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Research paper

Pupillometric and saccadic measures of affective and executive processing in anxiety☆

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ABSTRACT

Anxious individuals report hyper-arousal and sensitivity to environmental stimuli, difficulties concentrating, performing tasks efficiently and inhibiting unwanted thoughts and distraction. We used pupillometry and eye-movement measures to compare high vs. low anxious individuals hyper-reactivity to emotional stimuli (facial expressions) and subsequent attentional biases in a memory-guided pro- and antisaccade task during conditions of low and high cognitive load (short vs. long delay). High anxious individuals produced larger and slower pupillary responses to face stimuli, and more erroneous eye-movements, particularly following long delay. Low anxious individuals' pupillary responses were sensitive to task demand (reduced during short delay), whereas high anxious individuals' were not. These findings provide evidence in anxiety of enhanced, sustained and inflexible patterns of pupil responding during affective stimulus processing and cognitive load that precede deficits in task performance.

1. Introduction

Anxiety is characterised by hyperactivity in physiological, cognitive, and behavioural mechanisms in anticipation of threat and in response to threat cues (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & van IJzendoorn, 2007). Neuropsychological models of anxiety highlight maladaptive biases in threat appraisal and attention in the aetiology and maintenance of core symptoms that include distractibility, poor concentration, nervous apprehension, and worry (Behar, DiMarco, Hekler, Mohlman, & Staples, 2009; Grupe & Nitschke, 2013; Mogg & Bradley, 2016; Sylvester et al., 2012). Hyperactivity in bottom-up stimulus-driven mechanisms (i.e. increased amygdala activation) increase threat appraisal, autonomic arousal, and attentional bias to threat (Bishop, 2009). In addition, hypo-activity in goal-directed control processes (i.e., reduced activity in the dorsolateral prefrontal cortex) reduce attentional control and exacerbate attentional biases to threat distractors, particularly when task demands are high (Bishop, 2009). Recent methodological advances provide more sensitive indices of attention and related processes (e.g., pupillometry and eye-movement measures) to examine anxiety-related biases in emotional reactivity to emotional stimuli, and the impact of low and high cognitive load on attention biases and attentional control more broadly.

Pupillary responses of the human eye are modulated by affective and executive processes via central and peripheral sympathetic and parasympathetic divisions of the nervous system (see Andreassi, 2000; for a review). Pupil diameter increases in response to emotional stimuli (both visual and auditory) and correlates with subjective ratings of emotional arousal and autonomic skin-conductance responses (Bradley, Miccoli, Escrig, & Lang, 2008; Partala & Surakka, 2003; Rosa, Esteves, & Arriaga, 2015). Recent evidence suggests that pupillary responses are sensitive to individual differences in threat processing, as reflected in increased pupil responses to angry faces in anxious individuals (Kret, Stekelenburg, Roelofs, & de Gelder, 2013), fearful faces in anxious youths (Price et al., 2013), and to angry faces in children of anxious mothers (Burkhouse, Siegle, & Gibb, 2014).

Behavioural studies provide evidence of visuo-spatial biases in selective attention to threat in anxiety. For example, individuals with clinical and sub-clinical anxiety make speeded reaction times (RTs) to visual targets that appear in the spatial location of threat stimuli (e.g. negative pictures and facial expressions; review by Bar-Haim et al., 2007). Likewise eye-tracking methods reveal preferential and faster eye-movements towards threat cues in anxiety (Chen, Clarke, Watson, Macleod, & Guastella, 2014; Mogg, Garner, & Bradley, 2007). Biases in selective attention have been observed in a range of anxiety groups,

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including generalized anxiety, social phobia, specific phobias and high trait anxious 'sub-clinical' populations (review by Bar-Haim et al., 2007) and are exacerbated in individuals who concurrently report poor attentional control (Derryberry & Reed, 2002). Convergent evidence of visuospatial biases for threat in anxiety is consistent with models that propose 'hypervigilance' for threat increases distractibility and interrupts executive processes required to monitor and achieve performance goals (review by Richards, Benson, Donnelly, and Hadwin, 2014).

Attentional control theory (Eysenck & Derakshan, 2011; Eysenck, Derakshan, Santos, & Calvo, 2007) and related models (e.g. Processing Efficiency Theory; Eysenck & Calvo, 1992) further propose that anxiety reduces executive attention control resources that are required to maintain goal- focus and inhibit task-irrelevant (negative) distractors. These models predict that anxious individuals recruit more resources and increase effort to complete tasks effectively. Consequently, anxiety is thought to be associated with substantial impairment in processing efficiency (reflected in increased effort or time) alongside modest impairment in performance effectiveness, particularly when task demands are high. Anxiety-related deficits in attention control have been observed across several behavioural measures. Trait anxious individuals, for example, perform less well on the executive attention subtest of the attention network task (ANT; Pacheco-Unguetti, Acosta, Callejas, & Lupianez, 2010) and show deficits when required to inhibit task-irrelevant distractors or inhibit prepotent behavioural responses (review by Mobini and Grant, 2007). In addition, studies have demonstrated the negative impact of elevated anxiety on processing efficiency in child (Hadwin, Brogan, & Stevenson, 2005) and adult populations (see Eysenck et al., 2007).

Similarly, pupil diameter increases during periods of resource recruitment and mental effort (Beatty, 1982; Beatty & Lucero-Wagoner, 2000; Hess, 1975; Kahneman & Beatty, 1966; Karatekin, Marcus, & Couperus, 2007). Trait anxious individuals show larger pupillary responses (vs. low anxious individuals) during tasks that require sustained attention (e.g. simulated driving tasks; Wilson, Smith, Chattington, Ford, and Marple-Horvat, 2006), and pupillary responses are sensitive to anxiety-related deficits in other behavioural tasks such as learning paradigms (e.g. two-arm bandit learning task; Browning, Behrens, Jocham, O'Reilly, & Bishop, 2015).

The antisaccade task is a simple behavioural task that utilises eye movement measures to investigate individual differences in attention control across anxiety and mood disorders (review by Ainsworth and Garner, 2013). Participants are instructed to look away from a visual cue (i.e. to its mirror location) as quickly and accurately as possible. Attentional control is indicated in: (1) the ability to withhold (inhibit) reflexive saccades, and (2) the generation of volitional saccades to the correct location (Hutton & Ettinger, 2006). Consistent with predictions from Attentional Control Theory (Eysenck et al., 2007), anxious individuals are more likely to make erroneous eye-movements on antisaccade trials (i.e. more likely to look towards the distractor stimulus), and are slower (less efficient) at executing antisaccades (Ansari & Derakshan, 2011b; Garner, Attwood, Baldwin, James, & Munafo, 2011). Furthermore, anxiety-related deficits in antisaccade performance are greater in response to threat distractors (e.g. angry facial expressions; Derakshan, Ansari, Hansard, Shoker, & Eysenck, 2009; Reinholdt-Dunne et al., 2012) and when processing demands increase (Berggren, Richards, Taylor, & Derakshan, 2013).

The effects of task demand/load have been examined in studies that manipulate the time between which a stimulus is presented and an eye-movement response is required. For example, participants make more errors and are slower to make accurate antisaccades when asked to respond immediately after stimulus onset (no-delay) compared to after a short delay, which is argued to facilitate response preparation (e.g. 600 ms–1500 ms; Ansari & Derakshan, 2010, 2011a; Reuter, Jager, Bottlender, & Kathmann, 2007). Conversely, in an oculomotor delayed response (ODR) task a longer delay is introduced to increase demand on working memory. In this task, participants are required to encode the spatial location of a briefly presented visual cue and store information in working memory during a delay period (e.g. 5–10 s), while maintaining a central fixation before generating a memory-guided saccade (Curtis & D'Esposito, 2003; Luna & Velanova, 2011). Consequently, the ODR task might be particularly sensitive to anxiety-related deficits in processing efficiency by increasing task demands in high load (long delay) conditions (Curtis & D'Esposito, 2003). Furthermore, this task can incorporate concurrent online pupillometry measures that can profile the time-course of 'effort' expended throughout periods of high and low load (long and short delay respectively).

The current study asked whether individuals reporting elevated anxiety exhibit greater pupil reactivity to negative stimuli (threatening facial expressions) and subsequently have greater difficulty directing attention away from threat distractors, particularly when task demands are high. Specifically, we compared high and low anxious individuals' pupillary responses to centrally presented emotional (angry, fearful, happy, neutral) facial expressions and subsequent attention to faces presented in a memory-guided pro- and antisaccade ODR task under conditions of high and low cognitive load (following 10 s or 5 s delay, respectively). We hypothesised that individuals with elevated levels of trait anxiety (trait anxious individuals) would show (1) larger pupillary responses to negative (angry, fearful) facial expressions (consistent with increased threat appraisal), (2) larger pupil responses during oculomotor delay, particularly during the long delay (consistent with greater effort/poor processing efficiency), and (3) impaired task performance characterised by fewer and slower accurate eye-movements, particularly on antisaccade trials in response to negative faces following a long delay (consistent with reduced ability to orient away from/inhibit threat distractors under conditions of high load).

2. Method

2.1. Participants

Participants were recruited from the University of Southampton via posters and an online advertisement. High and low anxious participants were selected according to their scores on the trait version of Spielberger State-Trait Anxiety Inventory (STAI-T; Spielberger, Gorusch, Lushene, Vagg, & Jacobs, 1983). Consistent with previous research (see Ansari, Derakshan, and Richards, 2008) participants who scored ≤ 35 were categorised as low anxious (LA; n = 13, *mean* STAI-T = 27.92, *S.D.* = 4.11) and those scoring ≥ 50 as high anxious (HA; n = 14, *mean* STAI-T = 56.79, *S.D.* = 5.02).

Participants had normal or corrected-to-normal vision and wore glasses or contact lenses if necessary. Participants confirmed that they had not taken drugs, alcohol, or medication on the day preceding testing. They received either course credits or £6 for participation. All participants provided informed consent. The research protocol was approved by the University of Southampton Ethics and Research Governance committees.

2.2. Apparatus

Eye movements and pupillary responses were recorded using SR Research EyeLink 1000 desktop-mounted eye tracking system (SR Research Ltd., Ontario, Canada) with a sampling rate of 1 kHz. Pupillary responses were recorded using Centroid model based on pupil diameter in millimetres. The presentation was controlled by Experiment Builder v1.10.1025 software (SR Research Ltd., Ontario, Canada) on a 19-inch ViewSonic (P227f) monitor.

2.3. Stimuli

Sixty-four face stimuli were selected from the NimStim Face Stimulus Set (Tottenham et al., 2009) including angry, fearful, happy,