

Neural Processing of Fearful Faces: Effects of Anxiety are Gated by Perceptual Capacity Limitations

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Debate continues as to the automaticity of the amygdala's response to threat. Accounts taking a strong automaticity line suggest that the amygdala's response to threat is both involuntary and independent of attentional resources. Building on these accounts, prominent models have suggested that anxiety modulates the output of an amygdala-based preattentive threat evaluation system. Here, we argue for a modification of these models. Functional magnetic resonance imaging data were collected while volunteers performed a letter search task of high or low perceptual load superimposed on fearful or neutral face distractors. Neither high- nor low-anxious volunteers showed an increased amygdala response to threat distractors under high perceptual load, contrary to a strong automaticity account of amygdala function. Under low perceptual load, elevated state anxiety was associated with a heightened response to threat distractors in the amygdala and superior temporal sulcus, whereas individuals high in trait anxiety showed a reduced prefrontal response to these stimuli, consistent with weakened recruitment of control mechanisms used to prevent the further processing of salient distractors. These findings suggest that anxiety modulates processing subsequent to competition for perceptual processing resources, with state and trait anxiety having distinguishable influences upon the neural mechanisms underlying threat evaluation and "top-down" control.

Keywords: amygdala, attention, emotion, fMRI, perceptual load, prefrontal cortex

Introduction

The long-running debate over the extent to which selective attention can prevent the processing of task-irrelevant distractors (Kahneman and Treisman 1984; Lavie 2000, 2005) has recently been rekindled by claims about the "special" status of threat-related distractors. Specifically, a number of neuroimaging studies have reported that the amygdala response to threat-related stimuli such as fearful faces is not modulated by attentional focus, leading to the suggestion that threat stimuli may be processed "automatically," unconstrained by the availability of attentional resources, possibly as a result of a direct subcortical thalamo-amygdala pathway (Vuilleumier and others 2001; Dolan and Vuilleumier 2003).

Such claims for the automatic processing of threat-related stimuli have been countered by suggestions that the attentional paradigms used in these studies have placed insufficient demands on attentional resources, with spare attentional capacity facilitating the processing of threat-related distractors (Pessoa and others 2002). Indeed, using perceptually demanding versions of a task in which participants matched the orientation of bars presented in the periphery, Pessoa and others (2002, 2005) reported no differential amygdala response

to fearful versus neutral faces presented at fixation. This line of argument draws upon work by Lavie (1995, 2000) who proposed a model of selective attention according to which distractor processing is prevented when task-related processing exhausts perceptual capacity limits but under conditions of low perceptual load spare attentional resources result in the perceptual processing of distractors.

Until recently, these neuroimaging investigations of threat processing have proceeded relatively independently of the cognitive literature on anxiety. Here, studies using emotional "Stroop" and dot probe tasks have reported that clinically anxious participants show heightened interference from threat-related stimuli (MacLeod and others 1986; Williams and others 1996). Such findings have been observed even when awareness of threat stimuli is reduced or eliminated by backward masking (Mogg and others 1993; Fox 1996). This has led to models of anxiety in which a preattentive "threat-evaluation" system determines the threat value of stimuli entering the environment, the strength of the output signal from this system varying according to participants' anxiety levels (Mathews and others 1997; Williams and others 1997).

Initial attempts have been made to integrate this work with the neuroscience literature on the amygdala's response to threat. Models have been put forward which accord the amygdala a central role in a preattentive, automatic threat detection/evaluation system, the output of which is modulated by anxiety (Mathews and Mackintosh 1998; see also Öhman and Wiens 2004). To date, however, there have been few attempts to test these models directly. In an early study (Bishop and others 2004a), we adapted the paradigm used by Vuilleumier and others (2001) to examine the extent to which the amygdala response to threat distractors depends upon individual state anxiety levels. Volunteers were presented with 2 houses and 2 faces presented above and below and to the left and right of a central fixation cross. In one condition, their task was to ignore the houses and match the faces for identity. In the other condition, they matched the houses while attempting to ignore the faces. Critically, the expression of the faces could be either neutral or fearful. We found that low state anxious volunteers only showed an increased amygdala signal to attended threat-related stimuli (i.e., fearful faces), but high state anxious volunteers showed an increased amygdala signal to both attended and unattended threat-related stimuli. At first glance, this seems consistent with modulation by anxiety of a preattentive threat-evaluation mechanism. However, the recent studies by Pessoa and others (2002, 2005) raise an alternative possibility, namely, that the matching paradigm used allowed for spare perceptual resources to be allocated to nominally unattended locations in the visual display.

Consequently, the aim of the current study was to investigate the stage of processing at which anxiety modulates the neural response to threat distractors. Here, we drew on the recent literature on modulation of selective attention by perceptual load. Using manipulations of perceptual load, Lavie and colleagues have demonstrated that processing of salient distractors occurs under conditions of low perceptual load (where there are few items to be perceived and perceptual identification is not difficult) but is abolished under high perceptual load conditions (where there are many items to be perceived or perceptual identification is more demanding on attention). This characteristic modulation of distractor processing has been shown for a wide range of distractor stimuli, such as moving dot patterns, lexical stimuli that promote a conflicting response to that required by the current target, and colorful or novel scenes (Rees and others 1997; Lavie 2000, 2001, 2005). It has also been shown to be specific to manipulations of perceptual load, heightening working memory load conversely leading to an increase in distractor processing (Lavie 2005).

A finding of particular interest is that groups characterized by weakened attentional control—specifically the elderly and children—typically show larger distractor effects under low perceptual load but not high perceptual load than do groups with intact attentional control (Maylor and Lavie 1998; Huang-Pollock and others 2002). Lavie suggests that the increased distractor processing under low perceptual load shown by these groups may reflect a failure to actively recruit cognitive control mechanisms to prevent salient distractors from receiving further processing. Under high perceptual load conditions, it is held that the need to regulate competition from salient distractors does not arise, as distractors are not fully perceptually processed (Lavie 2000, 2005). This is effectively a hybrid of early and late accounts of selective attention, with the demands of the primary task determining whether or not distractors make it past the initial perceptual bottleneck, and active recruitment of top-down control processes being required to prevent the further processing of salient distractors that do pass this stage. The role of cognitive control in this account is extremely pertinent, as there is mounting evidence for impaired recruitment of cognitive control mechanisms in anxiety (Fox 1994; Bishop and others 2004b). Consideration of this model leads to the novel prediction that anxiety levels will modulate both the amygdala (“threat evaluation”) and prefrontal (“control”) response to threat distractors under low perceptual load, but not under high perceptual load—neither neutral nor threat-related distractors making it past an initial stage of limited perceptual processing resources under the latter condition. On the other hand, if anxiety amplifies threat-evaluation-related activity in the amygdala at a preattentive stage, as proposed by current cognitive models of anxiety (e.g., Mathews and Mackintosh 1998), there should be a modulatory effect of anxiety upon the amygdala response to threat distractors, irrespective of the level of perceptual load.

Materials and Methods

Participants

Eighteen participants (10 females and 8 males, all right handed, aged 18–46 years, mean = 27 years) performed a letter search task adapted from Jenkins and others (2005) while functional magnetic resonance imaging (fMRI) data were acquired. The study was approved by the Cambridgeshire Local Research Ethics Committee and performed in

compliance with their guidelines. Written informed consent was obtained from all participants. Individuals with a history of inpatient psychiatric care, neurological disease or head injury were excluded as were individuals on medication for anxiety or depression. Prior to the fMRI session, participants completed the Spielberger State-Trait Anxiety Inventory (STAI; Spielberger 1983) and a self-report measure of attentional control, the Attentional Control Scale (ACS; Derryberry and Reed 2002). The latter measure contains items tapping both attentional focusing (e.g., “When concentrating, I can focus my attention so that I become unaware of what’s going on in the room around me”) and attentional flexibility (e.g., “It is easy for me to read or write while I’m also talking on the phone”) and has been shown to have high internal consistency, $\alpha = 0.88$ (Derryberry and Reed 2002). On the STAI, participants’ state anxiety scores ranged from 20 to 48 (mean = 32, standard deviation [SD] = 8), their trait anxiety scores from 22 to 62 (mean = 41, SD = 10). These scores are similar to the published norms for this age group (state: mean = 36, SD = 10; trait: mean = 36, SD = 10; Spielberger 1983). Participants’ scores on the ACS ranged from 42 to 65 (mean = 51, SD = 6).

Task

Visual stimuli were back projected onto a translucent screen positioned behind the bore of the magnet, visible via an angled mirror placed above the participant’s head. The letter search task used was adapted from Jenkins and others (2005), experiment 2, and similar to ones used in previous perceptual load studies (reviewed by Lavie 2000, 2001). On each trial, a string of 6 letters superimposed on a task-irrelevant unfamiliar face was presented for 200 ms (Fig. 1). In the current study, the face stimuli used comprised 8 different individuals with fearful and neutral expressions taken from the Pictures of Facial Affect (Ekman and Friesen 1976) and cropped to remove extraneous background information. Fearful facial expressions of conspecifics act as cues to potential danger and have been shown to share some of the functional properties of “prepared” (intrinsically threat related) fear stimuli (Lanzetta and Orr 1986). They have also been used in the majority of studies arguing for the



Figure 1. Example stimuli. On each trial, a string of 6 letters was superimposed on a face presented in the center of the screen. Participants had to indicate whether the letter string contained an “X” or an “N,” a target always being present (face stimuli reproduced with permission, from Ekman and Friesen 1976).

preattentive and automatic processing of threat-related stimuli (Whalen and others 1998, 2004; Vuilleumier and others 2001).

There were 2 imaging acquisition runs, each comprising 12 blocks of 4 trials. The task was to decide whether the letter string contained an “X” or an “N.” In half of the blocks—the “*high perceptual load*” condition—the string comprised a single target letter (N or X) and 5 nontarget letters (H, K, M, W, Z) arranged in random order. In the other half of the blocks—the “*low perceptual load*” condition—the letter string comprised 6 Xs or 6 Ns, reducing attentional search requirements. This manipulation of perceptual load is identical to the one used in Jenkins and others (2005) and conforms to Lavie’s (2005) description of heightening perceptual load by 1) increasing the number of different-identity items that need to be perceived or 2) making perceptual identification more demanding on attention.

There was a 2 s interval between blocks. Within blocks, the interstimulus interval was randomly jittered using an exponential function with a mean of 4.5 s and a minimum of 3 s. A mixed block/event-related design (see Visscher and others 2003) was used—the level of perceptual load for the letter search task (high or low) being varied across blocks, the expression of the faces (fearful or neutral) being varied within blocks on a trial by trial basis. These 2 factors resulted in 4 conditions of interest: high load, fearful distractors; high load, neutral distractors; low load, fearful distractors; low load, neutral distractors. By examining the effect of perceptual load upon the neural response to fearful versus neutral face distractors in individuals with varying levels of anxiety, it was possible to test the competing hypotheses described above.

Image Acquisition

Blood oxygenation level-dependent contrast functional images were acquired with echo-planar T_2^* -weighted (EPI) imaging using a Medspec (Bruker, Ettlingen, Germany) 3T MR system with a head coil gradient set. Each image volume consisted of 21 interleaved 4-mm thick slices; interslice gap: 1 mm; inplane resolution: 3.75×3.75 mm; field of view: 24×24 cm; matrix size: 64×64 ; flip angle: 65.5° ; echo time: 30 ms; voxel bandwidth: 144 kHz; acquisition time: 1.0 s; repetition time: 1.1 s. Slice acquisition was transverse oblique, angled to avoid the eyeballs, and covering the whole brain. Data were acquired in 2 scanning runs of 5 1/2 min. The first 11 volumes of each run were discarded to allow for T_1 equilibration effects.

Image Analysis

Data were analyzed using statistical parametric mapping (SPM) software (Wellcome Department of Imaging Neuroscience, London, UK). Standard preprocessing was conducted using SPM 2 comprising slice timing correction, realignment, undistortion (Cusack and others 2003) and normalization of each participant’s EPI data to the Montreal Neurological Institute (MNI)/ICBM template. Images were resampled into this space with 2 mm isotropic voxels and smoothed with a Gaussian kernel of 10-mm full-width at half-maximum. Modeling was conducted in SPM 99 for comparability with our previous studies (SPM 2 was preferred to SPM 99 for preprocessing due to superiority of the later version for these stages). Trials were modeled with step functions of 0.2 s duration, convolved with the canonical hemodynamic response function to form regressors. Temporal derivatives of these regressors were also included as were realignment parameters for each session in order to account for residual movement-related variance. A high pass filter of 128 s was used to remove low frequency noise. A random-effects analysis was used to analyze data at a group level, modulations by anxiety and by self-reported attentional control being assessed by simple regression against state and trait anxiety scores from the STAI, and ACS scores, respectively. In addition, a multiple regression analysis was conducted in order to examine partial correlations with trait anxiety with ACS scores controlled for and vice versa.

Previously defined regions of interest (ROIs) for dorsal and rostral anterior cingulate cortex (ACC), dorsolateral prefrontal cortex (DLPFC) and ventrolateral prefrontal cortex (VLPFC) were used (Bishop and others 2004b). These comprised 8-mm-radius spheres centered on the following x, y, z coordinates: dorsal ACC (4, 14, 36); rostral ACC (-2, 44, 20); DLPFC ($\pm 34, 36, 24$); VLPFC ($\pm 38, 20, 0$). In addition, the MNI anatomical amygdala ROIs (Tzourio-Mazoyer and others 2002) were used and bilateral ROIs (8-mm-radius spheres) were created for superior

temporal sulcus (STS)—a region implicated in the processing of facial expression (Haxby and others 2000). The central coordinates for the STS ROIs ($\pm 48, -60, 8$) were taken from Hoffman and Haxby (2000). Data were analyzed using a random-effects model with voxel-wise comparisons and small volume corrections applied for activations within each ROI (Worsley and others 1996). All activations are reported using MNI coordinates.

Results

Neuroimaging Results

Increased Amygdala Response to Fearful Face Distractors under Low Perceptual Load

In order to test whether, across participants, perceptual load influenced the amygdala response to unattended fearful faces, we examined the interaction of distractor facial expression (fearful vs. neutral) by perceptual load (low vs. high) in bilateral amygdala ROIs; see Methods for ROI details. Across participants, there was a significant interaction of expression by load in the right amygdala ROI, the selective amygdala response to fearful versus neutral face distractors being greater under low than high perceptual load, $x, y, z = 18, 2, -16, Z = 2.75, P < 0.05$ small volume corrected (svc) (see Fig. 2).

Amygdala and STS Response to Fearful Face Distractors are Modulated by State Anxiety under Conditions of Low but Not High Perceptual Load

There was no significant interaction of distractor expression by load in the left amygdala ROI ($P > 0.1$ svc). However, there was an interaction of expression by load by state anxiety, $x, y, z = -24, 0, -12, Z = 2.36, P = 0.07, svc$ (see Fig. 3a). A median split on the STAI state anxiety subscale was used to divide participants into “low state anxious” and “high state anxious” groups. Figure 3(b) shows the peak mean percentage signal change in the left amygdala to fearful versus neutral face distractors by load and by group. Neither low nor high state anxious participants showed a significantly increased amygdala response to fearful versus neutral distractors under conditions of high perceptual load, whereas high state anxious participants alone showed a selective amygdala response to fearful distractors under conditions of low perceptual load. A parallel interaction of expression by load by state anxiety was also observed in the left STS ROI, $x, y, z = -42, -60, 12, Z = 3.18, P < 0.05, svc$ (see Fig. 3c,d) and a similar trend in the right STS ROI, $x, y, z = 54, -58, 4, Z = 2.42, P = 0.08, svc$.

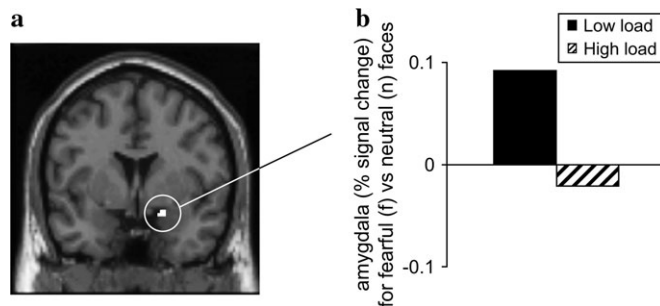


Figure 2. Amygdala activity to fearful versus neutral face distractors as a function of perceptual load (low vs. high). (a) Statistical map of the interaction (thresholded at $P < 0.05$ svc; overlaid on canonical single subject T_1 image). (b) Percent signal change for the peak voxel from (a) for fearful versus neutral face distractors against perceptual load (low, high).

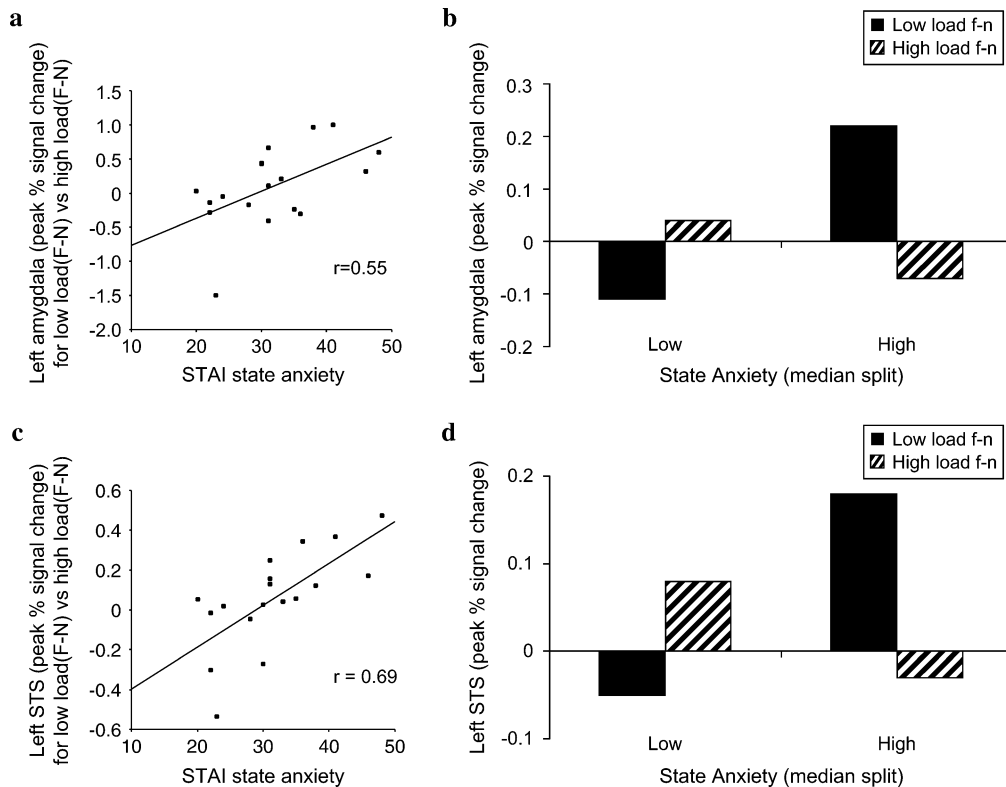


Figure 3. Amygdala and STS activity to fearful versus neutral face distractors (F-N) under low perceptual load relative to fearful versus neutral face distractors (F-N) under high perceptual load against STAI state anxiety. Panels (a) and (c): Activation plotted is mean percentage signal change associated with this contrast for the peak voxel from the left amygdala ROI, $x, y, z = -24, 0, -12, Z = 2.36, P = 0.07$ svc (a) and left STS ROI, $x, y, z = -42, -60, 12, Z = 3.18, P < 0.05$ svc (c). Panels (b) and (d): Amygdala (b) and STS (d) activity to fearful versus neutral face distractors by perceptual load and state anxiety level. Participants were divided into “low” and “high” anxious groups using a median split on state STAI scores. Activity is mean percentage signal change for the peak voxel from (a) and (c), respectively.

There was no significant interaction of expression by load by trait anxiety in either of the amygdala or STS ROIs (P values > 0.1 svc). Averaging across load conditions, there was no significant interaction of distractor expression by state anxiety or distractor expression by trait anxiety in either of the amygdala or STS ROIs (P values > 0.1 svc).

Prefrontal Response to Fearful Face Distractors Is Modulated by Trait Anxiety under Conditions of Low Perceptual Load

Lavie and colleagues’ work with developmental populations led us to predict that anxiety levels would differentially modulate the extent to which prefrontal “control” mechanisms were brought online in response to threat-related distractors under conditions of low versus high perceptual load. There was an interaction of expression by load by trait anxiety in the left VLPFC ROI, $x, y, z = -46, 20, 0, Z = 3.44, P < 0.01$ svc; the left DLPFC ROI, $x, y, z = -34, 44, 24, Z = 3.08, P < 0.02$ svc; and the dorsal ACC ROI, $x, y, z = -2, 12, 40, Z = 3.43, P < 0.01$ svc, (see Fig. 4, panels a, c and e) and a trend toward an interaction in the rostral ACC ROI, $x, y, z = -4, 48, 26, Z = 2.58, P = 0.06$ svc. Figure 4, panels b, d, and f, shows the peak mean percentage signal change in the VLPFC, DLPFC, and dorsal ACC ROIs to fearful versus neutral face distractors by load and by trait anxiety group (low, high; by median split on the STAI trait anxiety subscale). In all 3 regions, low trait anxious individuals showed a selective increase in neural activity to fearful versus neutral distractors under conditions of low perceptual load. No such increase was observed in high trait anxious individuals and neither group showed significantly increased activity in

these regions to fearful versus neutral distractors under conditions of high perceptual load. There was no interaction of expression by load by state anxiety in any of the prefrontal ROIs (P values > 0.1 svc).

Interest in the divergent effects of state and trait anxiety led us to conduct a number of additional analyses. Correlation analyses revealed that, in our current sample of volunteers, trait anxiety scores were significantly correlated both with state anxiety scores, $r = 0.46, P < 0.03$, 1-tailed, and with scores on the ACS, $r = -0.59, P < 0.005$, 1-tailed, the latter confirming previous findings (Derryberry and Reed 2002). There was no significant relationship between state anxiety and ACS scores, $r = 0.14, P > 0.1$. Analysis of the interaction of distractor expression by load by ACS scores showed a similar (but inverse) relationship to that for trait anxiety, with higher ACS scores being associated with an increased left VLPFC, left DLPFC, and dorsal ACC response to fearful versus neutral face distractors under low but not high load, $x, y, z = -46, 20, 0, Z = 3.37, P < 0.01$ svc, $x, y, z = -28, 40, 22, Z = 3.44, P < 0.01$ svc, $x, y, z = -2, 18, 38, Z = 3.75, P < 0.005$ svc, respectively.

A multiple regression analysis was conducted with both trait anxiety and ACS scores entered. This revealed that the interaction of distractor expression by load by trait anxiety in the left DLPFC, left VLPFC, and dorsal ACC ROIs did not survive after the variance accounted for by ACS scores was partialled out but that with the variance accounted for by trait anxiety scores partialled out, there was still a significant interaction of expression by load by ACS scores in left DLPFC and dorsal ACC and a trend toward an effect in left VLPFC; $x, y, z = -28, 40, 22,$

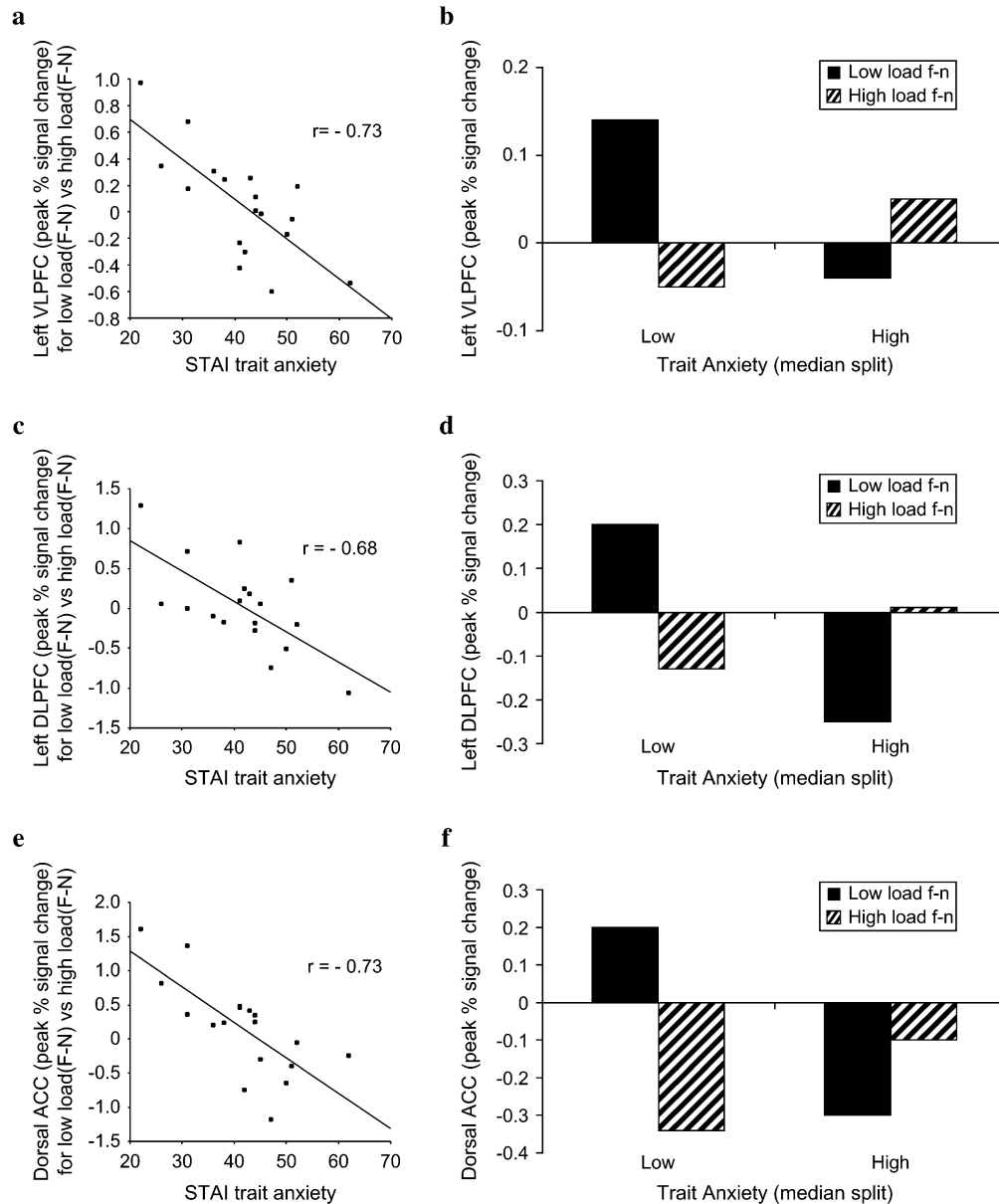


Figure 4. Panels (a), (c), and (e) show VLPFC (a), DLPFC (c), and dorsal ACC (e) activity to fearful versus neutral face distractors (F-N) under low perceptual load relative to fearful versus neutral face distractors (F-N) under high perceptual load against STAI trait anxiety. Activation plotted is mean percentage signal change associated with this contrast for the peak voxel from each ROI, $x, y, z = -46, 20, 0, Z = 3.44, P < 0.01$ svc, $x, y, z = -34, 44, 24, Z = 3.08, P < 0.02$ svc, $x, y, z = -2, 12, 40, Z = 3.43, P < 0.01$ svc, respectively. Panels (b), (d), and (f) show VLPFC (b), DLPFC (d), and dorsal ACC (f) activity to fearful versus neutral face distractors by perceptual load and trait anxiety level. Participants were divided into “low” and “high” anxious groups using a median split on trait STAI scores. VLPFC, DLPFC, and dorsal ACC activity is mean percentage signal change for the peak voxel from (a), (c), and (e), respectively.

$Z = 2.70, P < 0.05$ svc, $x, y, z = 4, 14, 28, Z = 2.84, P < 0.05$ svc, $x, y, z = -34, 14, 2, Z = 2.50, P = 0.07$ svc, respectively.

Additional Imaging Results

Given that task conditions with high perceptual load have been argued to engage attentional resources in task-relevant processing to a greater extent than low perceptual load conditions, leaving no spare capacity for the processing of task-irrelevant stimuli, we also looked to see whether there was a main effect of perceptual load in our prefrontal and ACC ROIs. In line with the high perceptual load task being more attentionally demanding, the high load condition was associated with significantly greater activity in the DLPFC, VLPFC, and dorsal ACC ROIs than the low

load condition (see Table 1). Additional whole-brain analyses (corrected for multiple comparisons) revealed that high versus low perceptual load was also associated with bilateral increases in activity in parietal regions (Table 1), in line with these regions forming part of a commonly coactivated fronto-parietal attentional network (Duncan and Owen 2000; Culham and others 2001). The extent to which activity in these regions was augmented under conditions of high versus low perceptual load was not modulated by either trait or state anxiety (P values > 0.1)

We also looked to see whether, within the high perceptual load blocks, error trials produced different activation to correct trials within these regions or any of our other ROIs (behavioral

Table 1

Neural regions showing increased activation under conditions of high versus low perceptual load

Brain regions	Coordinates	Z score	<i>P</i> (svc)
Right VLPFC	36, 16, 0	4.85	<0.001
Left VLPFC	-32, 24, 0	5.39	<0.001
Right DLPFC	34, 32, 22	4.36	<0.001
Left DLPFC	-40, 32, 26	3.82	<0.005
Dorsal ACC	4, 14, 44	4.61	<0.001
Right parietal	24, -62, 46	4.62	<0.05 ^a
Left parietal	-22, -72, 46	5.33	<0.005 ^a

^aWhole brain corrected for multiple comparisons.

data is given below). There was no differential activation associated with error versus correct trials either within or proximal to any of our ROIs, $P > 0.001$ uncorrected.

Behavioral Results

Mean reaction times and error rates for the 4 conditions of interest were as follows: low load, fearful distractors, mean reaction time (RT) = 760 ms, SD = 33 ms; mean error rate = 6.9%, SD = 2.6%; low load neutral distractors, mean RT = 767 ms, SD = 37 ms; mean error rate = 5.8%, SD = 1.6%; high load fearful distractors, mean RT = 1191 ms, SD = 64 ms; mean error rate = 30.6%, SD = 3.2%; high load neutral distractors, mean RT = 1220 ms, SD = 59 ms; mean error rate = 36.3%; SD = 3.1%. Participants were faster to identify the target letter present (X or N), and made fewer errors, in the low perceptual load (homogenous strings) than in the high perceptual load (mixed consonant string) conditions, $F_{1,17} = 91.94$, $P < 0.001$, $F_{1,17} = 137.53$, $P < 0.001$, respectively. This is in line with previous findings (Jenkins and others 2005) and together with the imaging results described above suggests that the perceptual load manipulation was effective, with the high perceptual load task placing more demands on processing resources than the low perceptual load task. There was also a significant interaction of distractor expression by load upon accuracy, $F_{1,17} = 7.57$, $P < 0.02$, with performance being marginally less accurate for trials with fearful face distractors under low load and more accurate for trials with fearful face distractors under high load. There was no significant interaction of distractor expression by load upon reaction times ($P > 0.1$).

The behavioral data were also examined for interactions of load, expression, or load by expression with trait or state anxiety or ACS scores. Both state anxiety and trait anxiety showed significant interactions with load in regards to error rates, with high anxious individuals making more errors on the letter search task under high perceptual load than low anxious individuals, $F_{1,16} = 23.75$, $P < 0.001$, $F_{1,16} = 7.31$, $P < 0.02$, respectively. In addition, state anxiety also showed a significant interaction with load for reaction times, with heightened anxiety being associated with slower responding under high perceptual load, $F_{1,16} = 8.08$, $P < 0.02$. There were no other significant interactions with any of the 3 self-report measures used (P values > 0.1).

Discussion

Across participants, the amygdala response to unattended fearful versus neutral faces was modulated by perceptual load, with task-irrelevant fearful faces producing a greater amygdala response than task-irrelevant neutral faces under conditions of low but not high perceptual load. Both state and trait anxiety

modulated the neural response to fearful face distractors under low perceptual load but not under high perceptual load. Under low perceptual load conditions, high state anxiety was associated with an elevated response to fearful face distractors in the amygdala and STS, whereas high trait anxiety was associated with reduced activation to fearful face distractors in regions associated with controlled processing (lateral PFC, dorsal ACC, rostral ACC).

Our cross-participant finding of an elevated amygdala response to fearful face distractors under low but not high perceptual load is analogous to Rees and others (1997) finding that neural regions sensitive to motion only show increased activity to moving distractors under conditions of low perceptual load and consistent with recent findings by Pessoa and others (2005) that an amygdala response to fearful face distractors is observed under “easy” but not “moderate” or “hard” versions of a bar-matching task. These findings do not seem easily reconcilable with models suggesting that threat-related stimuli receive automatic preattentive perceptual processing. We return to this issue later.

The main focus of our study, however, was the question of whether the extent to which the neural response to fearful face distractors was modulated by anxiety would vary with perceptual load. In particular, we were concerned with contrasting the predictions from 2 different literatures. Recent neurocognitive models of anxiety predict that anxiety should influence threat evaluation at a preattentive stage, elevating the amygdala response to threat distractors under conditions of both low and high perceptual load. In contrast, Lavie’s (2001, 2005) model of selective attention under load predicts that distractor perceptual processing will only occur under low perceptual load conditions, and that it is here that individual differences in the ability to prevent subsequent processing of salient distractors will be observed. Our findings support the latter account. Both state and trait anxiety modulated neural activity to fearful versus neutral distractors under conditions of low perceptual load but not under high perceptual load. Intriguingly, the present results suggest that 2 separate mechanisms may contribute to this modulation—one associated with state anxiety, and the other associated with trait anxiety. Under low perceptual load, high state anxiety was associated with increased activity to fearful face distractors in regions associated with the evaluation of facial expressions (amygdala, STS; see Haxby and others 2000). Meanwhile, high trait anxiety was associated with reduced activity to fearful face distractors in cortical regions associated with controlled processing. These findings provide some preliminary suggestion that state and trait anxiety, when not highly correlated in a given volunteer sample, may have distinguishable effects upon the neural mechanisms involved in threat evaluation and attentional control. This may result in a 2-pronged effect upon attentional control over threat distractors, potentially accounting for interactive effects of state and trait anxiety in behavioral attention paradigms (MacLeod and Mathews 1988).

Importantly, the finding that trait anxiety primarily modulated the lateral PFC and ACC response to fearful distractors under low perceptual load accords with Lavie and colleagues’ findings with populations characterized by impoverished attentional control (Maylor and Lavie 1998; Huang-Pollock and others 2002). This relationship between trait anxiety and reduced attentional control was further borne out by our finding that elevated trait anxiety was linked to lower scores on the ACS—a

self-report measure of attentional control. ACS scores in turn showed an independent relationship with lateral PFC and ACC activity to threat-related distractors under low perceptual load, over and above the shared relationship with trait anxiety. These findings suggest that trait anxiety may be associated with impoverished attentional control, which in turn may be associated with reduced recruitment of regions implicated in cognitive control in response to competition from threat-related distractors under conditions of low perceptual load.

Trait anxiety did not modulate the recruitment of “control” regions in response to the additional demands posed by the high perceptual load version of the letter search task. Rather, modulation of activity in these regions by trait anxiety was only seen under low perceptual load. This highlights the stages at which attentional influences may be observed. According to Lavie (2000, 2001), top-down controlled processing is initially used to determine priorities for perceptual processing between task-relevant and task-irrelevant stimuli. Second, when the processing of task-relevant stimuli does not exhaust perceptual capacity limitations, distractors receive some degree of involuntary perceptual processing and active recruitment of top-down control mechanisms is required to prevent them competing for further resources. One possibility is that individuals high in trait anxiety, like the young and elderly populations studied by Lavie and colleagues, are primarily impaired in the active recruitment of control mechanisms at this latter stage. Within the conflict monitoring and cognitive control framework proposed by Cohen and colleagues (Botvinick and others 2001, 2004), this could be seen as a weakness in using changes in information about competition for processing resources to alter top-down control to prevent the further allocation of resources to task-irrelevant stimuli (see also Bishop and others 2004b). State and trait anxiety may, however, have an additional impact upon the efficiency of the mechanisms used to facilitate task-related processing under high perceptual load (see Eysenck and Calvo 1992) given the increased error rates shown by high state and high trait anxious participants under these conditions.

One interesting question for future work is whether the cognitive control mechanisms more strongly recruited by low trait anxious volunteers in response to fearful face distractors under low perceptual load impede threat-related distractors from competing for postperceptual processing resources by facilitation of task-relevant information or by inhibition of the distractors themselves. Behavioural results from negative priming studies using threat-related stimuli have been taken to support the latter possibility (Fox 1994). However, recent findings from neuroimaging studies of response-conflict suggest that prefrontal control mechanisms act primarily by strengthening representations of task-relevant stimuli rather than by suppressing the representation of distractors (Egner and Hirsch 2005). In line with this, recent formulations of the selective attention under load account (Lavie 2005) do not specifically emphasize inhibitory processes in contrast to earlier versions, leaving open the precise process by which cognitive control mechanisms prevent salient distractors from competing for further processing resources under low perceptual load.

Our findings also revealed that state anxiety was associated with increased activity in the amygdala and STS in response to fearful face distractors under low but not high perceptual load. We have previously reported that elevated state anxiety is associated with an increased amygdala response to unattended

threat distractors (Bishop and others 2004a). The current findings extend and clarify that result, suggesting that state anxiety only modulates the amygdala response to threat distractors during task conditions with low perceptual processing demands. This may be taken to indicate that state anxiety does not increase the processing of threat-related stimuli by altering the activity of a preattentive amygdala-centered mechanism but that some limited-capacity perceptual processing of distractor stimuli is necessary before state anxiety can modulate the magnitude of the subsequent amygdala signal.

Here, it is important to be careful to separate issues of preattentive and obligatory processing. Specifically, it may be useful to distinguish questions regarding whether the amygdala's response to threat is 1) involuntary (requiring no volitional initiation), 2) can proceed in the absence of cortical involvement (for example following disruption to cortical circuitry), and 3) is subject to attentional competition when operating within a fully intact system. A “strong” definition of automaticity refers to processing that is both involuntary and independent of attentional competition (Kahneman and Treisman 1984; see also Pessoa 2005). In contrast, “weak” or “partial” definitions of automaticity do not require independence from attentional resources but instead emphasize the involuntary aspect of automatic processing, consistent with the obligatory processing of distractors that Lavie (2000, 2001) suggests occurs under low perceptual load (see also Yantis and Jonides 1990). It is conceivable that threat-related stimuli such as fearful faces receive rapid and involuntary processing under most conditions but are nonetheless still subject to attentional limits when task demands are such that the perceptual processing of other stimuli requires all available resources. We would argue that, in terms of neurocognitive models of anxiety such as those of Mathews and Mackintosh (1998) and Öhman and Weins (2004), early perceptual competition may be seen as gating entry to a threat evaluation system involving the amygdala. Once this system is activated, and this may be involuntary under conditions of low perceptual load, individual differences in state anxiety may influence the magnitude of the output signal and this in turn interact with prefrontal control mechanisms in determining the further processing of threat distractors. Our findings additionally indicate that individual differences in trait anxiety and self-reported attentional control may affect the strength of this “top-down” control signal.

In summary, our findings suggest that individual differences in state and trait anxiety interact with manipulations of perceptual load to determine the neural processing of task-irrelevant fearful faces. Increased amygdala activation to fearful versus neutral face distractors was only observed under low perceptual load, contrary to “strong” automaticity accounts of the amygdala response to threat. Additionally, individual differences in state and trait anxiety primarily influenced neural activation to fearful distractors under low perceptual load. This runs contrary to suggestions that anxiety modulates a preattentive threat evaluation system centered on the amygdala and instead supports Lavie's (2001, 2005) load model of selective attention according to which distractor processing is constrained by early perceptual capacity limitations. Our findings also extend the scope of Lavie's model in demonstrating that it can successfully account for the processing of emotionally salient distractors in both low and high anxious individuals. Here it is of note that, using salient but affectively neutral stimuli, Lavie and colleagues have demonstrated that although distractor processing is

reduced by increasing perceptual load, it is not reduced by increasing working memory load, or by increasing task difficulty by stimulus degradation, in line with only the first of these manipulations exhausting perceptual processing capacity (Lavie 2005). In future work we plan to test the prediction that the same will hold true for the processing of threat-related distractors.

Finally, we also report differential effects of state and trait anxiety upon the processing of fearful face distractors under low perceptual load. Heightened state anxiety was linked to increased signal in regions involved in the evaluation of threat from facial expressions; heightened trait anxiety was associated with reduced activation in regions implicated in attentional control. This provides initial evidence that state and trait anxiety may have partially separable and potentially additive effects upon the mechanisms underlying attentional regulation of threat-related stimuli, together influencing the neural response to threat distractors that pass an initial capacity-limited stage of perceptual processing.

Notes

This study was conducted at the University of Cambridge Wolfson Brain Imaging Centre. Resources were provided by the Behavioural and Clinical Neurosciences Institute, University of Cambridge, supported by a joint award from the Medical Research Council and Wellcome Trust, and by the Medical Research Council Cognition and Brain Sciences Unit. Additional support was provided in the form of a Medical Research Council Career Development Award (awarded to S.B.), a Betty Behrens research fellowship from Clare Hall, Cambridge University (awarded to S.B.), a Marie Curie Outgoing International Fellowship (awarded to S.B.), and a British Academy fellowship (awarded to R.J.). Our thanks go to John Duncan for comments, Brian Cox for graphical assistance, Matthew Brett and Rik Henson for advice on imaging analysis, and Vicky Lupson, Lucy Chamberlain, and Laura Germaine for assistance with fMRI data collection. *Conflict of Interest* None declared.

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