EDITOR'S CHOICE

Individuals with insomnia misrecognize angry faces as fearful faces while missing the eyes: an eye-tracking study

Jinxiao Zhang, Antoni B Chan, Esther Yuet Ying Lau, Janet H Hsiao

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Abstract

Individuals with insomnia have been found to have disturbed perception of facial expressions. Through eye movement examinations, here we test the hypothesis that this effect is due to impaired visual attention functions for retrieving diagnostic features in facial expression judgments. Twenty-three individuals with insomnia symptoms and 23 controls without insomnia completed a task to categorize happy, sad, fearful, and angry facial expressions. The participants with insomnia were less accurate in recognizing angry faces and misidentified them as fearful faces more often than the controls. A hidden Markov modeling approach for eye movement data analysis revealed that when viewing facial expressions, more individuals with insomnia adopted a nose–mouth eye movement pattern focusing on the vertical face midline while more controls adopted an eyes–mouth pattern preferentially attending to lateral features, particularly the two eyes. As previous studies found that the primary diagnostic feature for recognizing angry faces is the eyes while the diagnostic features for other facial expressions involve the mouth region, missing the eye region may contribute to specific difficulties in recognizing angry facial expressions, consistent with our behavioral finding in participants with insomnia symptoms. Taken together, the findings suggest that impaired information selection through visual attention control may be related to the compromised emotion perception in individuals with insomnia.

insomnia, eye-tracking, hidden Markov model, facial expression, visual attention control

Statement of Significance

We were the first to use an eye-tracking approach to understand the mechanism underlying impaired recognition of emotional facial expressions in individuals with disturbed sleep. In contrast to traditional methods of eye movement data analysis that only focus on group-level analysis of fixation locations, we used a state-of-the-art, machine-learning based approach (i.e. Eye Movement analysis with Hidden Markov Models, EMHMM) that accounts for individual differences in both spatial and temporal information of eye movements and enables quantitative measurements of eye movement pattern similarities. Through this analysis, we discovered for the first time in the literature the potential role of visual attention control in accounting for disturbed emotional perception in individuals with insomnia.

Introduction

Sleep loss is closely related to a range of emotional dysfunctions (for reviews, see ref. 1). In particular, compromised perception of emotional facial expressions, which has an important role in one's socioemotional functioning, has been frequently found among sleep-deprived individuals or those with insomnia symptoms. Nevertheless, existing studies are inconsistent in identifying the specific facial emotions that are most susceptible to the detrimental effects of sleep loss [2]. For example, Huck and colleagues [3] firstly reported that sleep deprivation reduced the overall performance on a task of categorizing six basic facial emotions but did not report any emotion specificity. van der Helm and colleagues [4] found reduced intensity ratings of angry and happy facial emotions (in the mid-intensity range) following sleep deprivation but null effect in sad faces. Killgore et al. reported that individuals after sleep deprivation were less accurate in recognizing happy and sad faces particularly [2]. Another study found that 31.5 hr sleep deprivation led to less accurate identification of sad faces but not happy, angry, or fearful faces [5]. In addition, an fMRI study found that sleep-deprived participants were more likely to classify facial expressions as threatening in an angry-neutral face discrimination task, and this effect was coupled with their diminished neural discrimination between threatening and neutral stimuli (in the anterior cingulate and anterior insula) [6]. Similarly, in insomnia research, individuals with physiological insomnia were found to rate fearful and sad faces as less emotional compared with good sleepers, and no difference in emotional intensity ratings was found in happy or angry faces [7]. Crönlein et al. reported that patients with physiological insomnia were less accurate to recognize happy and sad faces [8]. However, Kyle and colleagues did not find any difference in emotion categorization accuracy between the participants with insomnia and those with good sleep [7]. Thus, the underlying mechanism for the disturbed perception of emotional facial expressions due to sleep loss remains unclear [7].

In addition to emotional functioning, individuals with insomnia and sleep-deprived individuals are commonly found to have impaired performance in visuospatial attention tasks. For instance, after sleep deprivation, healthy participants were found to perform worse on visual attention tasks of tracking moving balls [9] and of shifting attention towards different orientations [10]. Similarly, people with insomnia were found to have selective attention bias to sleep-related stimuli [11] and difficulty maintaining visual attention to target stimuli [12]. Recent eye-tracking data also showed that compared with normal sleepers, individuals with insomnia over-attended to tired faces relative to neutral faces [13]. Such behavioral impairment in visuospatial attention control after sleep loss was associated with attenuated activation in the attention neural network comprising the prefrontal, parietal, and cingulate cortex as shown in fMRI studies [9, 10]. Of note, attenuated activations in the attention network were reported to be associated with less explorative eye movement patterns (i.e. holistic patterns, which focus at the face center but not the eye region) and worse performance in face recognition [14]. It is conceivable that individuals with sleep loss are more likely to adopt less explorative eye movement patterns compared with sleep-satiated individuals in emotional facial expression judgments as a result of their impaired visual attention control, leading to compromised recognition performance. Given the prominent role of visual attention in a variety of cognitive functions, it is of paramount importance to elucidate the impact of sleep loss on visual attention and its resultant behavioral deficits.

Here we aim to investigate the role of visual attention functions in accounting for compromised identification of emotional facial expressions in individuals with insomnia through eye-tracking. Individuals with and without insomnia symptoms completed an emotional facial expression judgment task, in which they were required to recognize emotional facial expressions and to rate the emotional intensity with eye tracking. To follow an earlier study investigating the recognition of facial happiness, sadness, fear, and anger in insomnia [7], here we examine participants' perception of these four facial expressions. The choice of the four expressions, instead of Ekman's six basic facial emotions [15], was also in line with a recent finding suggesting four latent and culturally common facial expression categories: "happiness," "sadness," "fear/surprise," and "anger/disgust" [16].

Although eye movements are important measures for visual attention functions, recent studies have reported substantial individual differences in eye movements in visual tasks (e.g. ref. 17), which were not adequately reflected in most of the current analysis methods. In view of this, Chuk, Chan, and Hsiao [18] have recently proposed a Hidden Markov Model (HMM, a type of time-series probabilistic model in machine learning)–based approach for analyzing eye movement data (Eye Movement analysis with Hidden Markov Models, EMHMM). This approach assumes that the current eye fixation during a task is conditioned on previous fixations. Thus, eye movements during the task can be considered a Markov process, which can be better understood using HMM. In this approach, each individual's eye movements are modeled with an HMM, including both person-specific regions of interests (ROIs) and transitions among the ROIs. Thus, it reflects individual differences in both spatial and temporal dimensions of eye movements. Individual HMMs can be clustered to discover common patterns among individuals [19], and similarities between individual eye movement patterns can be quantitatively assessed by calculating the likelihoods of the patterns being generated by a given HMM. Thus, this approach is especially suitable for examining the relationship between eye movement patterns and other outcome measures such as task performance and cognitive abilities [20, 21]. Here we aim to apply this method to examine the relationship among insomnia, eye movements, and performance in facial expression categorization.

We hypothesized that the majority of individuals with insomnia would adopt less explorative eye movement patterns that mainly attended to the face center but overlooked some diagnostic facial features, particularly the eye region, due to poor top-down visual attention control [9, 10, 14]. Recent research using the Bubbles technique has revealed that the diagnostic information for identifying each facial emotion is located in different face regions: a smiling mouth for “happiness,” the eye brows and corners of the mouth for “sadness,” and the eye region for both “fear” and “anger” (i.e. wide opened vs. frowned eyes) [22, 23]. Accordingly, individuals with insomnia may have particular difficulties in distinguishing angry and fearful expressions due to insufficient attention to the eye region.

Methods

Participants

Twenty-three individuals with insomnia symptoms and 23 controls without insomnia symptoms (total sample size = 46, estimated according to a power analysis with effect size $f = 0.25$, $\alpha = .05$, power = .80) grouped by the Chinese version of Sleep Condition Indicator (SCI) [24, 25] were recruited (Table 1). They were all students recruited from a university campus via mass email advertisement and a departmental participant pool. Participants in the two groups were individually matched in gender and age (absolute age difference ≤ 1). They were ethnically Chinese from Hong Kong and right-handed (Edinburgh Handedness Inventory, EHI) [26]. At the time of data collection, they reported to have normal or corrected-to-normal vision and no history of head trauma or psychiatric conditions. One left hander was excluded from the original sample. One more participant was excluded because of data loss.

Table 1.

Participants’ demographics and sleep conditions

	Control (*n* = 23)	Insomnia (*n* = 23)	Comparison test
Age (*M* ± *SD*)	18.91 ± 0.90	18.74 ± 0.81	$t(44) = .689$
Gender (%male)	30.43%	30.43%	$\chi^2(1) = 0$
SCI (*M* ± *SD*)	27.61 ± 1.80	15.70 ± 2.94	$t(44) = 16.54$**

SCI = Sleep Condition Indicator.

*$p < .05$; **$p < .01$.

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Materials

Sleep condition indicator

A validated Chinese version of the SCI was used to assess the participants’ self-reported insomnia symptoms [24]. The SCI asks eight items concerning an individual’s sleep condition during the recent month in a 0–4 Likert-style, with an item score of ≤2 considered as an item-wise insomnia symptom and an item score of ≥3 as no insomnia symptom. The Chinese SCI has been validated and recommended as a screening tool for clinical insomnia with an original insomnia/noninsomnia cutoff at 21/22 [25]. To increase the contrast between the two groups, the SCI criteria score for controls were moved from 22 to 24 to get average item score of ≥3 (control group), and accordingly the criteria score for individuals with insomnia symptoms were moved from 21 to 19 (insomnia group). The short-form SCI contains two most important items indexing insomnia symptoms (item 3: poor sleep nights per week and item 7: extent troubled by sleep problems) in the 8-item SCI [24]. Accordingly, we further excluded individuals in the control group whose item 3 and item 7 scores fell below 3, and those in the insomnia group whose item 3 and item 7 scores were greater than 3. Compared with the original cutoff at 21/22, our grouping method further excluded eight participants from analysis. This exclusion occurred after we checked the distribution of SCI score and before statistical analyses. It should be noted that participants in the insomnia group were with insomnia symptoms but not necessarily with insomnia disorder. In our sample, according to the SCI-item score threshold criteria for insomnia disorder (score ≤ 2), 16 participants scored at the threshold for item 1, 8 for item 2, 17 for item 3, 23 for item 4, 14 for item 5, 20 for item 6, 14 for item 7, and 16 for item 8.

Facial expression pictures

Pictures of happy, sad, fearful, and angry expressions of 26 models were selected from a database of emotional facial expressions made in our laboratory (104 pictures in total, resolution: 750 × 1000 pixels). Pictures from 20 models were used in the experimental task, and those from the remaining 6 models were used in the practice session. The pictures were taken from young Asian adults (age 18–32, half male and half female) in a white T-shirt with a white background. The face models sat in front of a camera fixed on a tripod at a distance of 2 m. They were instructed to express different emotions. To capture genuine facial expressions, emotions were induced through viewing pictures, watching video clips, listening to music, and/or recalling personal events. The face models were given sufficient time to arouse their emotions. The photographer monitored and captured the face models' facial expressions using a remote control. The head size was adjusted and the facial features (eyes, nose, and mouth) were aligned according to the standards of the FACES database [27] and the Radboud database [28]. The luminance and contrast of the pictures were matched using the Shine Matlab toolbox. We validated the quality of the pictures by inviting raters (n = 13) to rate the emotional intensity, genuineness, and perceived age of the models. The mean ratings of emotional intensity of the pictures (from low intensity to high intensity in 1–5 scale) were 3.48 for happiness, 3.18 for sadness, 3.81 for fear, and 3.40 for anger. The mean ratings of genuineness of the pictures (from low genuineness to high genuineness in 1–5 scale) were 3.79 for happiness, 2.91 for sadness, 3.35 for fear, and 3.12 for anger. The models were all rated as young adults (25.7 for happiness, 26.6 for sadness, 27.2 for fear, and 26.8 for anger). In the current experiment, for each facial expression, 6 pictures were used in practice and 20 were used in the test.

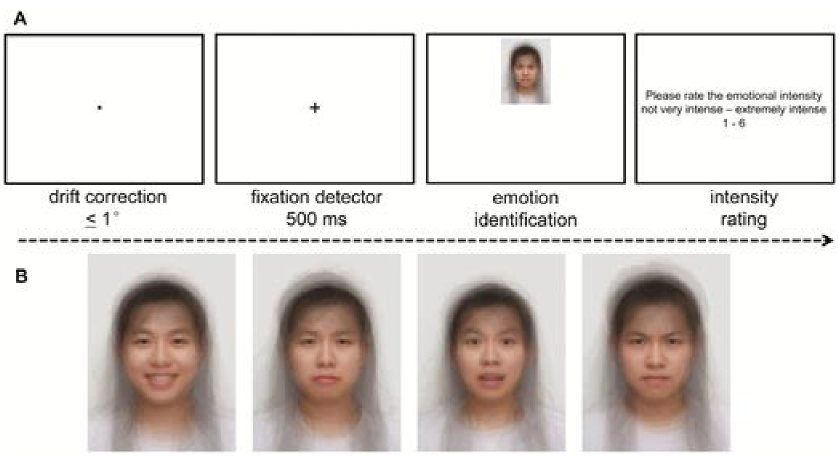
Eye tracking equipment

Eye movements of participants' dominant eye during the task were recorded by an EyeLink 1000 eye tracker. The standard 9-point calibration procedure was conducted at the beginning of each task block and was repeated whenever the drift-correction error was larger than 1° of visual angle. The tracking mode was pupil and corneal reflection and the sampling rate was 2000 Hz. During the task, the participants' chins were rested on a chinrest at a distance of 60 cm from a 22 inch monitor (resolution: 1024 × 768 pixels).

Procedures

This study was approved by the Human Research Ethics Committee at The University of Hong Kong. After giving informed consents, the participants firstly completed electronic forms of demographic information, the EHI, and the SCI. Then the participants completed an emotional facial expression judgment task adapted from Kyle et al. [7], which required participants to identify and rate emotional intensity of four emotional facial expressions (i.e. happiness, sadness, fear, and anger; Figure 1A). The task consisted of two blocks with 40 trials in each block (10 trials for each expression). In each trial, a solid dot first appeared at the screen center for drift correction, and it was replaced by a fixation cross for 500 ms. Once a fixation was detected at the fixation cross at the end of the 500 ms, a color picture of an Asian individual's face with an emotional facial expression (Figure 1B; 450 × 600 pixels) was presented either above or below the center of the screen until the participants categorized it as a happy, sad, fearful, or angry face by pressing corresponding buttons. Participants were asked to respond as quickly as possible. After a 250 ms pause, they were asked to rate the emotional intensity of the facial expression on a 6-point scale, ranging from "1-not very intense" to "6-extremely intense." All responses were made on an RB-840 Cedrus Response Pad. The faces spanned around 8° of visual angle at the viewing distance of 60 cm [29]. The participants had a practice session of 24 trials (6 trials for each expression) at the beginning of the task. Pictures were presented in a random order within each block and the order of the two blocks was counterbalanced across participants.

Figure 1.



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(A) A demonstration of a trial with an angry face. There are 40 trials (10 trials for each emotion) in either of the two blocks in the task. Each trial begins with a drift correction, followed by a cross fixation detector. Then the participants made responses in emotion identification and intensity rating. (B) The average pictures of the 20 stimuli used in each emotion. Half of the stimuli were from young Asian male adults and the other half are from young Asian female adults. From left to right: happiness, sadness, fear, and anger.

Data processing and analysis

Behavioral data

The behavioral performances of the two groups in the emotional face task (i.e. accuracy, response time, and intensity rating) were compared by repeated-measures ANOVAs to examine the effects of group (control vs. insomnia) and emotion (happy vs. sad vs. fearful vs. angry). Significant interactions and main effects in repeated-measures ANOVA were followed by post hoc independent *t*-tests between the two groups in each emotion or pairwise comparisons with Bonfferoni–Sidak adjustments.

Eye movement data

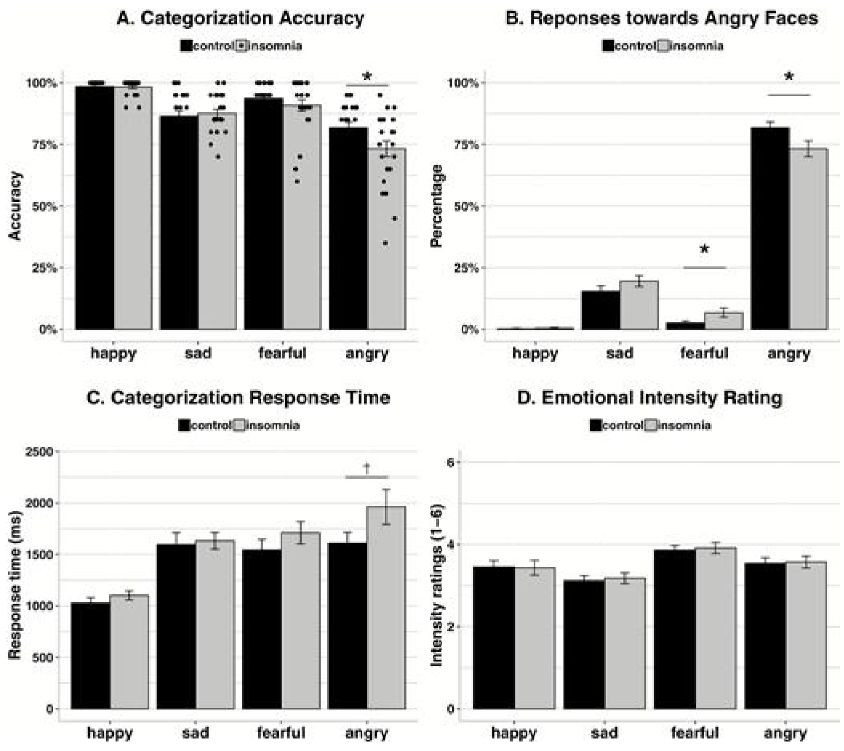
The eye movement data were analyzed using the EMHMM (Eye Movement analysis with Hidden Markov Models, http://visal.cs.cityu.edu.hk/research/emhmm/) [18] approach. (The processing procedures and algorithms are summarized in Supplementary Figure S1.) First, each participant's eye movements while viewing facial expressions were summarized with an HMM, including person-specific ROIs and transition probabilities among the ROIs. The optimal number of ROIs for each model was determined automatically through a variational Bayesian approach, by selecting the model with the highest marginal likelihood. Second, we clustered all 46 individual HMMs (one for each participant) into two groups according to their similarities using the variational hierarchical expectation-maximization (VHEM) algorithm [16]. Third, each group of individual HMMs was summarized into a representative eye movement pattern described using an HMM with group-specific ROIs and transition probabilities among the ROIs. We examined the frequency of individuals adopting the two representative eye movement patterns in the control and insomnia participant groups, and the correlations between similarity of their eye movement patterns to each representative pattern (measured with log-likelihood) and their behavioral performances.

Results

Behavioral results

A 2 (group: control vs. insomnia) by 4 (emotion: happy vs. sad vs. fearful vs. angry) repeated measures ANOVA revealed a significant interaction between group and emotion on the accuracy of the facial expression judgment task, $F(3, 132) = 2.68$, $p = .049$, $\eta_p^2 = .057$. Independent *t*-tests between the insomnia group and the control group in each emotion condition indicated that there was 8.4% higher accuracy on average to identify angry faces in the control group than the insomnia group, $t(44) = 2.12$, $p = .039$, Cohen's $d = .63$ (Figure 2A). This group difference was not found in other emotion conditions, p's > .05. There was also a significant main effect of emotion on the accuracy, $F(3,132) = 246.58$, $p < .001$, $\eta_p^2 = .514$. Adjusted post hoc pairwise comparisons indicated that the accuracy for recognizing emotional faces from the highest to the lowest was happy faces ($M = .984$, $SD = .033$), fearful faces ($M = .923$, $SD = .088$), sad faces ($M = .871$, $SD = .090$), and angry faces ($M = .775$, $SD = .140$), all p's < .05 (Figure 2A). There was no significant effect of group, $F(1, 44) = 2.53$, $p = .119$. To understand what led to the difference in recognizing angry faces between the two groups, we moved on to examine the responses participants made towards angry faces (Figure 2B; for other expressions, see Supplementary Figure S2). The 2 (group: control vs. insomnia) by 4 (response: happy vs. sad vs. fearful vs. angry) repeated measures ANOVA indicated a significant interaction between group and response, $F(3, 132) = 3.57$, $p = .016$, $\eta_p^2 = .075$. Between-group *t*-tests showed a significantly higher percentage of "fearful" responses in the insomnia group (6.74% ± .088) than the control group (2.61% ± .037), $t(44) = 2.07$, $p = .045$, Cohen's $d = .62$. Adjusted post hoc comparisons of the main effect of response ($F(3,132) = 515.82$, $p < .001$, $\eta^2 = .921$) indicated that the percentage of responses towards angry faces from the highest to the lowest was angry, sad, fearful, and happy, all p's < .05. Note that the low percentage of fearful responses towards angry faces in the control group (2.61%) suggested that angry expressions are rarely misidentified as fearful in a healthy person. Thus, compromised identification due to insomnia, although the error rate was only increased slightly (6.74%), could lead to a large effect size and affect daily life. Another contributing factor was the selective increase in misidentifying angry faces as fearful but not as any other expressions.

Figure 2.



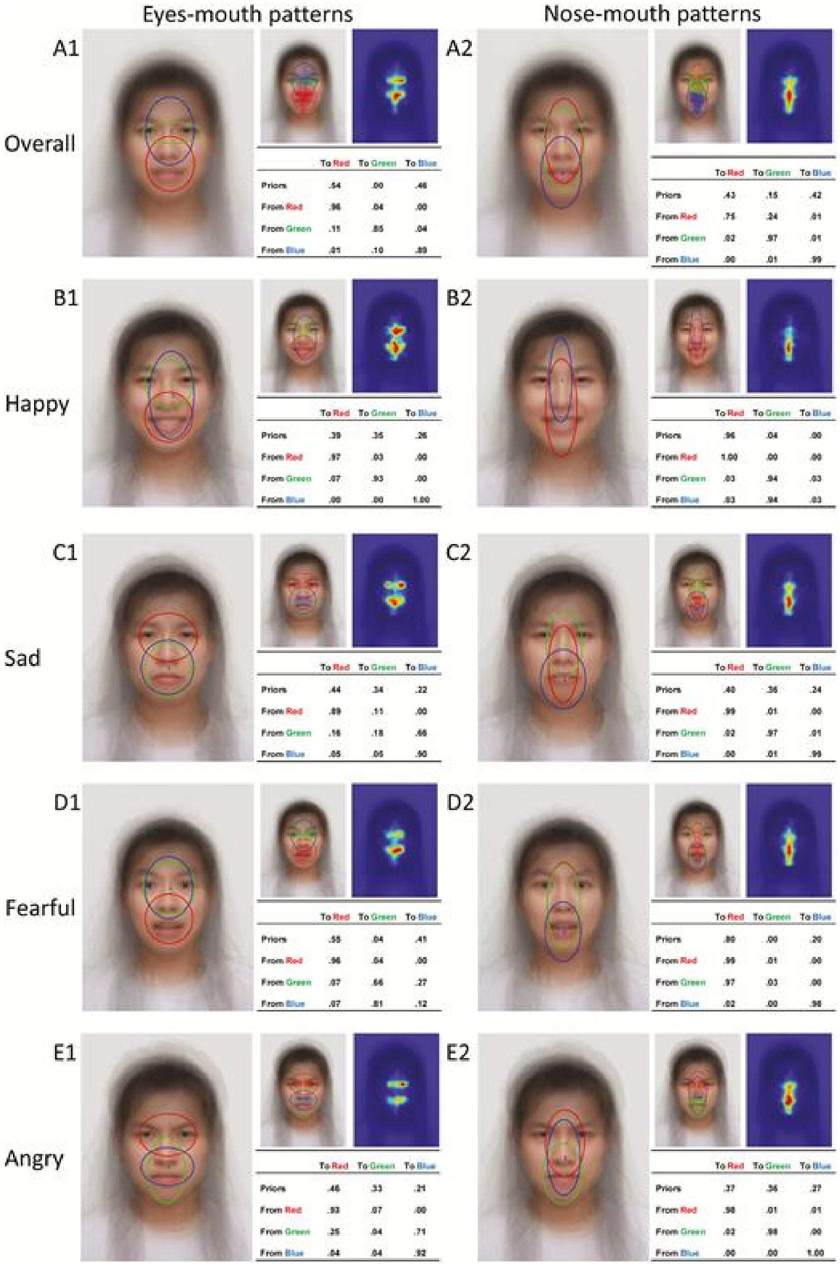
(A) The accuracy to identify happy, sad, fearful, and angry facial emotions in the control and the insomnia group (black dots represent individual data points). The insomnia group had a lower accuracy to identify angry faces than the control group. (B) Reponses made while angry faces were presented. Individuals with insomnia gave more mistaken "fearful" response than controls. (C) Response time to accurately identify emotional facial expressions. The insomnia group was marginally 350 ms slower than the control group to identify angry faces. (D) Emotional intensity rating of the four facial emotions in the two groups. (*$p < .05$; $^{\dagger}.05 < p < .10$; error bars: 1 s.e.m.).

In the data of response time (RT) for correct responses in the expression categorization task (Figure 2C), a 2 (group) by 4 (emotion) repeated measures ANOVA indicated a main effect of emotion, $F(3, 132) = 40.72$, $p < .001$, $\eta_p^2 = .48$. Post hoc pairwise comparisons revealed that the response time to happy faces was significantly shorter than the other three emotions, p's < .05, but there was no significant difference in the response time to identify sad, fearful, or angry faces. There was no main effect of group or interaction effect between group and emotion. When we examined the difference between the two groups in identifying different expressions separately, there was a trend that the insomnia group identified angry faces slower than the control group, $t(44) = 1.768$, $p = .084$, Cohen's $d = .53$. The group by emotion repeated measures ANOVA on emotional intensity rating showed a main effect of emotion (fearful > happy, angry > sad; Figure 2D), $F(3, 132) = 23.24$, $p < .001$, $\eta_p^2 = .35$. However, there was no main effect of group or group by emotion interaction.

Eye movement data

We modeled each participant's eye movements with an HMM for viewing all facial expressions and also for viewing each type of facial expressions separately. For all expressions combined together or each expression type, we clustered all participants' HMMs into two representative patterns according to their similarities and examined the frequencies of the participants with insomnia and without insomnia adopting the two patterns. The clustering results showed that in one of the representative patterns, participants looked primarily at the areas along the face midlines, particularly the region between the nose and the mouth, whereas in the other pattern, participants looked at lateral features more often, particularly the eyes, in addition to the midline/nose region (Figure 3). For the current purposes, we termed them "nose-mouth pattern" and "eyes-mouth pattern," respectively. We also examined whether the control and the insomnia groups differed in the number of fixations required for identifying the facial expressions (Table 2) and found that the two groups made similar numbers of fixations per trial across all facial expressions, all p's > .05.

Figure 3.



Representative eye movement patterns during facial expression recognition discovered through HMM clustering. (A1 and A2) The eyes–mouth and nose–mouth patterns for overall facial expression viewing. (B1 and B2) The eyes–mouth and nose–mouth patterns for viewing happy facial expressions. (C1 and C2) The eyes–mouth and nose–mouth patterns for viewing sad facial expressions. (D1 and D2) The eyes–mouth and nose–mouth patterns for viewing fearful facial expressions. (E1 and E2) The eyes–mouth and nose–mouth patterns for viewing angry facial expressions. There are three images and a table illustrating each representative pattern. Three images from left to right: three elliptical ROIs in three colors, assignments of the actual fixations to the ROIs, and a heat map of the eye fixations. The tables indicate the priors (i.e. the probability of the first fixation in each trial landed in each region) and transition probabilities of eye movements among the ROIs.

Table 2.

Average number of fixations during facial expression categorization in the control and insomnia group

	All trials		Correct trials	
	Control	Insomnia	Control	Insomnia
Overall	4.17 ± 1.21	4.23 ± 1.52	3.99 ± 1.15	4.07 ± 1.52
Happy	2.90 ± 0.83	2.92 ± 1.18	2.88 ± 0.81	2.92 ± 1.17
Sad	4.71 ± 1.51	4.49 ± 1.68	4.43 ± 1.40	4.23 ± 1.62
Fearful	4.58 ± 1.49	4.64 ± 1.82	4.49 ± 1.52	4.55 ± 1.67
Angry	4.51 ± 1.54	4.81 ± 2.03	4.34 ± 1.44	4.81 ± 2.46

Number of fixations per trial for the overall task and for viewing each facial expression are listed for all trials and only correct trials in a format of *M* ± *SD*.

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Overall face viewing

Figure 3A shows the two representative patterns while viewing all emotional facial expressions. The three ROIs are in red, green, and blue, respectively, and the table shows the priors (the probability of the first fixation being located at an ROI) of the ROIs and the transition probabilities among them. In the eyes–mouth pattern (Figure 3A1, $n = 19$), the first fixation was likely to be either in the lower part of the face (red ROI, 54%) covering the nose tip and the mouth region, or the upper part of the face (blue ROI, 46%) covering mostly the eyes and the nose bridge. The subsequent fixations were most likely to stay in the same ROI, but they also moved to a narrower eye region occasionally (green ROI; from red ROI to green ROI, 4%; from blue ROI to green ROI, 10%). In the nose–mouth pattern (Figure 3A2, $n = 27$), all three ROIs were along the central midline of a face from the medial forehead to the chin but did not expand to lateral regions, in particular, the eyes. Fixations were most likely to start from the face center around the nose (red and green ROI, 58%), or slightly less likely from the lower part of the face around the mouth (blue ROI, 42%). After the first fixation was made, subsequent fixations stayed in the same area. To summarize the two representative patterns while viewing emotional facial expressions in general, the eyes–mouth pattern attended to both the upper face covering the eyes and the lower face, whereas the nose–mouth pattern only attended to areas around the face midline. When viewing emotional facial expressions, the control group and the insomnia group differed significantly in their frequencies of adopting the two representative patterns, $\chi^2(1) = 4.39$, $p = .036$, with more controls (56.5%) adopting eyes–mouth patterns and more individuals with insomnia (73.9%) adopting nose–mouth patterns (Table 3). Note that this group difference was not readily observable using a traditional ROI analysis: when we examined the number of fixations and total fixation duration in a set of predetermined, commonly used facial ROIs (eyes, corrugator, nose, and mouth; Supplementary Figure S3), no significant difference was found between the two groups, all p's > .05 (Supplementary Tables S1 and S2). Of note, individuals adopting eyes–mouth patterns (accuracy: 84.5% ± .091) were more accurate to recognize angry faces than those adopting nose–mouth patterns (accuracy: 72.6% ± .150), $t(44) = 3.078$, $p = .004$, Cohen's $d = .93$, suggesting the advantage of eyes–mouth patterns for identifying angry faces. This effect was not observed in identifying happy, sad, or fearful faces. Indeed, the corrugator region, which signals anger, was better captured in the eyes–mouth pattern (the blue ROI in Figure 3A1) than in the nose–mouth pattern. To further examine this link between eye movement pattern and facial expression identification accuracy, we performed a trial-level analysis. More specifically, we classified the eye movement pattern in each trial where an angry face was presented across all participants into either the eyes–nose pattern or the nose–mouth pattern according to its similarity to the two representative patterns (i.e. as measured in the log-likelihood of being generated by the representative model). We found that among the trials where an eyes–nose pattern was used, there was a higher percentage of correct trials (344/425 trials, 80.9%) when compared with the trials where a nose–mouth pattern was used (348/467 trials, 74.5%; $\chi^2(1) = 5.28$, $p = .022$). These results were consistent with the previous finding that the eye region contains the most diagnostic information for angry expression recognition [22, 23].

Table 3.

Frequencies of participants in the control and the insomnia group adopting analytic and holistic patterns for overall face viewing and for viewing each emotional facial expression (happy, sad, fearful, and angry)

		Control (n = 23)	Insomnia (n = 23)	Total	Chi-square test
Overall	Eyes–mouth patterns	13 (56.5% control)	6 (26.1% insomnia)	19	$\chi^2(1) = 4.39^*$, p = .036
	Nose–mouth patterns	10 (43.5% control)	17 (73.9% insomnia)	27	
Happy	Eyes–mouth patterns	13 (56.5% control)	8 (34.8% insomnia)	21	$\chi^2(1) = 2.19$, p = .139
	Nose–mouth patterns	10 (43.5% control)	15 (65.2% insomnia)	25	
Sad	Eyes–mouth patterns	14 (60.9% control)	7 (30.4% insomnia)	21	$\chi^2(1) = 4.29^*$, p = .038
	Nose–mouth patterns	9 (39.1% control)	16 (69.6% insomnia)	25	
Fearful	Eyes–mouth patterns	17 (73.9% control)	8 (34.8% insomnia)	25	$\chi^2(1) = 7.10^{**}$, p = .008
	Nose–mouth patterns	6 (26.1% control)	15 (62.5% insomnia)	21	
Angry	Eyes–mouth patterns	12 (52.2% control)	5 (21.7% insomnia)	17	$\chi^2(1) = 4.57^*$, p = .032
	Nose–mouth patterns	11 (47.8% control)	18 (78.3% insomnia)	29	

*p < .05; **p < .01.

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Apart from examining the overall facial expression perception, we also studied the eye movement patterns for viewing each expression type given that the way people look at different facial expressions may be different. The eyes–mouth and nose–mouth patterns for recognizing each expression type discovered from HMM clustering were similar to the overall patterns.

Happy face viewing

Figure 3B shows the two representative patterns while viewing happy facial expressions. In the eyes–mouth pattern (Figure 3B1, n = 21), the first fixation was most likely to be in the lower face covering the mouth corners and the nose tip (red ROI, 39%), or the upper face region covering the two eyes and the nose bridge (green ROI, 35%). After the first fixation was made, subsequent fixations probably stayed in the same ROI but also occasionally transferred between the red and green ROIs (from red ROI to green ROI, 3%; from green ROI to red ROI, 7%). In the nose–mouth pattern (Figure 3B2, n = 25), the first fixation was around the face midline from the nose bridge to the chin (red ROI, nearly 100%) and subsequent fixations stayed there. To summarize the representative patterns for viewing happy faces, the eyes–mouth pattern looked both the eyes and the mouth region, and the nose–mouth pattern mainly looked at the mouth region but missed the eyes. Although over half of the controls adopted the eyes–mouth pattern (56.5%) and over half of the individuals with insomnia adopted the nose–mouth pattern (65.2%), the distribution of the control and the insomnia group in the two representative patterns did not differ significantly (Table 3).

Sad face viewing.

Figure 3C shows the two representative patterns while viewing sad facial expressions. In the eyes–mouth pattern (Figure 3C1, n = 21), the first fixation was most likely to be at the area of the nose tip and the mouth (green and blue ROI, 56%). It was also likely to be in the eye region (red ROI, 44%). The following fixations mostly stayed in its original area and also transited between the two areas sometimes. In the nose–mouth pattern (Figure 3C2, n = 25), all three ROIs were along the face midline from the forehead to the chin (from top to bottom: green, red, and blue). Fixations in one ROI rarely transited to another ROI (≤ 3%). To summarize the two patterns for viewing sad faces, the eyes–mouth pattern mainly attended to the two eyes and the mouth, whereas the nose–mouth pattern mainly attended to the nose and the mouth. When viewing sad facial expressions, the control group and the insomnia group differed significantly in their frequencies of adopting the two representative patterns, $\chi^2(1) = 4.29$, $p = .038$, with more controls (60.9%) adopting the eyes–mouth pattern and more individuals with insomnia (69.6%) adopting the nose–mouth pattern (Table 3).

Fearful face viewing.

Figure 3D shows the two representative patterns while viewing fearful facial expressions. In the eyes–mouth pattern (Figure 3D1, n = 25), the first fixation was most likely to be at the lower part of the face (red ROI, 55%) and slightly less likely to be at the eyes or the nose bridge (green ROI and blue ROI, 45%). Subsequent fixations also occasionally transited between the two areas (from green/blue ROI to red ROI, 7%; from red to green/blue ROI, 4%). In the nose–mouth pattern (Figure 3D2, $n = 21$), the fixation was most likely to start at the face center (red and green ROI, 80%) or less likely to be around the mouth (blue ROI, 20%). Fixations rarely transited between ROIs. To summarize the two representative patterns for viewing fearful faces, the eyes–mouth pattern mainly look at a wide mouth region and the eyes, whereas the nose–mouth pattern looked at the face center with an emphasis on the mouth. During fearful face viewing, the control group and the insomnia group differed significantly in their frequencies of adopting the two representative patterns, $\chi^2(1) = 7.10$, $p = .008$, with more controls (73.9%) adopting the eyes–mouth pattern and more individuals with insomnia (62.5%) adopting the nose–mouth pattern (Table 3).

Angry face viewing.

Figure 3E shows the two representative patterns while viewing angry facial expressions. In the eyes–mouth pattern (Figure 3E1; $n = 17$), the first fixation was most likely to be around the nose tip and the mouth (green ROI and blue ROI, 54%), or the horizontal elliptical area covering the two eyes (red ROI, 46%). Fixations around the nose and the mouth sometimes transferred to the eyes region (from green ROI to red ROI, 25%). Fixations around the eyes were most likely to stay there (from red ROI to red ROI, 93%). In the nose–mouth pattern (Figure 3E2; $n = 29$), all three ROIs were along the face midline and little transitions happened between the ROIs. Fixations were from the forehead center to the chin but did not cover the two eyes. During angry face viewing, the control group and the insomnia group differed significantly in their frequencies of adopting the two representative patterns, $\chi^2(1) = 4.57$, $p = .032$, with most individuals with insomnia (78.3%) adopting the nose–mouth pattern and over half controls (52.2%) adopting the eyes–mouth pattern (Table 3). Of note, it was found that in the control group, the response time to accurately recognize angry facial expressions was negatively correlated with the similarity of eye movements to the eyes–mouth pattern (as measured in log-likelihood of one's eye movement pattern being classified as the eyes–mouth pattern), $r = -.422$, $p = .045$: the more similar one's eye movement pattern to the eyes–mouth pattern, the faster the recognition of an angry face. This correlation was not significant in the insomnia group.

Discussion

In the current study, we aim to test the hypothesis that the compromised perception of emotional facial expressions in people with insomnia symptoms is related to impaired visual attention functions for selecting diagnostic features as revealed in their eye movements. More specifically, we hypothesized that impaired visual attention control function in people with insomnia symptoms may lead to less explorative eye movement patterns in viewing faces, which may consequently compromise perception of facial expressions, particularly those with diagnostic information in the eye region such as anger and fear. Consistent with our hypothesis, our results showed that individuals with insomnia symptoms were less accurate and marginally slower to identify angry faces than controls without insomnia. Furthermore, participants with insomnia symptoms misrecognized angry faces as fearful faces more often than controls. Through the EMHMM approach for eye movement data analysis [18], we discovered two common eye movement patterns among the participants when viewing emotional facial expressions: a nose–mouth pattern that primarily looked at areas along the face midline (forehead center to nose to mouth center), and an eyes–mouth pattern that fixated at more lateral features such as the two eyes and the mouth corner. Consistent with our hypothesis, significantly more controls adopted the eyes–mouth pattern and more individuals with insomnia adopted the nose–mouth pattern for viewing emotional facial expressions. In addition, individuals adopting the eyes–mouth pattern were more accurate in recognizing angry facial expressions than individuals adopting the nose–mouth patterns (with a large effect size). Together these results suggest that individuals with insomnia misidentified angry faces possibly due to missing the diagnostic feature in the eye region. The EMHMM approach is a data-driven method that reflects individual differences in both spatial and temporal dimensions of eye movements and provides quantitative assessments of similarities among individual eye movement patterns, making it possible to reveal these effects. In contrast to the Bubbles technique, which uses the reverse correlation method to discover diagnostic features for a given task [22], the EMHMM approach summarizes both the spatial and temporal dimensions of participants' eye movements to reveal their information retrieval strategies and requires a much smaller number of trials. Although it is possible to use the Bubbles technique to discover temporal dynamics of diagnostic features [30], the required number of trials increases significantly since the number of combinations of bubbles across time increases exponentially with time. Note that participants with insomnia and control participants made similar numbers of fixations during face viewing, suggesting that the worse recognition of expressions in individuals with insomnia was not simply because they might be too fatigued to make an adequate number of eye fixations.

Our finding is consistent with previous studies suggesting that insomnia and sleep loss are associated with compromised recognition of emotional facial expressions [5, 7]. In particular, previous studies also found altered perception of angry facial emotions due to sleep loss. For instance, participants after sleep deprivation were found to rate subtle angry facial expressions as less emotional than the ratings they gave with 8 hr normal sleep [4]. In another fMRI study, Goldstein-Piekarski and colleagues [6] found that experimental sleep deprivation impaired behavioral as well as neural discrimination of angry faces from neutral faces. Angry facial emotions signal social threats, and thus misidentification or slower detection of angry faces may undermine social interactions of individuals with insomnia. Interestingly, individuals with insomnia were more likely to misrecognize angry faces as fearful faces than controls, suggesting that they may misidentify social threats senders as social threats receivers. Of note, the deficits of the insomnia group in behavioral performance and eye movements in our data are moderate (medium-sized effects), which is consistent with the existing insomnia literature that attention-related daytime impairments of insomnia are generally subtle [31, 32].

The misrecognition of facial anger in individuals with insomnia corresponded to their eye movement patterns. Most of the individuals with insomnia adopted nose–mouth patterns that focused on the vertical face midline while missing the two eyes. In contrast, most controls adopted eyes–mouth patterns that looked at more lateral areas covering both the eyes and the mouth. Since participants adopting eyes–mouth patterns outperformed those adopting nose–mouth patterns in angry face recognition, the impaired recognition of angry faces in individuals with insomnia may be related to their use of nose–mouth patterns. Although the eye region has also been reported to be diagnostic for identifying fearful expressions, in the current study participants with insomnia symptoms did not show impaired fearful expression recognition when compared with controls. We speculated that this result may be because the mouth region also provided diagnostic information for identifying fearful expressions. Indeed, through the "Bubbles" reverse-correlation technique, Smith and colleagues [22] showed that eyes are the most diagnostic feature for recognizing angry expressions, whereas the most diagnostic features for recognizing the other three expressions (i.e. happy, sad, and fearful) are either mainly on the mouth region or comprise both the mouth and the eyes (see also ref. 23). Consistent with this finding, Eisenbarth and Alpers [33] showed that participants looked at the eyes longer than the mouth in recognizing angry and sad expressions, the mouth longer than the eyes for happy expressions, and the mouth and the eyes equally for fear and neutral expressions. The exclusive importance of the eye region for recognizing angry facial expressions may explain why we only observed behavioral performance differences between individuals with insomnia and controls in recognizing angry faces, since identifying other expressions do not require specific attention to the eye region as much as identifying angry expressions. In our eye movement data of the other three facial expressions, both the eyes–mouth and nose–mouth patterns captured at least one diagnostic feature for recognizing the corresponding facial expression. For happy faces, the eyes–mouth pattern and the nose–mouth pattern both captured the mouth region, which was the most salient diagnostic feature (Figure 3B). For sad faces, the nose–mouth pattern captured the mouth and the eyes–mouth pattern captured both the eyes and the mouth to recognize sad expressions (Figure 3C). For fearful faces, similarly, both patterns captured the mouth as a diagnostic feature and the eyes–mouth pattern additionally captured the eyes (Figure 3D). Despite its less vital effects on recognizing facial expressions other than anger, missing the eyes as a source of emotional information in the nose–mouth pattern, which may be adopted by most individuals with sleep loss, may help explain previous findings that individuals with insomnia or after sleep deprivation generally rated facial expressions as less emotionally intense [4, 7]. It should be noted that the above findings about the diagnostic features for facial expression identification were based on western Caucasian faces. Although the four expressions used here corresponded to the four latent and culturally common facial expression patterns discovered in Jack et al.'s analysis [16], future work may examine diagnostic features for Asian facial expression identification through the Bubbles technique to further examine this possibility.

In the literature, biased interpretation of emotional information after sleep loss has typically been attributed to impaired functioning of limbic structures such as amygdala and anterior cingulate cortex and the functional connectivity between the prefrontal cortex and these limbic structures towards emotional stimuli [6, 34]. In addition to this emotional brain network, the current study suggests that impaired attentional functioning may also play an important role in accounting for the misinterpretation of emotional information after sleep loss. Indeed, sleep loss is shown to affect visual attention control and activation in the attention brain network [9, 10]. Decreased activations in the attention brain network (e.g. the frontal eye field and intraparietal sulcus) are associated with maladaptive eye movement patterns and impaired recognition performance during face viewing [14]. Impaired visual attention functions may cause failure of selecting diagnostic information for emotional face perception, leading to biased interpretation of emotional information. Our findings are consistent with those of Cote et al. [5], which showed that impaired facial expression recognition in sleep-deprived individuals was reflected in early visual ERP components including reduced P1 and amplified N170 for all expressions, suggesting general impairment in visual attention functions. Our findings have important implications for clinical practice, as clinical professionals need to be aware of the impact of impaired attention control in socioemotional domains (in addition to cognitive domains) among individuals with insomnia, such as compromised recognition of emotional facial expressions and the consequential challenges in social interactions.

Although the current study only showed impaired recognition of angry expressions in individuals with insomnia, some previous studies have reported disturbed perception of happy, sad, and fearful faces in addition to angry faces in insomnia (e.g. refs. 7 and 8). Cote et al. [5] showed that altered early visual ERP responses due to sleep deprivation were observed for all expressions, whereas difference in identification accuracy between sleep-deprived individuals and controls was only observed in sad faces. This effect suggests that although the modulation of sleep loss in attentional functioning may apply to all expressions in general (leading to a less explorative eye movement pattern), whether it results in decreased recognition accuracy may depend on how it affects selection of diagnostic features, since different facial expressions differ in their diagnostic features [23]. It may also depend on the availability of diagnostic features in the stimuli. For example, in a recent study, Holding et al. reported an overall null effect of sleep loss on the recognition of various human emotions using video stimuli [35]. The video stimuli included much richer cues (i.e. dynamic facial, auditory, and bodily cues) for recognizing human emotions [35] than image stimuli, and thus may not provide adequate opportunity to reveal the consequence of impaired visual attention control on facial expression recognition.

There may also be individual differences in how features are selected and used for recognizing facial expressions. In particular, cultural differences between East Asians and Western Caucasians in facial expression perception have been recently reported. For example, by manipulating facial features independently, Yuki and colleagues [36] found that East Asians relied more on the eyes and Western Caucasians relied more on the mouth when interpreting others' facial expression. In addition, East Asians were also found to have a preference for emotionally expressive information in the eyes region in their mental representation compared with Westerners [37]. Since our sample consisted of East Asians (from Hong Kong), recognition of facial anger might be especially affected because of the exclusive featural importance of the eyes. In contrast, in a sample from Scotland to whom information from the eyes and the mouth may be more equally used [37], Kyle and colleagues [7] did not find difference in recognition accuracy but only in emotional intensity ratings between the participants with insomnia and the controls. Future work will examine these possibilities.

Whereas our current results showed that participants with insomnia symptoms tended to overlook the eye region during facial expression identification, some recent studies have reported that individuals with insomnia had preferential attention to the eye region during passive face viewing [13, 38]. This differential effect of insomnia on eye movement patterns due to task difference suggests that task demand may be an important factor to consider in the examination of sleep loss on visuospatial attention functions. Indeed, in the literature, it has been well demonstrated that eye movement behavior can be significantly altered by task [39, 40], and characteristics of the task can be inferred directly from one's eye movement pattern [17, 41]. Thus, difference in task demand may lead to discordant eye-tracking results across studies. Relatedly, a diversity in tasks may help explain discrepant behavioral findings about how sleep (sleep disorders and sleep deprivation) affects the perception of emotional faces as recently suggested [42].

Note that in addition to impaired visual attention control, insomnia symptoms are usually associated with emotional disturbances such as depression and anxiety [43]. Comparatively, controls without insomnia might have less emotional disturbances. This difference in emotional disturbance between individuals with and without insomnia symptoms might also contribute to their difference in the recognition of emotional facial expressions. Our study is limited in that we did not include measures of emotional symptoms or objective sleep. Data from these measures may help tease apart the contribution from visual attention control and emotional functioning in accounting for the compromised facial expression perception. Another limitation of the current study is that our participants were university students and were classified into insomnia and control groups using a self-reported screening questionnaire. Thus, our findings can only be generalized to other age groups and clinical insomnia populations with caution.

In conclusion, here we showed that individuals with insomnia misrecognize angry expressions because of missing diagnostic features in the eye region. This effect suggests that the impaired perception of facial expressions after sleep loss may be due to diminished visual attention control in addition to impaired emotional functioning. To the best of our knowledge, this is the first to report the role of eye movement in the biased perception of emotional information due to sleep loss. Future studies will examine eye movements in clinical insomnia samples and sleep-deprived individuals to further examine the role of visual attention control in emotional perception after sleep loss.

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