numbers and distribution of ROIs could be different between emotions and between individuals.

As mentioned, previous EMHMM studies (Chan, Suen, Hsiao, Chan, & Barry, 2020) discovered two dominant EM patterns (i.e., eye-centred and nose-centred) by clustering individual HMMs into two groups using the variational hierarchical estimation maximization (VHEM) algorithm (Coviello, Chan, & Lanckriet, 2014). The VHEM algorithm clusters a given collection of HMMs into groups of HMMs that are similar to each other and summarises each group by a representative HMM. In Coviello et al. (2014), the VHEM algorithm was compared to several alternative algorithms for clustering HMMs and it was shown to be capable of effectively and efficiently leveraging large amounts of data, reducing learning times and memory requirements while also improving model robustness. Based on these previous studies and our hypotheses, we also planned to cluster the individual HMMs into two groups according to their similarities and differences. The clustering algorithm was run separately for the two emotions. Since the numbers of ROIs vary between emotions and between individuals, we selected the most frequent number of ROIs among individuals and

[1] 200 times is a good balance between training time and breadth of the search, and training the HMM for more than 200 times does not provide any substantial benefit (Chan, Chan, Lee, & Hsiao, 2018).

used this number as the number of hidden states for the clustering algorithm. In the current study, the most frequent number of ROIs was five for angry faces (n = 23) and six for neutral faces (n = 24). Similar to training individual models, the clustering algorithm was run for 200 times with different initialisations, and the clustering result with the highest expected log-likelihood was selected. This resulted in two representative HMMs with five ROIs for angry faces, and two representative HMMs with six ROIs for neutral faces.

To show the ability of EMHMM in discovering individual differences in EMs, we also used the toolbox to summarise the EM patterns of the HSA and the LSA groups. The representative HMMs generated based on social anxiety (SA) symptoms grouping were then compared to the representative HMMs generated by the VHEM algorithm to see whether the representative HMMs based on VHEM is more informative in terms of individual differences. For illustrative purpose, we also generated the fixation density heatmaps for each of the representative HMMs using iMap (Lao, Miellet, Pernet, Sokhn, & Caldara, 2017).

EM patterns on angry faces

Two common patterns for angry-face-viewing were discovered in the current sample (see Figure S1 for representative HMMs). Two t-tests performed within the EMHMM toolbox showed significant difference between the two patterns (*p*s < .001), indicating that the clustering result was valid. The pattern in the top panel (n = 25) showed that people adopting this strategy had two ROIs that centred roughly between the two eyes (red and blue) and two ROIs that landed on the nose (green and cyan). The transition matrix indicated that participants with this pattern typically started a trial by looking at the eye region (40% for red and 24% for blue). They tended to stay in this region after the first fixation but occasionally shifted to the nose and then shifted back to the eyes. The heatmap showed that the fixations mainly fell on the eye region. Therefore, this pattern was called an eye-centred pattern.

The transition matrix of the other pattern (bottom panel, n = 35) showed that people in this group had 91% probability to first fixate on the red (66%) and blue (25%) regions, the ROI centres of which located on the nose. Although the red and blue ROIs in this pattern appeared to cover all facial features, based on the assumption of the algorithm that the fixation density is the highest at the centre of each ROI, it could be inferred that this group of people tend to initially orient to the nose. They also tended to stay in these two regions afterwards. Moreover, there was less than 1% probability that participants would first fixate on the purple region, which was the only ROI around the two eyes. In comparison to the eye-centred pattern, this pattern mainly focused on the face centre, and therefore it was called a nose-centred pattern. Difference between the two patterns was also illustrated by the difference heatmap in Figure S3 (left panel) where fixations of the nose-centred pattern were slightly shifted downwards to the nose compared to the eye-centred pattern.

The representative HMMs for angry-face-viewing by SA symptom grouping were shown in Figure S4. The difference between those with high (HSA, top panel) and low (LSA, bottom panel) SA symptoms was less clear as both groups appeared to be shifting between the eye region and the face centre. One possible explanation might be that people with higher HA symptoms might display different EM patterns even when shown the same set of faces. The difference heatmap generated when participants were grouped according to their SA symptom severity (see the left panel of Figure S6) was also more scattered compared to the one based on HMM similarities, demonstrating EMHMM's ability in reflecting individual differences.

EM patterns on neutral faces

Two common patterns for neutral-face-viewing were also found (see Figure S2 for representative HMMs). The clustering result was valid since two t-tests showed significant differences between the two patterns (*p*s < .001). Participants adopting the first pattern (top panel, n = 28) tended to look first at the red region that centred between the two eyes (40%) and stay in this region (97%). This pattern also had two ROIs that covered the left (purple) and right (blue) eyes. Although participants did not initially gaze at these two regions, they might shift between the two eyes and the face centre in subsequent stages of viewing (e.g., after first fixation in the cyan region). The heatmap showed that fixations mainly fell on the eyes and therefore this was called an eye-centred pattern.

Unlike the eye-centred group, people in the second group (bottom panel, n = 32) had their first fixations on the red (37%), blue (28%), and purple (15%) regions, the ROI centres of which landed roughly on the nose. Similarly, as the fixation density is the highest at the centre of each ROI, people in this group appeared to primarily focus on the nose region for the first fixations. These three regions were also largely overlapping with each other, indicating there was no apparent transition after initial fixations. The difference heatmap between this group and the eye-centred group was illustrated in Figure S3 (right panel), showing that the second group focused more on the face centre compared to the first group. This group is therefore referred to as the nose-centred group.

The representative HMMs for neutral-face-viewing by SA symptom grouping were shown in Figure S5. Similarly, when participants were grouped by levels of SA symptoms, difference in eye movements was harder to interpret as it was unclear to which region each group paid more attention. The difference heatmap based on SA symptoms (see the right panel of Figure S6) also did not appear to indicate a clear separation.

EMHMM data preparation

After participants' EM patterns were classified into two groups, the mean log-likelihoods (MLL) of participants' EM data were calculated. Specifically, the log-likelihoods of each individual's data to the representative HMMs were calculated. The MLLs indicated how likely a given individual's EM data belonged to each representative HMM. The larger the

MLL, the more similar a participant is to a representative HMM. For example, if a participant's MLL for the eye-centred pattern is larger than the MLL for the nose-centred pattern, then the person is more similar to the eye-centred pattern and less similar to the nose-centred pattern. Following a previous study (Chan, Chan, Lee, & Hsiao, 2018), the MLL data were then transformed into a unified measure called the Eye-Nose (E-N) Scale that quantifies the degree of similarity of individual HMMs to the representative HMMs using the following formula:

$$E - N\ Scale = \frac{(Eye - centred\ MLL) - (Nose - centred\ MLL)}{|Eye - centred\ MLL| + |Nose - centred\ MLL|}$$

A more positive E-N Scale value represents a pattern that is more similar to the eye-centred HMM, and a more negative value indicates a pattern more similar to the nose-centred HMM.

Each individual had one E-N Scale value for angry-face-viewing, and another such value for neutral-face-viewing. The E-N Scale values were then used as a continuous variable in subsequent data analyses. The toolbox also generated the group memberships indicating the pattern group a participant belonged to when viewing angry and neutral faces. These data were used as categorical variables in subsequent data analyses.

Participant characteristics

The two groups did not differ significantly in age, $t(57.18) = 0.72$, $p = .475$, $d = 0.18$, 95% CI [-0.33, 0.69], or gender ratio, $\chi^2(1) = 0.00$, $p = .979$, $\varphi = .00$, 95% CI [.00, .02]. The HSA group had significantly higher LSAS mean ($M = 60.33$, $SD = 17.09$) than the LSA group ($M = 18.11$, $SD = 10.45$), $t(58) = 11.22$, $p < .001$, $d = 2.91$, 95% CI [2.15, 3.60]. The two groups also differed significantly in depressive symptoms, $t(54.70) = 4.36$, $p < .001$, $d = 1.08$, 95% CI [0.53, 1.61]. Tests for symmetry (skewness) and flatness (kurtosis) of all variables in the study were also performed. Based on the acceptable limits of ±2 suggested by previous work (Gravetter & Wallnau, 2014; Trochim & Donnelly, 2006), all variables tested were within acceptable limits, indicating that the data was normally distributed.

Eye-movements and social anxiety symptoms (EMHMM analyses)

Two 2 (eye-centred vs. nose-centred groups for angry faces) × 2 (eye-centred vs. nose-centred groups for neutral faces) ANCOVAs with LSAS-Fear/Anxiety and LSAS-Avoidance as the dependent variables were conducted separately.

For LSAS-Fear/Anxiety, there was no main effect of group membership for angry faces, $F(1, 55) = 0.31$, $p = .581$, $\eta^2 = .01$, 90% CI [.00, .08], or main effect of group membership for neutral faces, $F(1, 55) = 0.50$, $p = .481$, $\eta^2 = .01$, 90% CI [.00, .09]. However, there was an interaction between the two factors, $F(1, 55) = 8.91$, $p = .004$, $\eta^2 = .14$, 90% CI [.03, .28]. Follow-up comparisons showed that people who were eye-centred for both face emotions had high levels of fear and anxiety in social situations than those who were eye-centred for neutral and nose-centred for angry faces, $F(1, 25) = 6.90$, $p = .015$, $\eta^2 = .22$, 90% CI [.03, .41], and those who were nose-centred for neutral and eye-centred for angry faces, $F(1, 22) = 5.65$, $p = .027$, $\eta^2 = .20$, 90% CI [.01, .41]. There was no significant difference in LSAS-Fear/Anxiety between those who were eye-centred for both emotions and those who were nose-centred for both emotions, $F(1, 34) = 0.87$, $p = .358$, $\eta^2 = .03$, 90% CI [.00, .16], or between people who used eye-centred strategy for one emotion and nose-centred strategy for another and those who did the opposite, $F(1, 20) = 0.05$, $p = .829$, $\eta^2 = .00$, 90% CI [.00, .09]. Furthermore, people who used the same EM strategy across face emotions were found to have higher fear and anxiety in social situations compared to those who switched strategies, $F(1, 57) = 8.52$, $p = .005$, $\eta^2 = .13$, 90% CI [.02, .27].

In terms of LSAS-Avoidance, there was no main effect of group membership for angry faces, $F(1, 55) = 1.41$, $p = .240$, $\eta^2 = .03$, 90% CI [.00, .12], or main effect of group membership for neutral faces, $F(1, 55) = 0.75$, $p = .390$, $\eta^2 = .01$, 90% CI [.00, .10]. However, there was an interaction between the two factors, $F(1, 55) = 6.89$, $p = .011$, $\eta^2 = .11$, 90% CI [.01, .25]. Follow-up comparisons showed that people who were eye-centred for both face emotions reported higher tendencies to avoid social situations than those who were eye-centred for neutral and nose-centred for angry faces, $F(1, 25) = 9.91$, $p = .004$, $\eta^2 = .28$, 90% CI [.06, .47], and those who were nose-centred for neutral and eye-centred for angry faces, $F(1, 22) = 5.19$, $p = .033$, $\eta^2 = .19$, 90% CI [.01, .40]. There was no significant difference in LSAS-Avoidance between those who were eye-centred for both emotions and those who were nose-centred for both emotions, $F(1, 34) = 2.23$, $p = .145$, $\eta^2 = .06$, 90% CI [.00, .22], or between people who used eye-centred strategy for one emotion and nose-centred strategy for another and those who did the opposite, $F(1, 20) = 0.07$, $p = .799$, $\eta^2 = .00$, 90% CI [.00, .12]. Moreover, people who used the same EM strategy across face emotions had higher tendencies to avoid social situations compared to those who switched strategies, $F(1, 57) = 6.12$, $p = .016$, $\eta^2 = .10$, 90% CI [.01, .23].

Eye-movements and social anxiety symptoms (traditional analyses)

Three 2 (angry vs. neutral) × 2 (HSA vs. LSA) ANCOVAs were performed for the three traditional EM indices (see Table S1). There was no main effect of group on first fixation proportion, $F(1, 57) = 0.30$, $p = .586$, $\eta^2 = .01$, 90% CI [.00, .07], first fixation latency, $F(1, 57) = 0.03$, $p = .856$, $\eta^2 = .001$, 90% CI [.00, .02], or dwell time, $F(1, 57) = 0.28$, $p = .598$, $\eta^2 = .01$, 90% CI [.00, .07]. No main effect of face emotion was found on first fixation proportion, $F(1, 57) = 1.64$, $p = .205$, $\eta^2 = .03$, 90% CI [.00, .13], first fixation latency, $F(1, 57) = 0.82$, $p = .368$, $\eta^2 = .01$, 90% CI [.00, .10], or dwell time, $F(1, 57) = 2.66$, $p = .108$, $\eta^2 = .05$, 90% CI [.00, .15]. Also, no interaction was found between the two factors for first fixation proportion, $F(1, 57) = 0.01$, $p = .933$, $\eta^2 = .00$, 90% CI [.00, .01], first fixation latency, $F(1, 57) = 0.71$, $p = .404$, $\eta^2 = .01$, 90% CI [.00, .09], or dwell time, $F(1, 57) = 0.52$, $p = .475$, $\eta^2 = .01$, 90% CI [.00, .09]. In brief, we were not able to find a link between social anxiety symptoms and EMs on faces using traditional indices.

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Supplementary Table

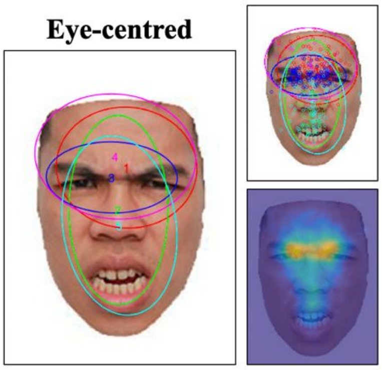
Table S1. *Means (SD) of Traditional EM indices for Angry and Neutral Faces*

	HSA (n = 33)		LSA (n = 27)	
EM Indices	Angry Faces	Neutral Faces	Angry Faces	Neutral Faces
Proportion of first fixations on the eyes	.33 (.18)	.32 (.21)	.35 (.16)	.33 (.17)
Latency of first fixation on the eyes (ms)	869.35 (454.20)	822.98 (449.11)	936.32 (498.47)	801.41 (493.55)
Total dwell time on the eyes (ms)	.46 (.03)	.49 (.03)	.44 (.03)	.45 (.04)

Note. SD = Standard Deviation. Total dwell time on the eyes was calculated in relation to total dwell time on the face.

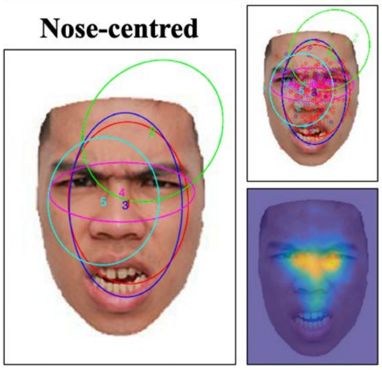
Supplementary Figures

Eye-centred



	To Red	To Green	To Blue	To Purple	To Cyan
Prior	.40	.12	.24	.01	.23
From Red	.92	.07	.00	.01	.00
From Green	.03	.53	.30	.10	.04
From Blue	.00	.18	.78	.03	.00
From Purple	.14	.14	.00	.72	.00
From Cyan	.00	.00	.00	.00	.99

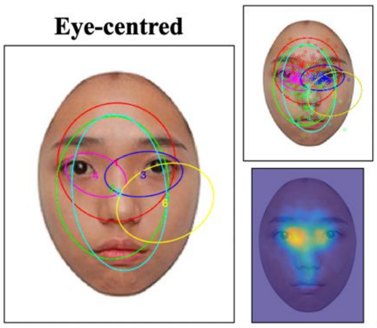
Nose-centred



	To Red	To Green	To Blue	To Purple	To Cyan
Prior	.66	.01	.25	.00	.08
From Red	1.0	.00	.00	.00	.00
From Green	.12	.88	.00	.00	.00
From Blue	.14	.00	.38	.48	.00
From Purple	.00	.00	.22	.78	.00
From Cyan	.00	.00	.00	.00	1.0

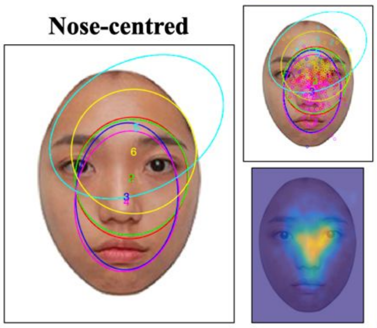
Figure S1 The eye-centred and nose-centred patterns for angry-face-viewing. Each representative HMM is illustrated by the distribution of ROIs. The smaller images show the assignment of actual fixations to different ROIs and the corresponding heatmap. The transition probabilities of eye movements among the ROIs are summarised in the transition matrix. The priors in each matrix show the probability that first fixations in each trial located at each ROI. We have obtained permission to use the face images in the current manuscript from the people in the photos.

Eye-centred



	To Red	To Green	To Blue	To Purple	To Cyan	To Yellow
Prior	.40	.26	.00	.00	.31	.02
From Red	.97	.03	.00	.00	.00	.00
From Green	.00	1.0	.00	.00	.00	.00
From Blue	.00	.00	.09	.55	.36	.00
From Purple	.00	.00	.53	.11	.37	.00
From Cyan	.02	.06	.15	.32	.45	.00
From Yellow	.00	.00	.00	.00	.00	1.0

Nose-centred



	To Red	To Green	To Blue	To Purple	To Cyan	To Yellow
Prior	.37	.00	.28	.15	.03	.17
From Red	.73	.24	.02	.00	.00	.00
From Green	.35	.64	.00	.00	.00	.00
From Blue	.18	.02	.37	.42	.00	.00
From Purple	.00	.00	.04	.96	.01	.00
From Cyan	.00	.00	.00	.07	.93	.00
From Yellow	.00	.00	.01	.01	.00	.98

Figure S2 The eye-centred and nose-centred patterns for neutral-face-viewing.

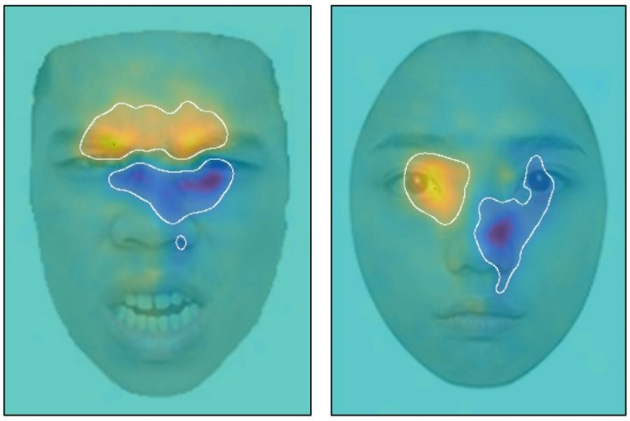
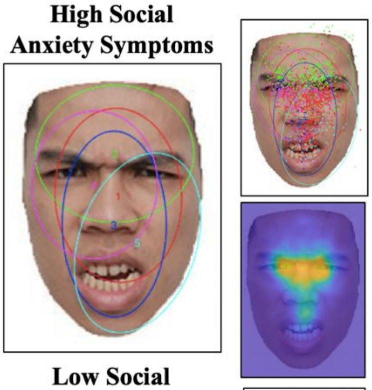


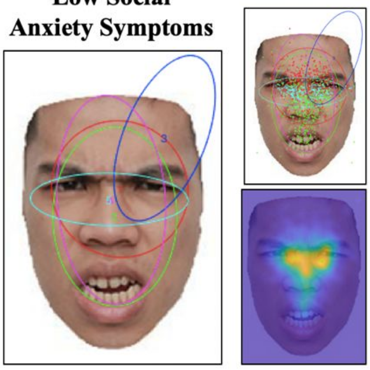
Figure S3 The Difference heatmaps between eye-centred pattern and nose centred pattern for angry- and neutral-face viewing. Red and blue regions indicate positive and negative differences in fixation density between the two patterns.

High Social Anxiety Symptoms



	To Red	To Green	To Blue	To Purple	To Cyan
Prior	.56	.28	.00	.13	.03
From Red	.99	.00	.00	.00	.00
From Green	.00	.89	.11	.00	.00
From Blue	.13	.39	.47	.02	.00
From Purple	.00	.00	.00	1.0	.00
From Cyan	.04	.00	.00	.00	.95

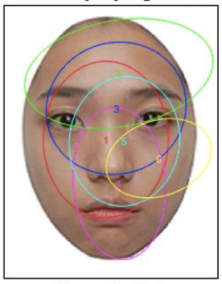
Low Social Anxiety Symptoms

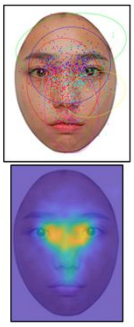


	To Red	To Green	To Blue	To Purple	To Cyan
Prior	.45	.34	.01	.20	.00
From Red	.97	.03	.00	.00	.00
From Green	.00	1.0	.00	.00	.00
From Blue	.00	.01	.99	.00	.00
From Purple	.29	.12	.00	.06	.53
From Cyan	.00	.00	.00	.07	.93

Figure S4 The eye movement patterns for angry-face-viewing in people with high and low social anxiety symptoms.

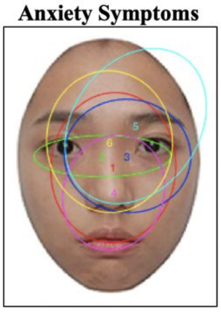
High Social Anxiety Symptoms

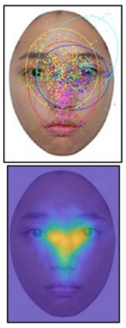




	To Red	To Green	To Blue	To Purple	To Cyan	To Yellow
Prior	.43	.02	.27	.04	.23	.01
From Red	.99	.01	.00	.00	.00	.00
From Green	.13	.87	.00	.00	.00	.00
From Blue	.02	.00	.97	.00	.00	.00
From Purple	.00	.00	.01	.83	.17	.00
From Cyan	.00	.00	.00	.03	.96	.00
From Yellow	.00	.00	.00	.00	.00	1.0

Low Social Anxiety Symptoms





	To Red	To Green	To Blue	To Purple	To Cyan	To Yellow
Prior	.48	.01	.18	.13	.04	.15
From Red	.98	.02	.00	.00	.00	.00
From Green	.05	.95	.00	.00	.00	.00
From Blue	.00	.00	.99	.00	.00	.00
From Purple	.01	.00	.00	.98	.00	.00
From Cyan	.00	.00	.00	.00	1.0	.00
From Yellow	.01	.00	.00	.00	.00	.99

Figure S5 The eye movement patterns for neutral-face-viewing in people with high and low social anxiety symptoms.

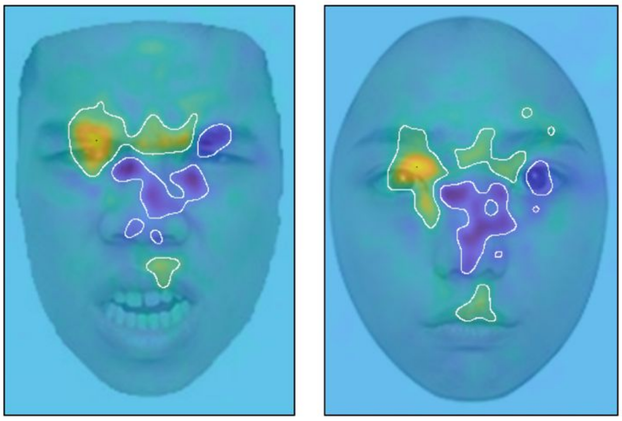


Figure S6 The Difference heatmaps between people with high and low social anxiety symptoms for angry- and neutral-face viewing.