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ORIGINAL ARTICLE

The interrelation between interpretation biases, threat expectancies and pain-related attentional processing

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Abstract

Background: Few studies examining the effect of pain-related threat on eye movements have incorporated a measure of interpretation bias. However, theories suggest that interpretation biases also play an important role in the anticipation of harm in situations where pain could be imminent. The current study investigates the association between interpretation biases and pain-related threat expectancies and their associations with eye movements to pain-related imagery.

Methods: Healthy adults' ($N = 91$) fear of pain, emotional functioning and interpretation biases were assessed prior to a threat manipulation where they were given either threatening or reassuring information about an upcoming cold pressor task. Participants were then asked to freely view scene images that were either pain-related or neutral.

Results: We used a data-driven machine learning method to analyse eye movements. We identified an explorative (i.e. greater dispersal of eye fixations) and a focused eye movement pattern subgroup (i.e. mainly focusing on foreground information) for scene viewing in the sample. Participants with more negative interpretation biases expected that the cold pressor task would be more harmful, and those with higher levels of anticipated harm used a more explorative strategy when viewing injury scene images. Subsequent analysis confirmed an indirect effect of interpretation biases on eye movements through expected bodily harm. No difference in eye movements was found between participants given threatening and reassuring information.

Conclusions: Interpretation biases may play a prominent role in threat-related attentional processing. By adopting a novel eye movement analysis approach, our results revealed interesting associations among interpretations, threat expectancies and eye movements.

Significance: Negative interpretation biases may be associated with greater threat expectancies for an upcoming experimental pain task. Anticipation of bodily harm may induce a stimulus non-specific hypervigilant style of scanning of pain-related scenes.

1 | INTRODUCTION

When anticipating pain, especially in conditions of high threat, people might prioritize signals related to such threats, which in turn results in information processing biases (Eccleston & Crombez, 1999). The fear-avoidance model and threat interpretation model also suggest that attentional biases for pain-related information may be dependent on the interpretation of pain as threatening and harmful (Todd et al., 2015; Vlaeyen & Linton, 2000). However, eye-tracking studies examining the associations between threat and information processing have generated mixed results. In particular, two studies recorded eye movements on word and face pairs in participants threatened or reassured about an upcoming cold pressor task. While Todd, Sharpe, Colagiuri, and Khatibi (2016) found that people reassured about pain preferentially attended to happy faces, Sharpe et al. (2017) suggested that people threatened about pain initially avoided looking at affective pain words.

In this type of threat manipulation research, it was typically assumed that those who were given threatening information would expect higher levels of pain/harm than those who were reassured. However, participants' threat expectancy may not depend solely on the information given to them, but is also likely to be influenced by their interpretations of the information. More specifically, it is possible that some participants receiving threatening information yet with more benign interpretations were not effectively threatened by the description, while some others receiving reassuring information yet with more negative interpretation biases would still consider the task as painful and harmful. Within-group inter-subject variability in interpretation biases has therefore been largely neglected in previous studies, which may be a potential explanation for the mixed findings.

As such, the present investigation assessed participants' interpretation biases prior to a threat manipulation (i.e. assigning different information about an upcoming cold pressor task), which was then followed by an eye-tracking task during which participants freely viewed injury and neutral scene images. We adopted a machine learning data-driven approach (i.e. Eye Movement analysis with Hidden Markov Models [EMHMM]) to analyse participants' eye movements on scene images. In previous scene perception studies adopting this technique, participants were clustered into an "explorative" eye movement pattern subgroup (i.e. greater dispersal of eye fixations) and a "focused" pattern subgroup (i.e. mainly focusing on foreground information) (Hsiao, Chan, Du, & Chan, 2019). These two patterns may be particularly relevant to the attentional bias literature because they may reflect the extent to which participants are vigilant towards threatening information within each scene.

We hypothesized that people with more negative interpretation biases may have higher threat expectancies for the cold pressor task. We also hypothesized that people who received threatening information, or those with greater threat expectancies, would in turn adopt a more explorative or a more focused strategy when viewing injury images than others. Moreover, there may be an indirect effect of interpretation biases on eye movements through threat expectancy. Here, we did not specify a direction for eye movements since previous findings have been mixed and no study within the pain literature has adopted EMHMM for scene-viewing tasks.

2 | METHODS

2.1 | Participants

Ethical approval was obtained from the Human Research Ethics Committee of the University of Hong Kong (reference number: EA1907024). The study was advertised through bulk emails sent to students and on noticeboards around the campus of the University of Hong Kong. Participants who met the following inclusion criteria were invited to participate: (a) over 17 years of age, and (b) able to read and understand traditional Chinese. The exclusion criteria were: (a) instances of prolonged pain in the 3 months prior to testing or current acute pain, and (b) past or current psychiatric or neurological diseases. On arrival, participants were randomly assigned to one of the two experimental conditions (high-threat or low-threat) using the list randomizer function from Random.org. Participants were given a cash reward upon completion.

Based on Todd et al. (2016), 90 participants would be needed to detect a medium effect of threat manipulation at 80% power and $p < 0.05$ (2×2 mixed ANOVA); 84 participants would be needed to detect moderate correlations at 80% power and $p < 0.05$ (simple correlations). In addition, a minimum of 68 participants would be needed to detect a medium indirect effect at 80% power and $p < 0.05$ (simple mediation) (Faul, Erdfelder, Lang, & Buchner, 2007). A total of 99 university students participated in the experiment. Three participants from the low-threat condition and one participant from the high-threat condition were excluded due to unsuccessful threat manipulations (i.e. participants did not fully understand the information given to them). One participant from the low-threat condition was excluded because of awareness of the study intention. Further, two participants from the low-threat condition and one participant from the high-threat condition were excluded from analyses due to missing eye movement data (i.e. data files overwritten due to technical error). Our final sample consisted of 91 participants (45 females, 49.5%) with 44 in the low-threat and 47 in the high-threat conditions. Participants' ages ranged from 17 to 29 years ($M = 20.36$, $SD = 1.87$) and all were local Hong Kong students.

2.2 | Measures

2.2.1 | Questionnaires

Participants' anxiety, depression and fear of pain were measured since these variables have been associated with eye movements (Armstrong & Olatunji, 2012; Yang, Jackson, Gao, & Chen, 2012). The 21-item Depression Anxiety Stress Scale (Antony, Cox, Enns, Bieling, & Swinson, 1998; Lovibond & Lovibond, 1995) was used to measure participants' depressive, anxious and stress symptoms (seven items each). Translation and back-translation were performed for this measure. Cronbach's alpha was 0.88 for the depression subscale, 0.75 for the anxiety subscale and 0.85 for the stress subscale. The 25-item Chinese version of the Fear of Pain Questionnaire-III (McNeil & Rainwater, 1998; Yang et al., 2012) was used to measure participants' fear of (a) minor, (b) severe and (c) medical pain. Cronbach's alpha was 0.91 for this measure. Higher scores in each questionnaire indicate worse symptoms or higher fear of pain.

2.2.2 | Interpretation bias task

We adopted an Interpretation Bias Task (IBT) (Chan, Takano, Lau, & Barry, 2020; Heathcote et al., 2016) to examine participants' interpretations for ambiguous situations. The IBT includes four domains of ambiguous situations describing immediate bodily injury, long-term illness, social rejection and performance failure. However, the current study only used the scenarios in the pain-/health-related domains (i.e. immediate bodily injury and long-term illness).

Participants were first presented with each ambiguous situation (i.e. a sentence with a blank) and were then offered a benign word and a negative word that resolved the situation. They were then asked to rate how likely it would be for each resolution to occur on a scale from 1 to 100 (1 = not at all likely; 100 = extremely likely). An example of immediate bodily injury scenario is: "Someone kicks a ball and it hits you in the face. In the mirror you see your face is covered in …" followed by "mud" and "blood". Higher rating for the word "mud" indicates a more benign interpretation and higher rating for the word "blood" indicates a more negative interpretation. Similarly, an example of long-term illness scenario is: "You begin to breath heavily. Your chest is quickly going up and down. You are …" followed by "exercising" and "asthmatic".

We calculated the mean likelihood of negative interpretations and the mean likelihood of benign interpretations within each domain. Interpretation biases in the two domains could then be indexed by a negative and a benign score, which add up to four average scores in total. Following Heathcote et al. (2016), we then created an interpretation bias score by subtracting ratings for benign interpretations from rating for negative interpretations for each domain separately. A more positive value of the interpretation bias score indicates a higher tendency to endorse more negative interpretations. The interpretation bias scores for the immediate bodily injury and the long-term illness domains were then used as variables of interest in subsequent data analysis.

2.3 | Threat manipulation

Participants read descriptions of a cold pressor task in an information sheet prior to the eye-tracking task. The information provided to the high-threat group used formal biomedical terminologies, describing the cold pressor task as a "pain detection task" or a "vasodilation task" that stimulates the sympathetic nervous system (Boston & Sharpe, 2005; Schoth, Yu, & Liossi, 2014). Participants in this group were told that the task would induce "cold pain similar to frostbite" but it "would not cause any permanent tissue damage", and they could withdraw from the experiment if their pain became "too intense" or if they were "too distressed" (Schoth et al., 2014). In contrast, the low-threat information used common language and outlined the task as a "temperature detection task" (Schoth et al., 2014). Participants in the low-threat group were told that "mild cold may be experienced" and that the task "would not cause any harm". They were also told that they could stop at any time if they felt "uncomfortable" (Schoth et al., 2014). The cold pressor task was not actually administered since the aim of the present study was to examine participants' responses to threat of pain.

2.4 | Threat expectancies

Participants' threat expectancies were measured by four questions which were rated on an 11-point numerical scale (0–10). These four questions asked how worried participants were about the task (0 = not at all, 10 = the worst possible task), how painful they thought the task would be (0 = not at all, 10 = worst pain imaginable), how harmful they thought the task would be (0 = not at all, 10 = the most harmful task) and how well they thought they would be able to cope with the task (0 = no problem at all, 10 = cannot cope at all) (Todd et al., 2016). Responses to these questions were used as a check for the threat manipulation and as variables of interest in subsequent data analyses.

An additional question with three different statements was also asked to directly check whether participants attended to and understood the orienting information presented to them. Participants needed to identify the statement closest in meaning to the information they just read from the three options. One option would be correct and the other two would be distractor options, although a distractor for one condition might be the correct answer for the other condition. Participants were excluded if they chose the wrong option.

2.5 | Eye-tracking task

Twenty-four coloured scene images depicting everyday situations (12 injury and 12 neutral scenes), validated in a previous study (Meng et al., 2012), were used as stimuli in the eye-tracking task. Injury scenes depicted injuries to extremities (e.g. hand, arm and foot) in everyday situations (e.g. finger cut when slicing cucumbers), whereas neutral scenes presented extremities in non-painful daily activities (e.g. slicing cucumbers). Each scene image was 512 × 384 pixels (width × height).

Eye movements were recorded by an EyeLink 1000 eye tracker (SR Research). Participants sat 60 cm in front of a 22” CRT monitor with a resolution of 1,024 × 768 pixels. The tracking mode was pupil and corneal reflection. The sampling rate was 1,000 Hz. Nine-point calibration was employed prior to 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 8,000 degree/square second and saccade velocity threshold was 30 degree/s, which were the EyeLink defaults for cognitive research.

Participants sat 60 cm in front of a computer screen for the eye-tracking task during which they freely viewed the 24 scene images one at a time. The free-viewing task commenced after calibration and validation of eye fixations. Nine-point calibration was administered. Each trial began with a drift check (i.e. a dot at the centre of the screen). After confirming the participants fixated at the dot, a fixation cross replaced the dot for 500 ms and participants were instructed to gaze at the cross. Subsequently, one of the images was presented for 5,000 ms either on the left or on the right side of the screen. Images were not presented at the screen centre because we wanted to capture participants' first fixations when they saccade to a target image, which is an important indicator of their information processing strategy (Hsiao, Cottrell, & Regan, 2008). Each image was only presented once. Following an inter-trial interval of 500 ms, the next trial started with the drift correction check. Twelve injury and 12 neutral scenes were presented individually in a randomized order during the free-viewing task. The valence (injury vs. neutral), body site injured (i.e. foot, forearm and hand) and location of scene images were also counterbalanced. The eye-tracking task consisted of 24 experimental trials. Participants were instructed to freely explore these images and no response was needed.

2.6 | Procedure

Participants were randomized into either the high-threat or the low-threat group prior to the experiment. After giving written consent, participants completed the questionnaires and the IBT on a computer with no eye-tracking function. Participants were then given instructions of the eye-tracking task as well as an information sheet about the cold pressor task. They were told that they would first complete the eye-tracking task in the current room and would then enter another room to perform the cold pressor task. After reading the information thoroughly, participants were asked to complete the five manipulation check questions to make sure they fully understand the information. Participants were then seated in front of another computer for the eye-tracking task. Finally, participants were debriefed and were told that they did not need to do the cold pressor task. The experimenter also asked a series of questions (i.e. “Were you aware of the threat manipulation? (Yes/No)”, “Did you believe that there would be a cold pressor task? (Yes/No)”) after debriefing to ensure that the participants were not aware of the manipulation and study intention. In addition, all participants were asked to not inform others about the threat manipulation and deception included in the study.

2.7 | Data handling and analysis plan

2.7.1 | Eye Movement Analysis with Hidden Markov Models (EMHMM)

The current study adopted the Eye Movement Analysis with Hidden Markov Models (EMHMM) approach (retrieved from http://visal.cs.cityu.edu.hk/research/emhmm/) to analyse eye movement data on scene images. A hidden Markov model (HMM) is a type of machine learning model for handling sequential data, which considers that the observable data (i.e. eye fixation locations) arise from an underlying dynamic process (i.e. the sequence of regions of interest [ROIs] viewed) (Chuk, Chan, & Hsiao, 2014). 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 (Chuk et al., 2014). Based on the sequence of fixation locations, the HMM uses a probabilistic model to estimate the locations and sizes of the ROIs (Chuk et al., 2014). Using this approach, the properties of ROIs are no longer predefined by researchers but are automatically estimated for each individual based on the assumption that each ROI can be represented by a two-dimensional normal (Gaussian) distribution (Chuk et al., 2014), which indicates that the density of fixations would be the highest at the centre of each ROI and lowest near the border. This approach also generates the initial ROI probabilities and a transition matrix for each participant, which indicates the probability an individual first fixates on an ROI, and the probability to shift the eye gaze from one ROI to another ROI during scene viewing.

Eye movement data on scene images were split into two sets based on image valence (i.e. sequence of fixation locations on injury scenes and sequence of fixation locations on neutral scenes) and were run separately using the EMHMM toolbox. All fixations that occurred within the boundaries of the images during the 5,000 ms stimulus presentation period were analysed. Sinceeach scene image has a different feature layout, we used EMHMM with co-clustering (Hsiao et al., 2019) to analyse the eye movement data. Specifically, we trained one HMM for each scene image per participant, resulting in 12 HMMs for injury and 12 HMMs for neutral scenes for each individual. Following previous studies that used EMHMM to analyse eye movements on scene images (Hsiao et al., 2019), we set the number of hidden states (i.e. number of ROIs) to three. Therefore, each HMM in the current study was represented by three personalized ROIs and the transition probabilities among them. Each HMM was trained for 200 times with different random initializations,[1] and the one with the largest marginal likelihood was kept.

After each participant's gaze behaviour was summarized with personalized ROIs and transition probabilities among the ROIs, EMHMM then enabled these HMMs to be clustered into groups using a co-clustering algorithm (Hsiao et al., 2019). This algorithm performs the clustering process on HMMs for each image separately, generating representative HMMs (common patterns) for each group that are unique for that image, while also ensuring that the cluster memberships are consistent across all images. That is, the co-clustering algorithm finds groups of participants that share common eye gaze strategies across all the image stimuli. The output of the co-clustering algorithm is a grouping of participants, where each group is associated with a set of representative HMMs (one for each image). Similarly, the co-clustering algorithm was also performed 200 times with different random initializations, and the one with the largest log likelihood was retained. Using this algorithm, 2019, Hsiao, Zheng, and Chan (2019) found two common viewing patterns for scene images: a "focused" pattern where participants mainly looked at the foreground of scene images, and an "explorative" pattern where participants' fixations were more scattered. Based on this antecedent, we also clustered our sample into two pattern subgroups. We applied co-clustering separately for the injury and neutral scenes, resulting in two subgroups for each type of scene.

Finally, the EMHMM toolbox quantified participants' eye movement patterns by calculating the Explorative-Focused (E-F) Scale. The E-F Scale quantifies the degree of similarity of individual HMMs to the representative HMMs. A more positive E-F Scale value represents a pattern that is more similar to the explorative HMM, and a more negative value indicates a pattern more similar to the focused HMM. Each individual had one E-F Scale value for eye movements on neutral scenes, and another such value for eye movements on injury scenes. The E-F Scale values were then used as continuous variables in subsequent data analyses.

2.7.2 | Statistical analysis plan

Independent samples *t*-tests and Chi-square tests were first performed to see if the high-threat and low-threat groups differed significantly in age, gender, questionnaire responses and interpretation biases. A manipulation check was also performed to see if the high-threat group was more worried about the cold pressor task, had higher expectations for pain and harm resulting from the task and thought they had more problems coping with the task than the low-threat group. To test the differences in eye movements between participants receiving threatening and reassuring information, we performed a two-way mixed ANOVA on E-F Scale values with condition (high-threat vs. low-threat) as the between-subject factor and image valence (injury vs. neutral) as the within-subject factor. We followed up with other comparisons to examine the findings if any significant main effect or interaction was revealed. We also performed correlation tests to examine the associations among interpretation biases measured by the IBT, threat expectancies measured by the four threat expectancy questions and eye movement indices quantified by the E-F Scale values.

Given our hypothesis that there may be an indirect effect of interpretation biases on eye movements through threat expectancies, in the presence of significant correlations among these variables, we then examined these possible indirect effects using the "lavaan" package (Rosseel, 2012) in R 3.5.1 (R Core Team, 2018). We conducted bias-corrected bootstrapped mediation analysis using 10,000 bootstrapped resamples. The indirect effects were considered significant in the case that the 95% confidence intervals did not capture zero. All other tests were conducted using SPSS.

Effect sizes for Cohen's *d* values of 0.80, 0.50 and 0.20, respectively, were considered to be large, moderate and small in magnitude (Kotrlik & Williams, 2003; Vacha-Haase & Thompson, 2004). Similarly, correlation coefficients of 0.50, 0.30 and 0.10 were considered to be large, moderate and small (Kotrlik & Williams, 2003). Eta-squared values of 0.14, 0.06

and 0.01 were regarded as large, moderate and small effect sizes (Lakens, 2013).

3 | RESULTS

3.1 | Participant characteristics

There was no significant difference between the high-threat and low-threat groups in age, $t(89) = -1.24$, $p = 0.218$, $d = -0.26$, 95% CI [−0.67, 0.16], gender ratio, $\chi^2(1) = 0.54$, $p = 0.531$, $\varphi = 0.08$, 95% CI [0.00, 0.28], fear of pain, $t(89) = 0.74$, $p = 0.464$, $d = 0.15$, 95% CI [−0.26, 0.56], depressive symptoms, $t(89) = -0.46$, $p = 0.645$, $d = -0.10$, 95% CI [−0.51, 0.31], anxious symptoms, $t(89) = 0.67$, $p = 0.508$, $d = 0.14$, 95% CI [−0.27, 0.55] or stress, $t(89) = 0.28$, $p = 0.779$, $d = 0.06$, 95% CI [−0.35, 0.47]. There was also no significant difference between participants in the two conditions in their interpretation bias scores for immediate bodily injury situations, $t(89) = -0.02$, $p = 0.986$, $d = -0.004$, 95% CI [−0.41, 0.41], or that for long-term illness situations, $t(89) = 1.14$, $p = 0.259$, $d = 0.24$, 95% CI [−0.18, 0.65]. Table 1 presents means and standard deviations of these variables for each group.

3.2 | Group differences in threat expectancy

Participants in the high-threat group were significantly more worried about the cold pressor task, $t(83.13) = 7.56$, $p < 0.001$, $d = 1.57$, 95% CI [1.09, 2.02], expected higher levels of pain, $t(89) = 11.58$, $p < 0.001$, $d = 2.43$, 95% CI [1.87, 2.95], anticipated more harm, $t(80.39) = 2.95$, $p = 0.004$, $d = 0.61$, 95% CI [0.19, 1.03] and thought they had more problems coping with the cold pressor task, $t(89) = 2.95$, $p = 0.004$, $d = 0.62$, 95% CI [0.19, 1.03], compared to those in the low-threat group (see Table 1). This confirmed that the threat manipulation was successful.

3.3 | Eye movement patterns on scene images

We found two common scene-viewing patterns in our current sample, namely an explorative pattern and a focused pattern, which were consistent with previous studies on scene perception (Hsiao et al., 2019). Figures 1 and 2 illustrate these two eye movement patterns for injury and neutral scenes, respectively. Since there were 12 HMMs for each representative

TABLE 1 Mean (*SD*) for self-reported measures, threat expectancy, interpretation bias scores and eye movement indices for high-threat and low-threat groups

	Conditions					
Measure	High-threat ($n = 47$)	Low-threat ($n = 44$)	t value	df	p	Cohen's d
Age	20.13 (1.81)	20.61 (1.92)	−1.24	89	0.218	−0.26
Gender	25 females (53.2%)	20 females (45.5%)	—	1	0.531	—
Fear of pain	68.66 (12.40)	66.68 (13.26)	0.74	89	0.464	0.15
Emotional functioning						
Depression	10.91 (4.12)	11.32 (4.21)	−0.46	89	0.645	−0.10
Anxiety	10.98 (3.04)	10.55 (3.17)	0.67	89	0.508	0.14
Stress	13.15 (4.34)	12.89 (4.56)	0.28	89	0.779	0.06
Threat expectancy						
Worry	3.62 (2.00)	0.89 (1.42)	7.56	83.13	0.000	1.57
Pain	5.00 (1.56)	1.25 (1.53)	11.58	89	0.000	2.43
Harm	1.26 (1.36)	0.55 (0.90)	2.95	80.39	0.004	0.61
Cope	2.68 (2.59)	1.14 (2.40)	2.95	89	0.004	0.62
Interpretation bias scores						
Immediate bodily injury scenarios	−0.73 (23.97)	−0.65 (21.50)	−0.02	89	0.986	−0.004
Long-term illness scenarios	−42.79 (18.54)	−47.25 (18.82)	1.14	89	0.259	0.24
Explorative-Focused Scale						
Injury scenes	0.015 (0.013)	0.012 (0.014)				
Neutral scenes	0.007 (0.004)	0.009 (0.007)				

Note: SD, Standard Deviation.

pattern, for conciseness, the HMMs for three example stimuli for each pattern subgroup are presented in Figures 1 and 2.[2]

Figure 1a presents the explorative pattern for three example injury scene images and Figure 1b presents the focused pattern for these three stimuli. The fixation plots for injury scenes showed that people in the focused group allocated most of their fixations to image regions where the injuries occur while those in the explorative group exhibited a pattern where fixations were more scattered. Similarly, Figure 2a presents the explorative pattern for three example neutral stimuli and Figure 2b presents the focused pattern for these three stimuli. The fixation plots show that people using the explorative strategy had more fixations that fell on the background of the stimuli compared to people using the focused strategy, whose fixations mainly fell on the body sites (i.e. hands) and the objects that might cause potential injury (i.e. knife, scissors and needle).

In sum, the explorative patterns showed greater dispersal of eye fixations compared to the focused patterns. It is of note, however, that the terms "explorative" and "focused" do not imply any underlying cognitive mechanisms in the context of EMHMM (Chuk et al., 2014). Instead, these names were only used to indicate the distribution of fixations and ROIs within each eye movement pattern subgroup.

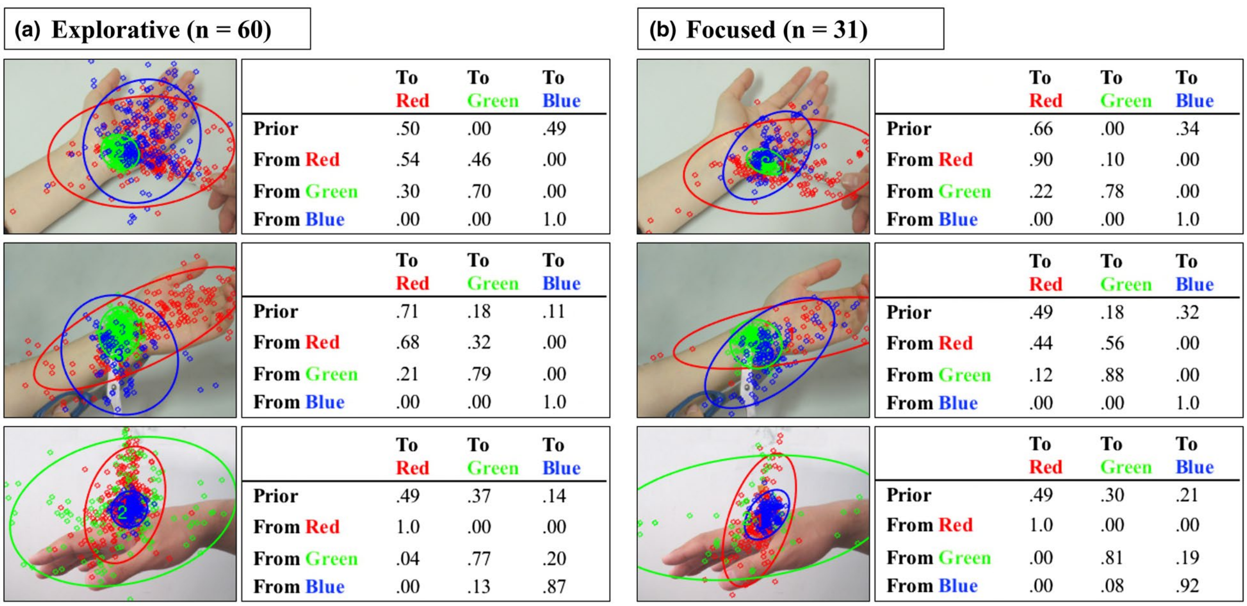
3.4 | Group differences in eye movements

We performed a 2 (high-threat vs. low-threat) × 2 (injury vs. neutral) mixed ANOVA on the E-F Scale values for scene viewing (see Table 1). Since the two groups did not differ in their levels of trait fear of pain, emotional functioning (i.e. depression, anxiety and stress symptoms) or interpretation biases, these variables were not included as covariates in the ANOVA. Results showed that there was a main effect of valence, $F(1, 89) = 10.67$, $p = 0.002$, $\eta^2 = 0.11$, 90% CI [.03, 0.21]. There was no main effect of group, $F(1, 89) = 0.62$, $p = 0.435$, $\eta^2 = 0.01$, 90% CI [.00, 0.06], or interaction between group and valence, $F(1, 89) = 2.02$, $p = 0.159$, $\eta^2 = 0.02$, 90% CI [.00, 0.09].

However, the main effect of valence is likely attributable to the fact that the explorative and focused patterns for the two valences were based on different HMMs. Put otherwise, the E-F Scale value for injury scenes indicates similarity to the explorative pattern generated for injury images, while the E-F Scale value for neutral scenes indicates similarity to the explorative pattern generated for neutral images. It is unclear whether the explorative patterns for the two valences were equivalent. Within-group comparisons between these two values may therefore be misleading and so were not conducted. In summary, although the threat manipulation effectively manipulated threat expectancies, there was no evidence of an effect of the threat manipulation on eye movements.

3.5 | Correlations

Correlations among participants' interpretation bias scores, threat expectancies (i.e. worry, pain, harm and ability to cope) and eye movement indices were tested. Table 2 shows the results of these correlations. There was a significant, positive



(a) Explorative (n = 60)

	To Red	To Green	To Blue
Prior	.50	.00	.49
From Red	.54	.46	.00
From Green	.30	.70	.00
From Blue	.00	.00	1.0

	To Red	To Green	To Blue
Prior	.71	.18	.11
From Red	.68	.32	.00
From Green	.21	.79	.00
From Blue	.00	.00	1.0

	To Red	To Green	To Blue
Prior	.49	.37	.14
From Red	1.0	.00	.00
From Green	.04	.77	.20
From Blue	.00	.13	.87

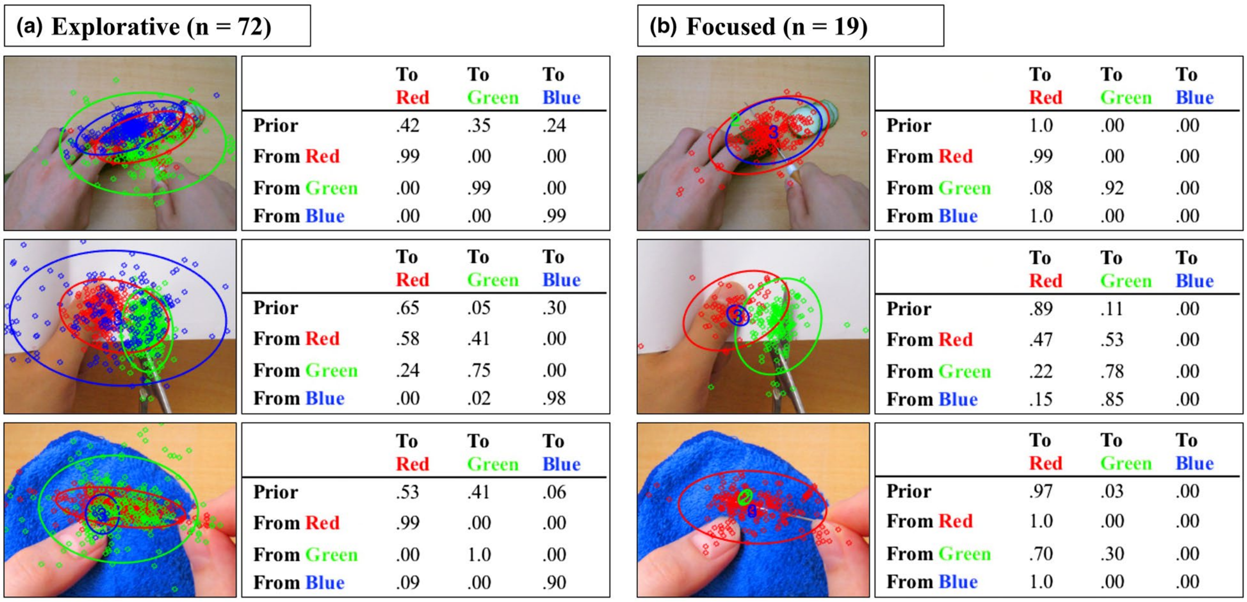
(b) Focused (n = 31)

	To Red	To Green	To Blue
Prior	.66	.00	.34
From Red	.90	.10	.00
From Green	.22	.78	.00
From Blue	.00	.00	1.0

	To Red	To Green	To Blue
Prior	.49	.18	.32
From Red	.44	.56	.00
From Green	.12	.88	.00
From Blue	.00	.00	1.0

	To Red	To Green	To Blue
Prior	.49	.30	.21
From Red	1.0	.00	.00
From Green	.00	.81	.19
From Blue	.00	.08	.92

FIGURE 1 Eye movement patterns on injury scene images. Figure 1a (the left panel) shows the explorative pattern on injury scenes. Figure 1b (the right panel) shows the focused pattern on injury scenes. The images in each panel (left to right) show the spatial distribution of fixations in each ROI and the transition probability matrix of the ROIs for three example injury scene images. HMMs for other injury scene images are available in supplementary materials



(a) Explorative (n = 72)

	To Red	To Green	To Blue
Prior	.42	.35	.24
From Red	.99	.00	.00
From Green	.00	.99	.00
From Blue	.00	.00	.99

	To Red	To Green	To Blue
Prior	.65	.05	.30
From Red	.58	.41	.00
From Green	.24	.75	.00
From Blue	.00	.02	.98

	To Red	To Green	To Blue
Prior	.53	.41	.06
From Red	.99	.00	.00
From Green	.00	1.0	.00
From Blue	.09	.00	.90

(b) Focused (n = 19)

	To Red	To Green	To Blue
Prior	1.0	.00	.00
From Red	.99	.00	.00
From Green	.08	.92	.00
From Blue	1.0	.00	.00

	To Red	To Green	To Blue
Prior	.89	.11	.00
From Red	.47	.53	.00
From Green	.22	.78	.00
From Blue	.15	.85	.00

	To Red	To Green	To Blue
Prior	.97	.03	.00
From Red	1.0	.00	.00
From Green	.70	.30	.00
From Blue	1.0	.00	.00

FIGURE 2 Eye movement patterns on neutral scene images. (a) (the left panel) shows the explorative pattern on neutral scenes. (b) (the right panel) shows the focused pattern on neutral scenes. HMMs for other neutral scene images are available in supplementary materials

correlation between participants' tendency to endorse negative interpretations for long-term illness situations and their anticipated harm of the cold pressor task, $r(91) = 0.23$, $p = 0.026$. Moreover, this expected harm of the cold pressor task was positively associated with participants' tendency to be more explorative when viewing injury scenes, $r(91) = 0.29$, $p = 0.006$. No other correlation was statistically significant.

3.6 | Indirect association between interpretation biases and eye movements

Based on the correlation results, we then tested an indirect effect with 10,000 bootstrap samples to examine if the tendency to negatively interpret illness-related scenarios increased participants' anticipated bodily harm of the cold pressor task, which then contributed to a higher tendency to adopt an explorative strategy for injury scenes. Results confirmed that there was a significant indirect effect of interpretation biases for long-term illness scenarios on the E-F Scale value for injury scenes through anticipated harm of the cold pressor, $b = 0.07$, $SE = 0.04$, 95% CI [.002, 0.14] (see Figure 3). In contrast, the direct effect was not significant, $b = -0.09$, $SE = 0.09$, 95% CI [−0.28, 0.09]. The total effect was not significant either, $b = -0.02$, $SE = 0.10$, 95% CI [−0.21, 0.17].

4 | DISCUSSION

The present study manipulated the threat context by giving participants threat-related or reassuring information about a cold pressor task. The primary aim of the study was to

TABLE 2 Correlations between interpretation bias scores, threat expectancy and eye movement indices

	1	2	3	4	5	6	7	8
1. Interpretation bias – injury	—							
2. Interpretation bias – illness	0.32**	—						
3. Worry	0.02	0.11	—					
4. Pain	0.04	0.14	0.79**	—				
5. Harm	0.08	0.23*	0.59**	0.50**	—			
6. Cope	0.18	0.03	0.52**	0.46**	0.41**	—		
7. E-F scale – injury	−0.05	−0.02	0.14	0.03	0.29**	0.09	—	
8. E-F scale – neutral	0.14	−0.01	−0.002	0.01	0.08	−0.05	−0.23*	—

*$p < 0.05$.

**$p < 0.01$.

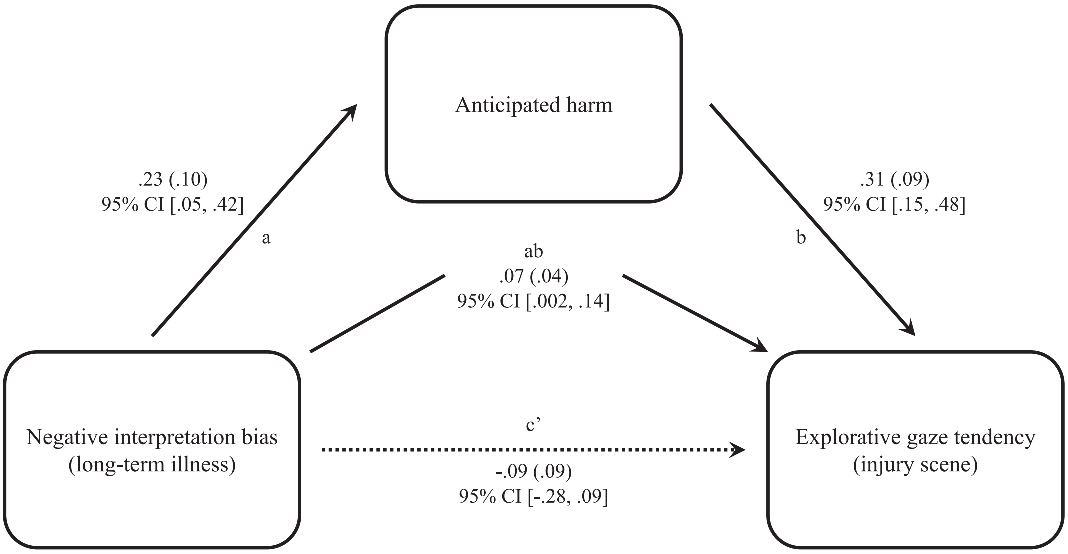


FIGURE 3 An indirect effect of negative interpretation biases for long-term illness scenarios on explorative gaze tendencies for injury scene images through the anticipated harm of the cold pressor task. Path a, association between interpretation bias score for long-term illness scenarios and anticipated harm. Path b, association between anticipated harm and the tendency to be more explorative for injury scene images. Path c', association between interpretation bias score for illness-related scenarios and E-F Scale value for injury images, controlling for the indirect effect. Path ab, the index of the indirect effect of negative interpretation bias on eye movements. The 95% CI for this indirect path does not include 0, suggesting that the indirect effect is significantly different from 0. Path values represent standardized coefficients (standard errors) and 95% CIs

examine the effect of this threat manipulation on eye movements during a subsequent free exploration of injury and neutral scene images. Results showed that the threat manipulation was successful, but participants receiving threatening and reassuring information did not differ in their eye movement patterns, which contradicted our hypotheses. Despite the non-significant group comparisons for eye movements, correlation tests showed that those with more negative illness interpretations expected more harm from the cold pressor task, which was in turn associated with a more explorative eye movement pattern when viewing injury images. These correlations were further confirmed by mediation analysis.

The methodological strength of the present study was the employment of a machine learning data-driven approach to analyse gaze behaviours (i.e. EMHMM). This method does not require predefining ROIs or splitting data into multiple time segments and therefore has its advantages over conventional analysis approaches in observing individual differences in eye movement patterns. In particular, replicating recent studies (Hsiao et al., 2019), we identified an explorative and a focused eye movement pattern in the current sample for both injury and neutral scenes. While people adopting the explorative strategy exhibited a more dispersed pattern of eye fixations, people using the focused strategy had relatively static gaze tendency and focused mainly on the foreground information.

Contrary to our hypothesis, however, we found no significant difference in eye movements between the two conditions. One possible explanation for this overall null effect may be that although participants in the high- and low-threat conditions differed significantly in their threat expectancies on a group level, substantial inter-subject variability in these expectations may exist within each condition. It is possible that some participants in the high-threat group were not effectively threatened by the description, while some others in the low-threat group still perceived the task as painful and harmful. Indeed, when the relationships between threat expectancies and eye movements were assessed within the whole sample (i.e. regardless of condition), we found that people who expected higher levels of bodily harm from the cold pressor task were more likely to adopt an explorative eye movement strategy for injury images.

The tendency to be more explorative for injury scenes might not necessarily be reflective of vigilance towards or avoidance of a particular type of stimuli, but instead might represent a stimulus non-specific vigilance that has not yet been documented in the pain literature. In social anxiety research, however, it has been suggested that patients with social phobia exhibit a generalized hypervigilant style of viewing in the environment on top of a certain vigilance to or avoidance of a specific kind of stimulus (Armstrong & Olatunji, 2012; Chen & Clarke, 2017; Moukheiber et al., 2010). This hyper-scanning pattern has been suggested to involve excessive monitoring of potential threats and scanning of the surroundings and might be characterized by a more erratic scan path with increased distance between fixations (Chen & Clarke, 2017). Similarly, in the present study, participants who expected higher levels of bodily harm might be adopting a more explorative strategy when viewing injury scenes because the presence of injuries might have signalled threat and activated a generalized hypervigilant state in which individuals excessively monitor the status of foreground information (i.e. the injury) and, simultaneously, actively search for other potential threats in the background (i.e. the surrounding environment). In contrast, participants who did not expect a high level of harm exhibited a relatively static gaze tendency, focusing on foreground information that is more salient than the background. This finding is consistent with theories suggesting that pain-related threat can interrupt ongoing attentional engagement and behaviour (Eccleston & Crombez, 1999).

Another interesting finding is that the varying degrees of threat expectancies in the participants may be influenced by their interpretative processes. In particular, there was a positive correlation between participants' negative interpretation bias for illness situations and their anticipated bodily harm. In the current study, both groups were told that the cold pressor task would not cause any permanent tissue damage, and yet those with more illness-related interpretation biases still rated the task as being more harmful than others. Therefore, whether participants were expecting harm does not only depend on the information given to them, but is also likely to depend on how they interpreted the information given to them. This finding suggests the importance of including a measure of interpretation biases in future threat manipulation studies.

Subsequent mediation analysis confirmed an indirect effect of an illness-related interpretation bias on explorative gaze tendency for injury images through anticipated bodily harm. This suggests that negative interpretation biases might be a maladaptive style of information processing because it might result in catastrophic misinterpretation of bodily sensations even when these sensations are supposed to be pain-free and harmless. This higher expectation for harm of a harmless activity might then lead to a biased attentional strategy whereby people spend more time scanning non-salient information in the surroundings (i.e. background) at the sacrifice of focusing on more important information (i.e. foreground) as a means to cope with this impending harm. Previous eye-tracking studies in the domain of pain research have largely focused on the effect of threat on selective attention when both neutral and pain-related stimuli are present. However, our study showed that a generalized hypervigilant style of scanning might also be relevant to this particular field. Furthermore, select studies have found preliminary evidence that biased attentional processing strategies may be a potential risk factor of worse pain outcomes (Jackson, Yang, & Su, 2019; Sharpe, Haggman, Nicholas, Dear, & Refshauge, 2014). Future studies should investigate whether this hyper-scanning pattern is evident in patients with chronic pain and whether it is also related to later functioning and disability.

It is of note that the current study only identified a link between interpretation biases for long-term illness scenarios and anticipated bodily harm of the cold pressor task. We did not find an association between interpretation biases for immediate bodily injury scenarios and anticipated pain. It is possible that the information regarding immediate pain caused by the cold pressor task was less ambiguous than the information regarding long-term harm because participants were given specific examples of the pain experience (i.e. "cold pain similar to frostbite"; "reaching into a bucket of ice for a cold drink"). Therefore, the relatively ambiguous description of long-term harm (i.e. "will not cause permanent tissue damage"; "will not cause any harm") might have allowed for greater variability in the effect of interpretation biases on threat expectancies. Relatedly, the explorative gaze tendency for injury images was only associated with anticipated harm but not anticipated pain in the present study. It may be that the viewing of injury images involves appraisals for both immediate pain and long-term harm caused by the injuries, and it may be the aspect of long-term harm that plays a more important role in the association between threat expectancies and eye movements.

Several limitations warrant acknowledgment. First, we did not administer a cold pressor task in the experiment and therefore were not able to assess the effect of threat context and cognitive biases on participants' experimental pain outcomes. Second, our conceptualization of the explorative pattern as a hyper-scanning strategy should be interpreted with caution as the scene images used in the current study did not reflect complex scenes; the background of the current images may therefore provide little information about additional threats in the environment that participants could actively search for. Future studies that adopt real-world complex scenes are needed to confirm our interpretation of the results. Also, our study was not designed to directly test the threat interpretation model. This model suggests that as the level of threat increases, people are more likely to interpret pain-related stimuli as threatening, which then leads to initial vigilance to these stimuli (Todd et al., 2015). However, in our study, interpretation biases were assessed prior to threat manipulation and therefore might be measuring a more stable trait interpretation bias rather than a state interpretation bias that can be altered by the threat context. Nevertheless, our results reinforce the growing recognition of the role of interpretation in attentional biases (Crombez, Heathcote, & Fox, 2015; Todd et al., 2015). Finally, caution should be taken in interpreting our results given that the correlation tests were performed without any correction. Additional replications that confirm our hypotheses are warranted.

In summary, the current study provides evidence that interpretation biases might alter one's expectation for an experimental pain task, which might then influence their gaze behaviours for real-world scene images depicting injuries. This study also identified a hyper-scanning pattern of injury scene viewing in healthy adults that is not evident in previous pain research. Future studies that use longitudinal designs, include assessments of multiple forms of cognitive biases and adopt novel eye movement analysis approaches are needed.

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CONFLICT OF INTEREST

None.

AUTHOR CONTRIBUTIONS

All authors provided a significant contribution to this study, and all have discussed the results and commented on the manuscript.

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ENDNOTES

[1] 200 times is a good balance between training time and breadth of the search. Training the HMM for more than 200 times does not provide any substantial benefit.

[2] HMMs for other stimuli are available via this link: https://osf.io/w4rfn/?view_only=8d841c97187c42c18c026a156ae91e5d.

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