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Research article

Context-specific effects of threatening faces on alerting, orienting, and executive control: A fNIRS study

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ABSTRACT

Real-world threatening faces possess both useful and irrelevant attributes with respect to the current goal. How these attributes interact and affect attention, which comprises at least three processes hypothesized to engage the frontal lobes (alerting, orienting, and executive control), remains poorly understood. Here, the neurocognitive effects of threatening facial expressions on the three processes of attention were examined through the emotional Attention Network Test (ANT) and functional near-infrared spectroscopy (fNIRS). Forty-seven (20M, 27F) young adults performed a blocked version of the arrow flanker task with neutral and angry facial cues applied in three cue conditions (no, center, and spatial). Hemodynamic changes occurring in participants' frontal cortices during task performance were recorded by multichannel fNIRS. Behavioral results indicated that alerting, orienting, and executive control processes existed in both the neutral and angry conditions. However, depending on the context, angry facial cues affected these processes differently compared with neutral facial cues. Specifically, the angry face disrupted the classical decrease in reaction time from the no-cue to center-cue condition specifically during the congruent condition. Additionally, fNIRS results revealed significant frontal cortical activation during the incongruent vs. congruent task; neither cue nor emotion significantly affected frontal activation. Thus, the findings suggest that the angry face affects all three attentional processes while exerting context-specific effects on attention. They also imply that during the ANT, the frontal cortex is most involved in executive control. The present study offers essential insights into how various attributes of threatening faces interact and alter attention.

1. Introduction

Facial expressions convey abundant information about the emotional states of self and others [1]. Due to the evolutionary significance of threat-related stimuli, threatening facial expressions (e.g., angry faces) are perceptually prioritized over neutral ones [2,3]. Because humans have limited resources available for mental processes [4], the preferential processing of threatening faces has a significant impact on cognitive task performance, depending on the relationship of these faces to the current task demand [5,6]. According to the biased competition theory, stimuli compete for processing, and emotional stimuli tend to grab attention, leaving fewer resources for processing other stimuli [6–8]. As such, threatening faces enhance task performance if they are the targets of attention during the task. By contrast, they hinder task performance if the emotional content of these faces is irrelevant to the present

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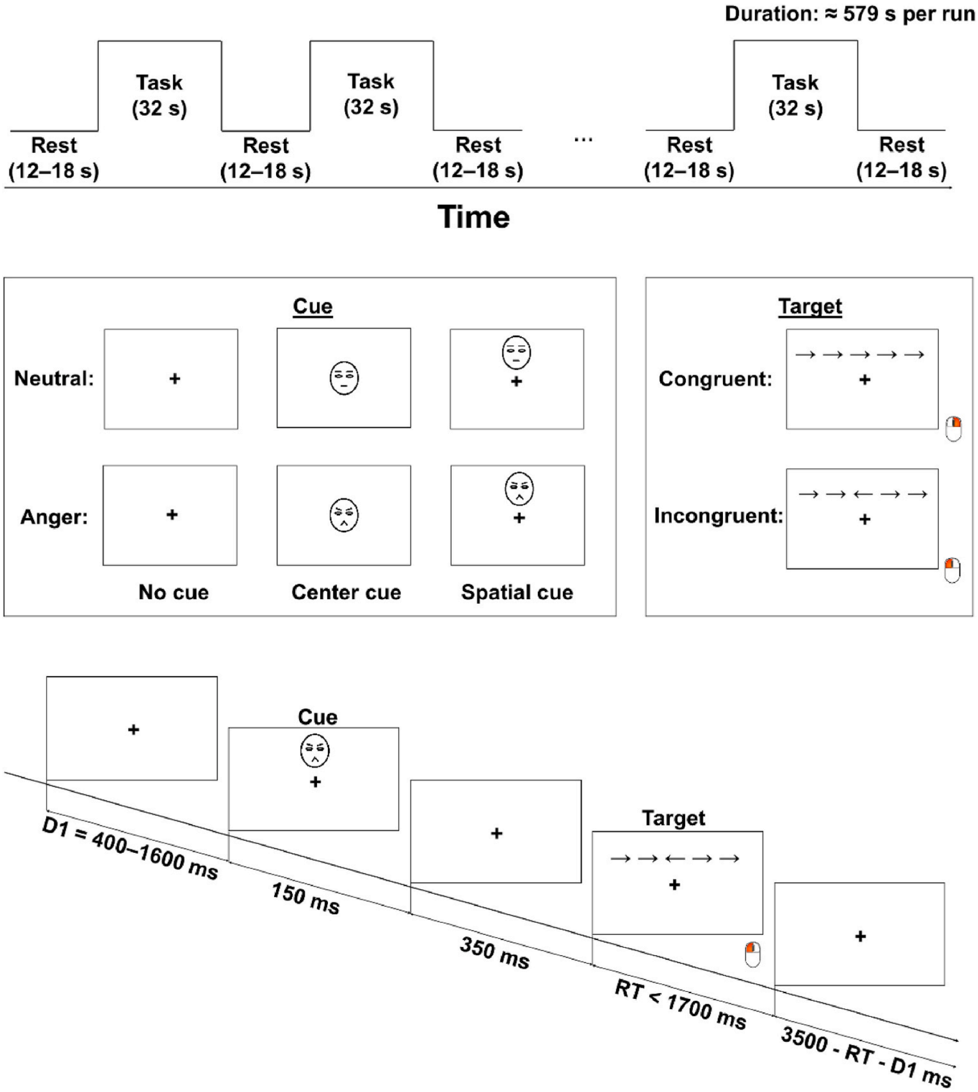

			Bottom-up process	Top-down processes		
Emotion	Cue	Congruency	Threat salience	Conflict resolution	Temporal prediction	Spatial prediction
Neutral	No	Congruent	N	N	N	N
		Incongruent	N	Y	N	N
	Center	Congruent	N	N	Y	N
		Incongruent	N	Y	Y	N
	Spatial	Congruent	N	N	Y	Y
		Incongruent	N	Y	Y	Y
Angry	No	Congruent	N	N	N	N
		Incongruent	N	Y	N	N
	Center	Congruent	Y	N	Y	N
		Incongruent	Y	Y	Y	N
	Spatial	Congruent	Y	N	Y	Y
		Incongruent	Y	Y	Y	Y

Fig. 1. Flow Diagram and Design of the Emotional Attention Network Test. *Note.* N = No; Y = Yes. The faces shown are not the actual faces used in the task.

task [5].

Although threatening faces often grab attention, whether they affect all types of attention is still unclear. According to Posner's tripartite model of attention, there are three distinguishable processes of attention [9,10]. The alerting function refers to the ability to achieve and maintain a heightened sensitivity to incoming stimuli. The orienting function refers to the capacity to localize specific targets in space. The executive control function refers to the ability to monitor and resolve conflicts. These processes can be simultaneously examined using the Attention Network Test (ANT) [11]. During the ANT, participants are shown horizontal arrays of five arrows on the top or bottom of the screen, one array at a time. The task is to judge, via button press, the pointing direction of the central arrow while ignoring the surrounding arrows. The central and surrounding arrows either point in the same (congruent) or opposite (incongruent) direction. Prior to arrow presentation, a warning signal is occasionally shown. This cue takes the form of one asterisk, appearing at the center (center cue) or on the top or bottom (spatial cue), or two asterisks, one on the top and one at the bottom (double cue). The center or double cue provides information about when the target will occur, and the spatial cue provides additional information about the target's location. The reduction in reaction time (RT) from the no-cue to center- or double-cue condition reflects alerting efficiency. The decrease in RT from the center-cue to spatial-cue condition represents orienting efficiency. The difference in RT between the congruent and incongruent conditions represents executive control efficiency, with a smaller difference indicating more efficient conflict resolution.

Most studies employing the ANT to study attention have done so in emotionally neutral contexts (see Ref. [12] for review), and only a few studies have adapted the ANT to study the impact of facial emotions on attention. In one variant designed to probe the priming effects of facial emotions, an emotional or neutral face is always presented at the beginning of each trial, preceding the asterisk cue, if any. The face informs neither the timing/location of the cue nor that of the target. Studies using this paradigm have so far yielded mixed results. Specifically, one study showed that sad faces significantly improved executive control, but not alerting or orienting efficiency, compared with fearful and happy faces [13], whereas another study revealed that angry and fearful faces facilitated orienting, but not alerting or executive control, compared with happy faces [14]. Neither study manipulated the presence and absence of emotional stimuli necessary for investigating the impact of facial emotions on alertness. Thus, whether threatening faces affect all three attentional processes remains unclear.

Past research on emotion–attention interactions has focused on the effect of either task-related or task-irrelevant emotional stimuli on isolated aspects of attention, notably orienting toward emotion-laden stimuli (e.g., Refs. [15,16]) and distraction by threat-related stimuli (e.g., Ref. [17]; see Refs. [12,18] for review). In the real world, threatening facial expressions possess multiple attributes [19]. While some attributes are useful and guide behavior, others convey information that is irrelevant to the current goal. For example, the occurrence of an angry face predicts a direct threat toward oneself, and the timely detection of the face is useful for preparing an action to deal with the threat. By contrast, the emotional content of an angry face often does not provide information about the necessary action but can hold visual attention toward the face, particularly for anxious individuals [20,21]. Thus, the processing thereof can distract oneself from quickly preparing an appropriate response to avoid or deal with the threat.

According to the biased competition theory, bottom-up (stimulus-driven) saliency and top-down (goal-directed) relevancy help determine the processing priority of stimuli [7,8]. When encountering a threatening face that conveys both task-irrelevant emotional content and task-relevant attributes, bottom-up and top-down mechanisms predict different effects of threatening faces on cognitive task performance. According to the bottom-up account, the task-irrelevant emotional content would draw attentional resources away from the task-related attributes of the face, resulting in poor utilization of task-relevant information. In contrast, according to the top-down account, task goals would prioritize utilization of the task-relevant attributes of the facial stimulus over the task-irrelevant emotional content of the face. Both bottom-up and top-down biases are argued to interact and influence the competition between objects or visual features [7,22]. For multi-attribute threatening faces, however, the ways in which the task-irrelevant emotional content and the useful attributes of threatening faces interact to influence attention are currently poorly understood.

The aim of the present study was to apply the tripartite model of attention and the biased competition theory to clarify the effects of multi-attribute threatening faces on attention. These effects were studied using the emotional ANT, implemented in blocks of trials of the same combination of emotion (neutral, angry), cue (no, center, spatial), and congruency (congruent, incongruent) to create varying contexts (Fig. 1). Two notable features of this task enabled testing of the tripartite model of attention and the biased competition theory. First, neutral and angry faces instead of asterisks served as cues; as such, the effects of threatening faces on alerting, orienting, and executive control could be investigated simultaneously. Second, different angry-cue blocks involved similar bottom-up biases in terms of threat salience but varying levels of top-down biases in terms of the expectancy of conflict and target's location. The level of control processes was low when conflict was absent and when the cue prohibited anticipation of the target's location. Considering the well-documented effects of emotional stimuli on attention, we hypothesized that threatening faces would significantly affect all three attentional processes. Based on the bottom-up vs. top-down framework, the interfering effect of angry faces was expected to decrease with increasing levels of control processes that occurred at the moment. Specifically, the interfering effect was hypothesized to be greatest during congruent-flanker, center-cue blocks and smallest during incongruent-flanker, spatial-cue blocks.

Some researchers have identified a key role for frontal lobe subregions in alerting, orienting, and executive control [9,10]. Thus, to gain insights into the neural mechanisms underlying the effects of threatening faces on attention, the present study also used functional near-infrared spectroscopy (fNIRS), an optical imaging technique that monitors hemodynamic changes in the cortical surface, to examine frontal cortical activation during the emotional ANT. This technique utilizes the fact that neuronal activity induces a net increase in oxyhemoglobin concentration (HbO) and a net decrease in deoxyhemoglobin concentration (HbR) [23,24]. Although fNIRS has poorer spatial resolution and shallower measurement depth compared with fMRI, it is relatively resilient to head movement and allows for brain-activity measurement in a naturalistic setting [25]. Because head movements might inevitably occur while orienting attention to the spatial cue and the target during the emotional ANT, the present study used fNIRS to measure frontal cortical activation.

2. Methods

2.1. Participants

Fifty-four Chinese young adults aged 18–39 years were recruited via poster advertisement on the campus of the Hong Kong Polytechnic University. Exclusion criteria, which were based on self report, included: (1) a history of any psychiatric or neurological disorder, (2) stroke or traumatic brain injury that required hospitalization, (3) current use of any psychotropic medication, and (4) left-handedness as determined by the short form of the Edinburgh Handedness Inventory (EHI-SF) [26]. All participants self-reported normal or corrected-to-normal vision, and none received a diagnosis of prosopagnosia.

Seven participants were later excluded for analysis for the following reasons: feeling unwell during fNIRS recording ($n = 4$); being left-handed ($n = 1$; mean EHI-SF score $= -100$); achieving an almost 0% accuracy across the incongruent conditions of the emotional ANT ($n = 1$); and having a missing fNIRS channel cluster due to excessive bad channels ($n = 1$). Thus, the analytic sample consisted of 47 young adults (20 males, 27 females) aged 18–39 ($M = 25.7$, $SD = 5.5$). The included and excluded individuals were statistically comparable in age and sex distribution (t-test and Fisher's exact test: $ps > .69$). This study was approved by the Human Subjects Ethics Sub-committee of the Hong Kong Polytechnic University (HSEARS20201110006) and conducted according to the Declaration of Helsinki.

2.2. Procedure and materials

Eligible individuals were invited to the University Research Facility in Behavioral and Systems Neuroscience of the Hong Kong Polytechnic University to take part in this study. Participants were instructed to abstain from caffeine and alcohol intake on the day of the experiment. After obtaining written informed consent, participants performed the emotional ANT in a quiet, dimly lit room. Meanwhile, the participants' frontal lobe activation was measured with fNIRS.

The emotional ANT was adapted from Fan et al. [11], in which the cue was represented by a neutral or an angry face instead of an asterisk (Fig. 1). The task was further adapted for fNIRS and implemented with the blocked design. The emotional ANT manipulated three factors, including emotion (neutral, angry); cue (no, center, spatial); and congruency (congruent, incongruent). Each condition was presented in blocks of eight 4-s trials, which were separated by a jittering fixation period ranging from 12 to 18 s ($M = 15$ s) to allow the hemodynamic response to return to the baseline (~12 s for HbO and HbR) while minimizing anticipatory effects [25]. Participants performed two runs of the task, each of which consisted of one block for each condition. As such, each condition was represented by 16 trials, which was comparable to, if not greater than, that of behavioral and fMRI studies using the original and modified ANT.

Participants sat 70 cm away from the screen. Test stimuli were presented on a 17-inch Dell monitor (5:4 aspect ratio) using E-Prime 3.0 (Psychology Software Tools, Pittsburgh, PA). Task stimuli consisted of horizontal arrays of five single-headed arrows. Each arrow subtended 1.5° of visual angle, and the contours of adjacent arrows were separated by 0.2° of visual angle. The entire array of arrows subtended 8.3° of visual angle. In addition, cue stimuli consisted of photographs of front-facing neutral and angry faces, which were taken from the Tsinghua facial expression database and have been validated in the Chinese adult population [27]. The width and height of the image subtended 4.7° and 6.3° of visual angle, respectively. The stimulus set consisted of 24 Chinese adult actors, including 6 younger men (Y15M, Y24M, Y28M, Y29M, Y47M, Y58M), 6 younger women (Y4F, Y22F, Y38F, Y39F, Y40F, Y42F), 6 older men (O12M, O17M, O50M, O58M, O66M, O69M), and 6 older women (O4F, O7F, O19F, O29F, O40F, O45F). The same set of actors was used to depict the neutral and angry expressions. Each photograph was presented four times, twice for each run.

Throughout the task, a fixation cross was presented at the center of the screen. Each trial began with a variable fixation period of 400–1600 ms ($M = 1000$ ms) to minimize the anticipation of the cue onset. Then, the fixation cross remained onscreen for another 500 ms. Meanwhile, except for the no-cue condition, a warning cue in the form of a neutral or an angry face was presented either at the center of the screen (i.e., center cue) or on the top or bottom of the screen (i.e., spatial cue; 6.6° of visual angle) for 150 ms. Next, a horizontal array of arrows was shown either on the top or bottom of the screen. Participants were asked to judge the pointing direction of the central arrow as accurately and quickly as possible via a button press. The correct answers for trials with left- and right-pointing central arrows were left and right button presses, respectively. The arrows remained onscreen for 1700 ms or until a response was made. The arrows were then followed by a varying interval, depending on the pre-cue interval and the RT, to achieve a duration of 4000 ms for the entire trial.

Both the center and spatial cues provided useful information about the time of occurrence of the target, and the spatial cue also predicted the location of the target. In addition, the spatial cue and central arrow appeared within areas of the visual field where young adults could recognize neutral and angry expressions with similar accuracy (~82%) [28]. Most studies have reported minimal differences in RT between the center- and double-cue conditions and between the neutral- and congruent-flanker conditions [11,29]. Therefore, neither the double-cue nor the neutral-flanker condition was implemented to avoid fatigue and the habituation of the emotional response over extended testing (see Ref. [30] for the same approach). Before the first run of the official task, participants practiced eight trials of the task using a neutral male young adult face (Y1M). They continued practicing until they achieved 80% accuracy.

2.3. fNIRS measurement

A 48-channel ETG-4000 fNIRS device that utilized 695 and 830 nm lights (Hitachi Medical Co., Tokyo, Japan) was used to measure hemodynamic changes occurring in the frontal lobes during the emotional ANT. The sampling rate was 10 Hz. Each participant wore an EasyCap mounted with 16 emitters and 16 detectors, and the cap size was determined based on their head circumference (Fig. 2A). The emitters and detectors were arranged in two 4 × 4 arrays, centering at Fz overall. The interoptode distance varied from 29 to 31 mm (30 mm for the 56 cm head size), such that the optode locations were fixed with respect to the 10–20 system.

Taking advantage of the known probes' coordinates in the 10–20 system, the probes and channels were rendered onto the Montreal Neurological Institute (MNI) standard brain using the NFRI toolbox (Fig. 2B) [31]. The probabilistic anatomical locations of channels were then labelled based on the Brodmann area (BA) atlas. Based on the highest probabilistic value of the neural structure underneath each fNIRS channel, five subregions were formed—the frontopolar (BA 10), dorsomedial (BA 6, 8), dorsolateral (BA 9, 46), ventrolateral (BA 44, 45, 47), and posterolateral (BA 6) frontal lobes (Fig. 2C). Because fNIRS variables have been found to exhibit higher test–retest reliability when analyzed at the cluster level than at the channel level [32], statistical analyses were conducted at the cluster level in the present study. One participant was excluded for having all bad channels across the bilateral ventrolateral frontal lobes.

All regions except the frontopolar cortex have been implicated in alerting [30], orienting [33,34], and/or executive control [35,36] (see Ref. [9] for review). Therefore, the present study focused on the dorsomedial, dorsolateral, ventrolateral, and posterolateral regions of interest (ROIs). In addition, the two hemispheres were collapsed due to no hypotheses regarding laterality effects within individual ROIs.

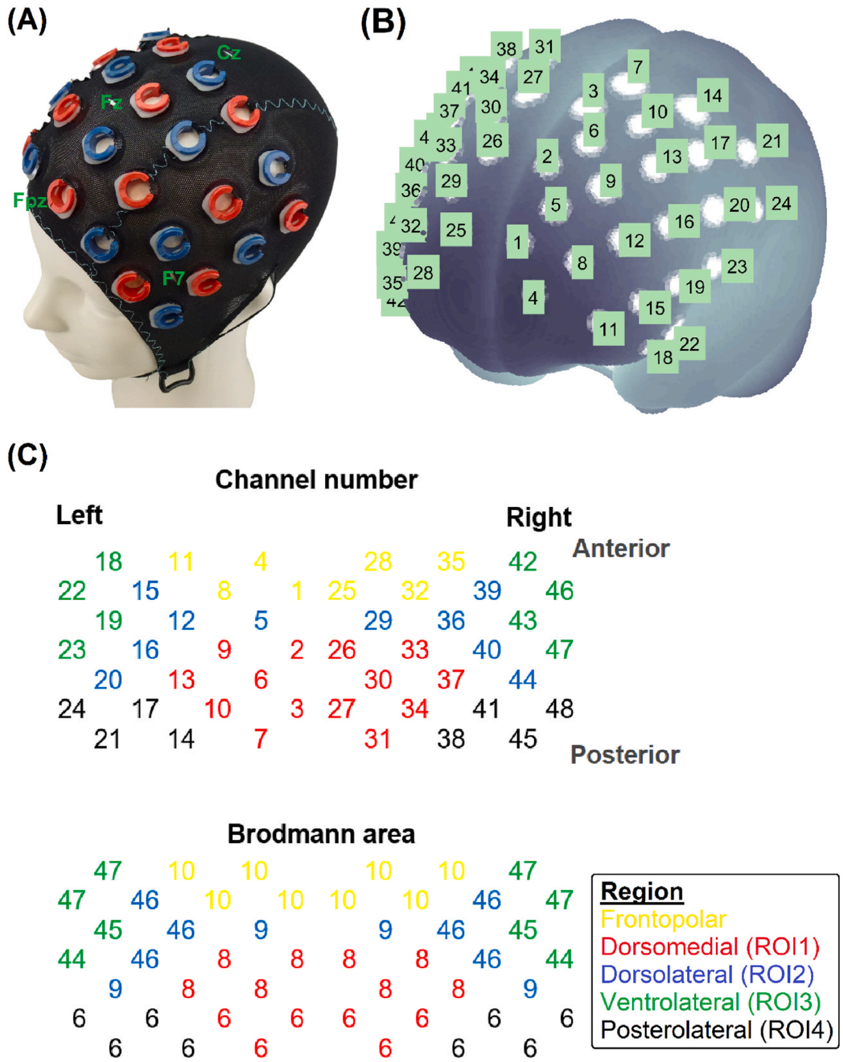

Fig. 2. Optode and Channel Arrangement for Functional Near-Infrared Spectroscopy Measurement. *Note* (A) Example of a recording cap (red: emitters; blue: sources). (B) Spatial registration of channels. (C) Four regions of interest (ROIs) classified based on Brodmann areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.4. fNIRS data preprocessing

The fNIRS data were preprocessed using HomER3 [37] and custom scripts on MATLAB R2020a (The MathWorks, Inc., Natick, MA). First, channels with an overall signal-to-noise ratio <20 dB (noisy channels) [38] or > 65 dB (saturated channels) were rejected. Following this procedure, an average of 4.5% of channels ($SD = 5.4\%$) was rejected. Negative values in intensity due to noisy data were corrected, followed by the conversion of raw intensity signals to optical density changes. The temporal derivative distribution repair (TDDR) algorithm was then applied to remove baseline shift and spike artifacts [39]. Also, principal component analysis (PCA) was performed to remove systemic confounds. Because the first component has been found to have the highest correlation with the global average signal, this component was removed for each participant [40]. Next, a 5th order 0.01–0.5 Hz Butterworth bandpass filter was applied to remove cardiac artifacts and slow signal drifts.

The optical density data were converted to HbO and HbR changes via the modified Beer–Lambert law. The differential pathlength factor was corrected for wavelength and age in accordance with the general equation [41]. Next, block averaging was conducted, and all time points within each 32-s task block were averaged across repetitions for each condition and for HbO and HbR separately. The mean values were corrected for baseline using the 2 s before the block onset. Finally, data were averaged across all channels with the notable exception of bad channels for each ROI. HbO was analyzed because it has been shown to have a better signal-to-noise ratio than HbR [42].

2.5. Data analysis

Accuracy and mean RT were first calculated for each condition of the emotional ANT. The mean RT calculation was based on correct trials, and *RT*s < 150 ms and 2.5 *SD*s above the respective mean were excluded. One participant achieved almost 0% accuracy across the incongruent conditions, suggesting incomprehension of the task. This participant was excluded from analysis. For the remaining participants ($n = 47$), a ceiling effect was detected for accuracy across conditions (i.e., mean accuracies >97.6%).

For mean RT, alerting (no cue > center cue), orienting (center cue > spatial cue), and executive control (incongruent > congruent) scores were first examined and compared between the neutral and angry conditions separately. Larger alerting and orienting scores and smaller executive control scores represent greater efficiency. Then, a repeated measures ANOVA with emotion (neutral, angry), cue (no, center, spatial), and congruency (congruent, incongruent) was conducted to fully describe task performance. The Greenhouse–Geisser correction was applied when the sphericity assumption was violated. Significant main and interaction effects, if any, were followed up by conducting further repeated measures ANOVAs and paired *t*-tests with Bonferroni correction. Planned comparisons between the no-cue and center-cue conditions and between the center-cue and spatial-cue conditions were conducted to understand cue effects. Furthermore, taking advantage of the fact that participants had been repeatedly exposed to trials of the same condition, additional analyses were performed after dividing each block into two equal halves (trials 1–4 and 5–8) to examine the evolution of attention efficiency over time (i.e., time-on-task and habituation effects).

A similar analytic procedure was undertaken to analyze fNIRS data. First, the overall changes in frontal HbO were examined for the alerting (center cue > no cue), orienting (spatial cue > center cue), and executive control (incongruent > congruent) contrasts. For all contrasts, a larger difference represents greater activation. A repeated measures ANOVA with emotion, cue, congruency, and region (dorsomedial, dorsolateral, ventrolateral, and posterolateral) was then conducted on the mean change in HbO. The Greenhouse–Geisser correction was applied where appropriate, and the Bonferroni tests were used for post-hoc testing. Significant effects, if any, were followed up by performing further ANOVAs and *t*-tests. False discovery rate (FDR) correction suitable for fNIRS data was applied to control for multiple comparisons [31,43]. Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 26.0 (IBM Corp., Armonk, NY). Statistical tests were two-tailed, and the alpha level was set at 0.05, unless otherwise specified. For ANOVAs, the partial eta-squared ($\eta p2$) effect size estimates were extracted from the SPSS. According to Cohen [44], $\eta p2 = 0.01$, $\eta p2 = 0.06$, and $\eta p2 = 0.14$ indicate small, medium, and large effect sizes, respectively.

Table 1
Means and standard deviations of accuracy and mean reaction time (RT).

	Neutral			Angry		
	No cue	Center cue	Spatial cue	No cue	Center cue	Spatial cue
Accuracy (%)						
Congruent	99.6 (1.5)	99.6 (2.0)	99.5 (3.6)	99.1 (2.6)	98.3 (2.8)	99.5 (2.9)
Incongruent	99.2 (2.1)	97.6 (3.6)	97.7 (4.6)	97.6 (4.2)	98.9 (2.7)	98.1 (3.7)
Mean RT (ms)						
Congruent	560 (78)	468 (62)	458 (72)	567 (102)	570 (60)	460 (83)
Incongruent	643 (79)	583 (68)	545 (84)	653 (85)	591 (66)	546 (81)

Note. Standard deviations are in parentheses.

3. Results

3.1. Task performance

Table 1 presents the accuracy and mean RT in each condition. Due to ceiling effects, accuracy was not statistically analyzed. For mean RT, the three attention network scores were first examined and compared between the neutral and angry conditions. The scores are presented in Fig. 3A. The alerting, orienting, and executive control scores were significantly different from zero in both the neutral and angry conditions, $ts > 3.40$, $ps < .001$. More interestingly, angry facial cues resulted in significantly smaller alerting, $t(46) = 5.80$, $p < .001$, and executive control scores, $t(46) = 9.60$, $p < .001$, but a significantly larger orienting score, $t(46) = 4.07$, $p < .001$, compared to neutral facial cues.

A repeated measures ANOVA with emotion, cue, and congruency as factors was then conducted on mean RT to fully understand the behavioral effects (Table 2). There were significant main effects of emotion, $F(1, 46) = 43.27$, $p < .001$, $\eta p2 = 0.49$, cue, $F(2, 92) = 154.78$, $p < .001$, $\eta p2 = 0.77$, and congruency, $F(1, 46) = 541.08$, $p < .001$, $\eta p2 = 0.92$. In addition, the Emotion × Cue, $F(1.70, 78.06) = 31.61$, $p < .001$, $\eta p2 = 0.41$, and Emotion × Congruency, $F(1, 46) = 16.55$, $p < .001$, $\eta p2 = 0.27$, interactions were significant, but the Cue × Congruency interaction was not, $F(2, 92) = 2.95$, $p = .057$, $\eta p2 = 0.060$. The three-way Emotion × Cue × Congruency interaction was also significant, $F(2, 92) = 28.70$, $p < .001$, $\eta p2 = 0.38$. Therefore, the effects of cue and congruency were analyzed separately for the neutral and angry conditions (Fig. 3B).

In the neutral condition, a repeated measures ANOVA with cue and congruency as factors showed significant main effects of cue, $F(2, 92) = 157.82$, $p < .001$, $\eta p2 = 0.77$, and congruency, $F(1, 46) = 328.58$, $p < .001$, $\eta p2 = 0.88$, along with a significant Cue × Congruency interaction, $F(1.77, 81.52) = 5.59$, $p = .007$, $\eta p2 = 0.11$. Planned t-tests revealed significantly faster RTs following a center cue than following no cue in both the congruent and incongruent conditions, $ts > 8.09$, $ps < .001$, $ds > 1.18$. In addition, RTs were significantly faster after a spatial cue than after a center cue in the incongruent condition, $t(46) = 4.44$, $p < .001$, $d = 0.65$, but not in the congruent condition, $t(46) = 1.48$, $p = .15$, $d = 0.22$. Furthermore, there was a significant congruency effect across all three cue conditions, $ts > 9.91$, $ps < .001$, $ds > 1.44$. Hence, the significant Cue × Congruency interaction was driven by a larger congruency effect after a center cue than following no cue or a spatial cue. The congruency effects in the latter two cue conditions did not significantly differ from each other.

In the angry condition, a repeated measures ANOVA with cue and congruency as factors similarly revealed significant main effects of cue, $F(1.77, 81.42) = 99.21$, $p < .001$, $\eta p2 = 0.68$, and congruency, $F(1, 46) = 176.76$, $p < .001$, $\eta p2 = 0.79$, as well as a significant Cue × Congruency interaction, $F(2, 92) = 21.41$, $p < .001$, $\eta p2 = 0.32$. However, planned t-tests demonstrated significantly faster RTs following a center cue than following no cue in the incongruent condition, $t(46) = 6.76$, $p < .001$, $d = 0.99$, but not in the congruent condition, $t(46) = 0.28$, $p = .78$, $d = 0.04$. In addition, RTs were significantly faster after a spatial cue than after a center cue in both the congruent and incongruent conditions, $ts > 5.60$, $ps < .001$, $ds > 0.82$, but this orienting effect was greater for the congruent condition. Congruent RTs were significantly faster than incongruent RTs across all three cue conditions, $ts > 3.68$, $ps < .001$, $ds > 0.54$. Therefore,

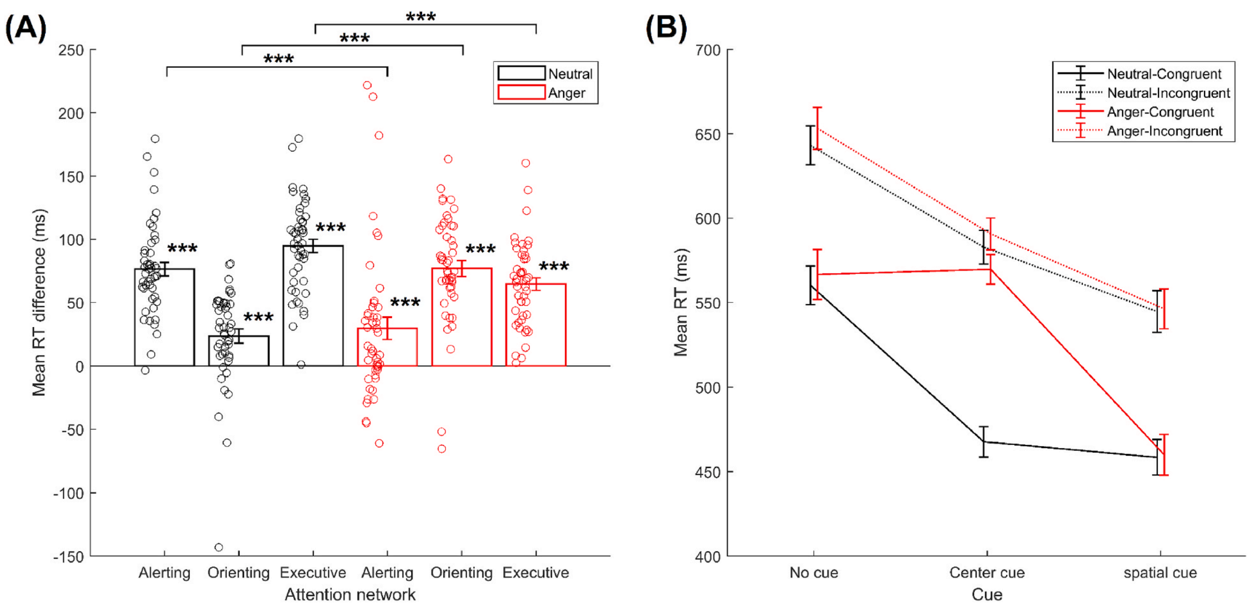

Fig. 3. Mean Reaction Times (RTs) in the Emotional Attention Network Test. *Note.* This figure illustrates (A) the alerting (center cue > no cue), orienting (spatial cue > center cue), and executive control (incongruent > congruent) network scores, and (B) mean RTs in individual conditions. Error bars represent 1 standard error ± the mean. Asterisks indicate the level of significance of one-sample and paired t-tests (two-tailed). ***$p < .001$.

Table 2
Repeated measures ANOVA with emotion (neutral, angry), cue (No, center, spatial), and congruency (congruent, incongruent) as factors conducted on mean reaction time (RT).

	df	*F*	*p*	*η*p2
Emotion	1, 46	43.27	<.001***	.49
Cue	2, 92	154.78	<.001***	.77
Congruency	1, 46	541.08	<.001***	.92
Emotion × Cue	1.70, 78.06	31.61	<.001***	.41
Emotion × Congruency	1, 46	16.55	<.001***	.27
Cue × Congruency	2, 92	2.95	.057	.06
Emotion × Cue × Congruency	2, 92	28.70	<.001***	.38

Note. Asterisks indicate the level of significance. ***$p < .001$.

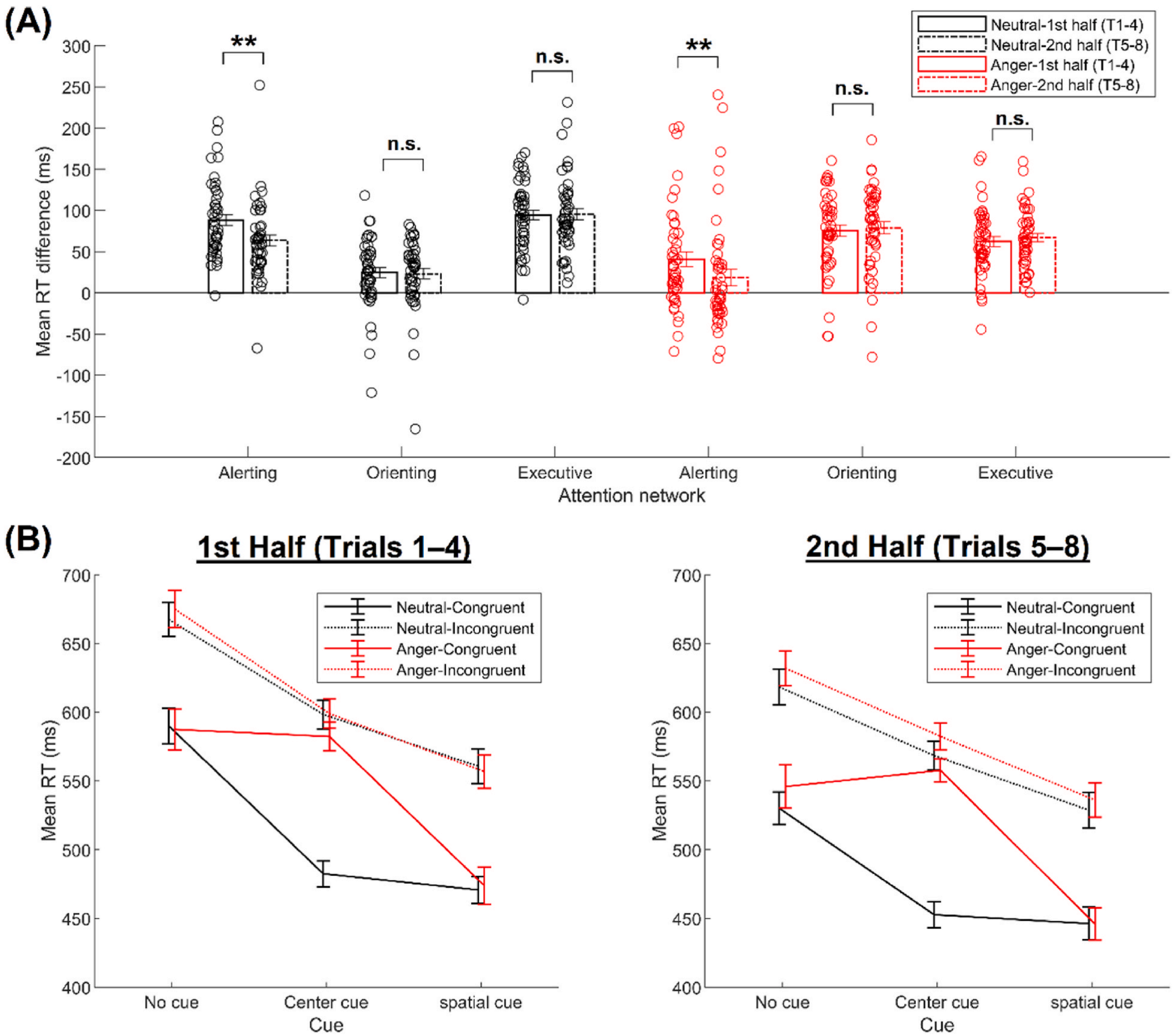

Fig. 4. Mean Reaction Times (RTs) during the Two Halves within Each Block of the Emotional Attention Network Test. *Note.* This figures shows (A) the alerting, orienting, and executive network scores, and (B) mean RTs in individual conditions. Error bars represent 1 standard error ± the mean. Asterisks indicate the level of significance of paired *t*-tests (two-tailed). **$p < .01$.

the significant Cue × Congruency interaction was driven by a smaller congruency effect after a center cue than following no cue or a spatial cue. The congruency effect in the latter two cue conditions was statistically comparable.

3.2. Stability of attention efficiency over time

Next, the stability of attention efficiency over time was investigated by comparing task performance between the two halves of each block. A repeated measures ANOVA with time and emotion as factors was conducted on each attention network score (Fig. 4A). For alerting, the main effect of time was significant, $F(1, 46) = 18.92$, $p < .001$, $\eta p2 = 0.29$, but the Time × Emotion interaction was not, $p = .77$. For orienting and executive control, neither the main effect of time nor the Time × Emotion interaction was significant, $ps > .54$. Thus, while alertness declined over time, orienting and executive control efficiency remained stable over time, regardless of the presence of a threatening stimulus.

Next, a repeated measures ANOVA with time, emotion, cue, and congruency as factors was conducted to fully investigate the evolution of task performance over time (Fig. 4B). Focusing on time-related effects, the main effect of time was significant, $F(1, 46) = 216.92$, $p < .001$, $\eta p2 = 0.83$, implying that participants reacted faster over time. In addition, a significant Time × Emotion interaction was detected, $F(1, 46) = 4.24$, $p = .045$, $\eta p2 = 0.08$, which was attributable to a greater improvement in RT over time in the neutral

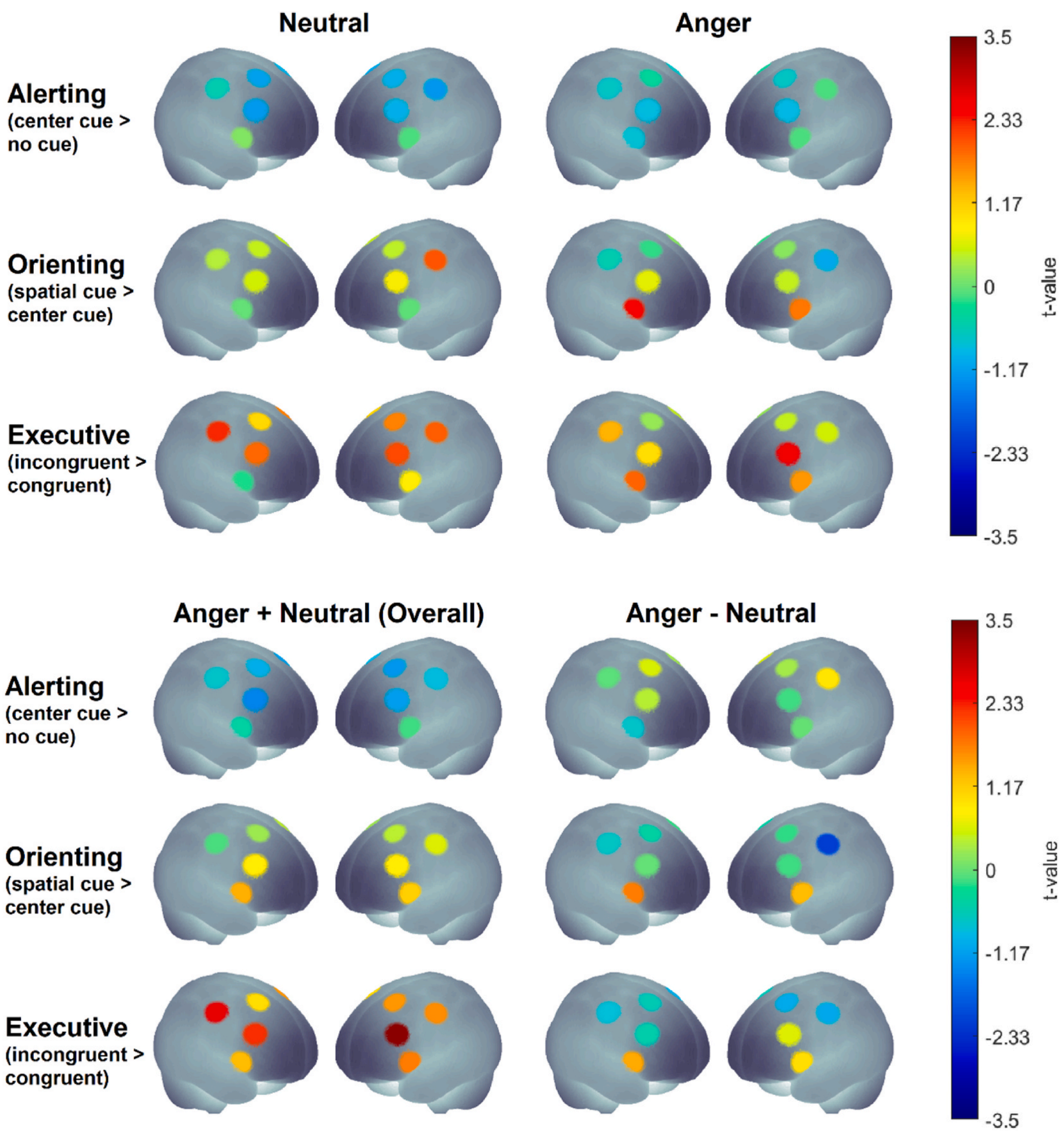

Fig. 5. Topographical Distribution (t-Map) of Mean Changes in Oxyhemoglobin Concentration for the Three Attentional Networks during the Emotional Attention Network Test. *Note.* The circles represent the centroids of the regions of interest, including the dorsomedial, dorsolateral, ventrolateral, and posterolateral frontal lobes.

condition than in the angry condition. A significant Time × Cue interaction was also present, $F(2, 92) = 13.31$, $p < .001$, $\eta p2 = 0.22$, which was driven by a decline in the alerting effect over time. No three-way and four-way interaction effects involving time were significant, $ps > .44$, suggesting that the context-specific effects of angry faces persisted over the passage of time.

3.3. Relationships among the attention network scores

Considering the ongoing controversy regarding the relationship among the three processes of attention [11,29,45], we calculated Pearson's correlations among the three attention network scores (across all trials) separately for the neutral and angry conditions. In the neutral condition, none of the correlations were significant after Bonferroni correction, rs from −0.27 to 0.13, ps from 0.071 to 0.84. In contrast, all three correlations were significant in the angry condition after Bonferroni correction. Specifically, the alerting score was significantly negatively correlated with the orienting score, $r(45) = -0.44$, $p = .002$, and positively with the executive control score, $r(45) = 0.36$, $p = .013$. In addition, the orienting score was significantly negatively correlated with the executive control score, $r(45) = -0.40$, $p = .005$.

3.4. fNIRS Results

Fig. 5 illustrates the topographical distribution of mean changes in frontal HbO during the emotional ANT. In addition, Table 3 presents the means and standard deviations of these changes in individual ROIs and across ROIs. Given that various frontal ROIs have been implicated in the alerting, orienting, and executive networks, we first analyzed the mean changes in HbO collapsed over ROIs for the three attentional networks, followed by comparisons between the neutral and angry conditions (Fig. 6A). First, a series of planned t-tests were conducted for each contrast. We found a significant increase in mean HbO for the executive attention network in both the neutral condition, $t(46) = 2.19$, $p = .033$, and the angry condition, $t(46) = 2.21$, $p = .032$. However, no other contrasts and no comparisons between the neutral and angry conditions yielded significant results, ts from −1.19 to 0.85, ps from 0.24 to 0.52.

Next, a repeated measures ANOVA with emotion, cue, congruency, and region as factors was conducted for a more detailed investigation of frontal activation during task performance (Table 4). We detected a significant main effect of congruency, $F(1, 46) = 10.09$, $p = .003$, $\eta p2 = 0.18$, owing to a larger overall increase in frontal HbO in the incongruent condition than in the congruent condition. No other effects were significant, except for the Congruency × Cue × Region interaction, $F(3.16, 145.14) = 2.91$, $p = .034$, $\eta p2 = 0.060$. Nevertheless, a repeated measures ANOVA with cue and region as factors conducted for the congruent and incongruent conditions separately revealed no significant cue effects in either condition, $ps > .09$. Another repeated measures ANOVA with cue and congruency as factors conducted for each ROI also showed no significant cue effects in any region, $ps > .12$.

The ANOVA provided no information about the change in HbO from baseline to the task period. Therefore, we conducted one-sample t-tests to determine whether the mean change in HbO collapsed over ROIs was significantly different from zero in each of the 12 (2 emotion × 3 cue × 2 congruency) individual conditions (Fig. 6B). After FDR correction, 8 of the 12 tests were significant (critical p-value = .032). Specifically, the increase in HbO was significant across all six incongruent conditions, ts from 2.57 to 4.29, $ps < .022$. In the congruent condition, we detected a significant HbO increase only in the neutral no-cue and angry spatial-cue conditions, ts from 2.22 to 2.69. ps from 0.010 to 0.032. No other conditions yielded significant results, $ps > .13$. Thus, the PFC was activated mainly during the incongruent condition.

4. Discussion

This study applied Posner's tripartite model of attention and the biased competition theory to understand the impact of threatening facial expressions with multiple, competing attributes on attention. Using the emotional variant of the ANT implemented in blocks of

Table 3
Means and Standard Deviations of Mean Changes in Oxyhemoglobin Concentration (HbO; in μMol).

	Neutral			Angry		
	No cue	Center cue	Spatial cue	No cue	Center cue	Spatial cue
Congruent						
Dorsomedial	32.5 (130.2)	11 (139.4)	24.8 (171.8)	12 (136.9)	36.7 (163.1)	31.5 (189.4)
Dorsolateral	38.3 (85.9)	11.6 (109.3)	16.1 (130.1)	31.9 (130.7)	21.6 (118.1)	33 (117)
Ventrolateral	57.2 (155.3)	16.4 (177.1)	14.8 (218.8)	24.6 (188.5)	−22.4 (208.9)	58.3 (169.1)
Posterolateral	9.8 (154.8)	11.6 (152.8)	21 (167.2)	26.4 (125.6)	31.7 (174)	22.5 (172.8)
All regions	34.4 (86.8)	12.6 (94.4)	19.2 (133.1)	23.7 (104.9)	16.9 (107.8)	36.3 (111.2)
Incongruent						
Dorsomedial	68.7 (144.7)	35.2 (164.3)	42 (135.1)	63.6 (169.4)	13.9 (125.5)	19.7 (159.2)
Dorsolateral	49.2 (95.2)	37.5 (111.7)	58.3 (120.9)	67.1 (144.7)	45.7 (98.1)	55.2 (132.8)
Ventrolateral	6.1 (168.3)	47.8 (144.9)	47.8 (150.2)	42.6 (219.3)	69 (163.3)	91.3 (240)
Posterolateral	73.5 (121.5)	26 (137.4)	72.4 (153.1)	72.2 (181.3)	47 (136.1)	16.9 (160.9)
All regions	49.4 (78)	36.6 (104.8)	55.1 (98.9)	61.4 (138.4)	43.9 (87.7)	45.8 (121)

Note. Channels were classified into four regions of interest based on Brodmann areas (DL: dorsomedial, BA 6, 8; DL: dorsolateral, BA 9, 46; VL: ventrolateral, BA 44, 45, 47; PL: posterolateral, BA 6). Standard deviations are in parentheses.

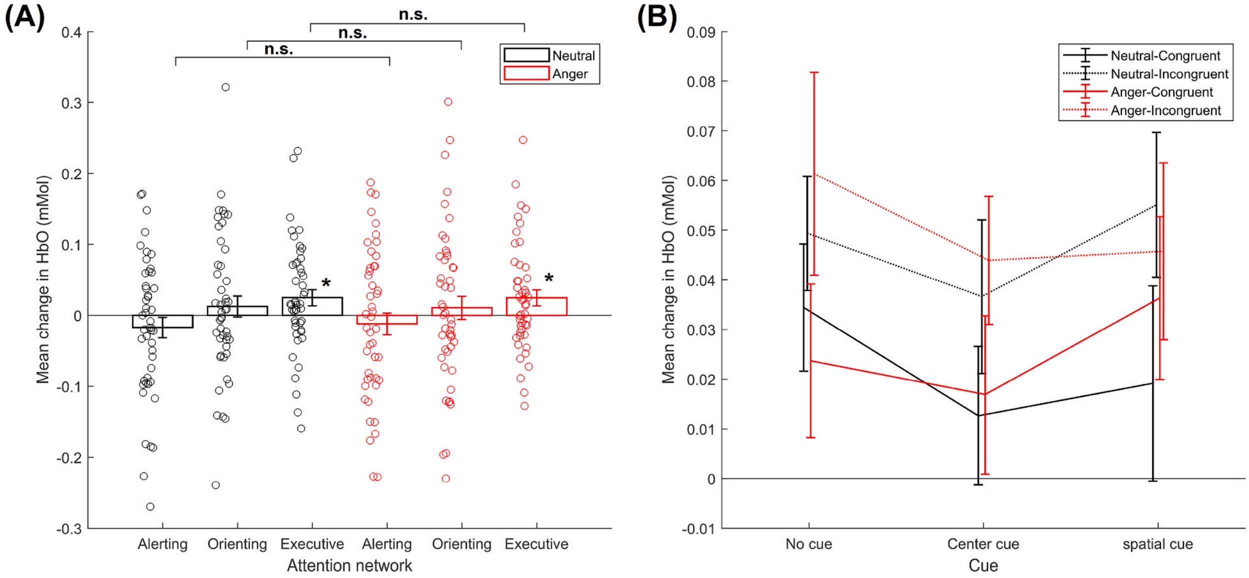

Fig. 6. Mean Changes in Frontal Oxyhemoglobin Concentration (HbO) Collapsed over All Regions of Interest during the Emotional Attention Network Test. *Note.* This figure demonstrates (A) mean changes representing the alerting (center cue > no cue), orienting (spatial cue > center cue), and executive (incongruent > congruent) contrasts, and (B) mean changes in individual conditions. Error bars represent 1 standard error ± the mean. Asterisks indicate the level of significance of paired *t*-tests (two-tailed). *$p < .05$.

Table 4
Repeated measures ANOVA with emotion, cue, congruency, and region as factors conducted on mean change in oxyhemoglobin concentration.

	df	*F*	*p*	ηp2
Emotion	1, 46	0.12	.73	.00
Cue	2, 92	0.98	.38	.02
Congruency	1, 46	10.09	.0027**	.18
Region	1.5, 66.6	0.15	.80	.00
Emotion × Cue	2, 92	0.03	.97	.00
Emotion × Congruency	1, 46	0.00	.99	.00
Cue × Congruency	2, 92	0.02	.98	.00
Emotion × Cue × Congruency	2, 92	0.64	.53	.01
Emotion × Region	1.7, 77.6	0.74	.46	.02
Cue × Region	3.0, 139.6	0.93	.43	.02
Emotion × Cue × Region	3.0,137.1	1.59	.19	.03
Congruency × Region	1.7, 79.4	0.37	.66	.01
Emotion × Congruency × Region	1.3, 61.7	2.06	.15	.04
Cue × Congruency × Region	3.2, 145.1	2.91	.034*	.06
Emotion × Cue × Congruency × Region	2.7, 129.8	0.26	.83	.01

Note. Asterisks indicate the level of significance. *$p < .05$, **$p < .01$.

trials of the same condition, as well as fNIRS, the effects of angry faces compared to neutral faces were examined by comparing flanker task performance (1) in the presence and absence of a facial cue (alerting), (2) in the presence of a spatially predictive and non-predictive facial cue (orienting), and (3) in the context of automatic and effortful processing after the cue presentation (executive control). Behavioral results showed that angry faces affected all three processes, and these effects were intercorrelated. More importantly, the interfering effects of angry faces occurred only during the congruent-flanker, center-cue condition, and such effects persisted over the passage of time. In addition, fNIRS results revealed frontal cortical activation during executive control only, and neither emotion nor cue significantly moderated such activation. Overall, the present study found context-specific effects of the angry face on various processes of attention, although the underlying neural mechanisms require further investigations.

The present task differed from the standard ANT in two major aspects. First, a face instead of an asterisk was used as the cue. Second, the blocked design instead of the event-related design was used. Notwithstanding these adaptations, results in the neutral (i.e., control) condition suggest that the present neutral condition was comparable to the standard ANT, and that the task manipulation was successful. Specifically, participants displayed behavior consistent with the existence of the alerting, orienting, and executive control processes. In addition, the magnitude of the three attention network scores (alerting: $M = 76$ ms; orienting: $M = 24$ ms; executive control: $M = 95$ ms) was comparable to that reported in a pioneer event-related fMRI study on the ANT (alerting: $M = 60$ ms; orienting: $M = 31$ ms; executive control: $M = 102$ ms) [30]. Furthermore, the present findings generally agree with previous research showing a larger congruency effect after a center cue than after no cue or a spatial cue [11,29].

Threatening faces often have a significant impact on cognitive task performance [5,6]. According to the biased competition theory, stimuli compete for processing, and emotional stimuli tend to grab attention, leaving fewer resources for processing other stimuli [6–8]. However, according to Posner's tripartite model [9,10], attention consists of at least three distinguishable processes, and whether threatening faces affect all three processes was poorly known. In the present study, the alerting, orienting, and executive control indices were found to be different between the angry and neutral conditions, suggesting that threatening faces indeed affect all three attentional processes. Unlike this study, two previous studies found no significant difference in RTs between angry and neutral face trials in any of the three attentional processes [13,14]. However, the current task differed from that task in two fundamental ways. First, while those studies focused on how facial emotions affected the subsequent attentional processing of the asterisk cue, the present study investigated how threatening faces directly moderated the three processes of attention. Second, while previous studies used task-irrelevant emotional stimuli, the present study used threatening faces that conveyed both useful and irrelevant information with respect to the current goal.

More importantly, the current study showed that the interfering effect of threatening faces was observed only during the congruent-flanker, center-cue condition. This finding is in keeping with the biased competition theory. Specifically, according to this theory, both bottom-up and top-down mechanisms interact and influence the competition between objects or visual features [7,8]. In the context of the emotional ANT, bottom-up processes were comparable among angry-cue blocks due to similar levels of threat salience. However, the degree of control processes varied among angry-cue blocks: the level of control processes was lowest during the congruent-flanker, center-cue condition because there was neither expectancy of conflict nor anticipation of the target's location. As such, top-down biases were smallest during this condition, and bottom-up biases towards the task-irrelevant emotional content eliminated the benefits of the cue. In contrast, other angry-cue conditions involved the anticipation of conflict, target's location, or both. These enabled top-down biases toward the task-relevant attributes of the face, which led to the preservation of cue benefits. Thus, the current findings support the adequacy of using the bottom-up vs. top-down framework in the biased competition theory to explain the context-specific effects of multi-attribute threatening faces on attention. They offer essential insights into how various attributes of threat-related social stimuli interact and alter attention.

The present findings of null correlations in the neutral condition support the notion that alerting, orienting, and executive control are three minimally related attentional processes in the absence of emotion [11,30]. However, the three attentional network scores were found to be significantly interrelated when angry faces were present, implying that these scores reflected a common influence: sensitivity to threat or negative emotion. Specifically, the negative correlation between the alerting and orienting scores implies that the more likely an individual's attention was drawn toward the angry center cue and away from the target's location, the more likely the person's attention would be directed to the angry spatial cue's location (i.e., the target's location). Because threatening faces had a significant impact on attention in the congruent condition but not in the incongruent condition, the alerting and orienting scores were also correlated with the executive control score, which varied as a function of the difference between congruent and incongruent RTs.

Regarding fNIRS results, significant activation in the frontal cortex was observed during conflict resolution. This congruency effect has been widely reported in the fMRI and fNIRS literature [46,47] and is consistent with the broader role of the lateral PFC in cognitive control [48,49]. Unexpectedly, we identified no significant frontal lobe activation during the alerting and orienting processes. These findings add to the mixed literature regarding the role the frontal lobes play in alerting and orienting during the ANT. Lesion studies have provided evidence that the PFC and premotor cortex contribute to conflict resolution only, whereas subcortical structures (e.g., thalamus and brain stem) and the parietal cortex contribute to alerting and orienting functions, respectively [50,51]. In fMRI studies, some studies [30,52] but not all [53] observed frontal lobe activation for the alerting network. However, the major activation site was the left inferior frontal gyrus in Fan et al. [30] but the dorsomedial frontal cortex in Xuan et al. [52]. Due to the use of different cues and cue duration across studies, task characteristics may moderate frontal lobe involvement during the alerting process. For the orienting process, the major activation sites varied considerably across studies [30,52,53], and the most consistently activating region was the precentral gyrus (i.e., primary motor cortex). Therefore, the null orienting effect could be because this region was out of reach of the present fNIRS measurement. Overall, the frontal cortex appears to be more involved in executive control (conflict resolution) than in alerting, orienting, or the emotional modulation of attention.

4.1. Limitations and future directions

This study has several limitations, including those inherent in the fNIRS technique. First, the fNIRS measurement was confined to the frontal cortical surface and did not cover nonfrontal regions that have previously been implicated in alerting (locus-coeruleus and thalamus), orienting (superior parietal cortex), executive control (intraparietal lobule), and emotion (amygdala and insula) [33,35,49, 54]. Second, due to hardware limitations, systemic noise in fNIRS signals was removed using PCA and filtering instead of short-separation regression. Third, the present sample consisted of nonpsychiatric young adults. Because of structural and functional changes that take place in different parts of the brain throughout development and during the ageing process, the findings of this study may not be generalizable to other age groups. To further understand the neurocognitive effects of threatening faces on attention, future work would benefit from using more comprehensive neuroimaging methods (e.g., fMRI) and studying other populations.

4.2. Conclusions and implications

Through application of the tripartite model of attention and the biased competition theory, the present study clarifies the influence of threat-related social stimuli on attention, as well as the boundary of the effect. The findings have several important implications. For example, the finding that anger could prevent someone from utilizing or paying attention to task-relevant details suggests that displaying anger (task-irrelevant information) while teaching someone certain knowledge or skills (task-relevant information) may result in ineffective teaching. In addition, a better characterization of the interaction between socioemotional and attentional processes would facilitate a more holistic understanding of attention in various neuropsychiatric conditions, including mood and anxiety disorders that are prone to negative attentional bias [55,56] and autism spectrum disorder that is associated with socioemotional impairments [57,58].

Author contribution statement

Michael K. Yeung: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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