**Individual reactions to stress predict performance during a critical aviation incident**

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**Abstract**

Understanding the influence of stress on human performance is of theoretical and practical importance. An individual's reaction to stress predicts their subsequent performance; with a 'challenge' response to stress leading to better performance than a 'threat' response. However, this contention has not been tested in truly stressful environments with highly skilled individuals. Furthermore, the effect of challenge and threat responses on attentional control during visuomotor tasks is poorly understood. Thus, this study aimed to examine individual reactions to stress, and their influence on attentional control, among a cohort of commercial pilots performing a stressful flight competency assessment. Sixteen pilots performed an 'engine failure on take-off' scenario, in a high-fidelity flight simulator. Reactions to stress were indexed via self-report; performance was assessed subjectively (flight instructor assessment) and objectively (simulator metrics); gaze behaviour data were captured using a mobile eye tracker, and measures of attentional control were subsequently calculated (search rate, stimulus driven attention, and entropy). Hierarchical regression analyses revealed that a threat response was associated with poorer performance and disrupted attentional control. The findings add to previous research showing that individual reactions to stress influence performance, and shed light on the processes through which stress influences performance.



**Key words:** Challenge and threat, biopsychosocial model, eye tracking, attention, pilot.

## Introduction

On the 15th January 2009, US Airways flight 1549 experienced loss of power to both engines during take-off. Within minutes, the plane was forced to make an emergency crash landing in the Hudson River, Manhattan. Surprisingly, all 155 passengers were safely evacuated, and this positive and unlikely outcome was attributed to the skills and capabilities of the pilot, Captain Chesley Sullenberger. Despite the inevitable stress he experienced, Captain Sullenberger managed to remain focused, maintain control of the plane, and execute an effective emergency landing. Had he reacted poorly to the stress that he experienced, the outcome of this event may have been very different!

It is clear from such an example that developing a better understanding of the influence of stress on human performance is of theoretical and practical importance, particularly in safety-critical industries such as aviation, emergency medicine, and the military. For example, in the aviation industry, researchers have revealed that high levels of stress are a prominent cause of pilot error (Causse, Dehais, Péran, Sabatini, & Pastor, 2013; Fornette, Bardel, Lefrançois, Fradin, Massioui, & Amalberti, 2012). Indeed, with improvements in technology reducing the influence of mechanical errors, such human error is now the leading cause of aviation accidents (Nall, 2011; Shapell, Detwiler, Holcomb, Hackworth, Boquet, & Wiegmann, 2007). The current study seeks to collate the predictions of two prominent theories within performance psychology, and exploit the unique opportunities provided by aviation simulation to further our understanding of how stress influences human performance.

Early attempts to draw a direct relationship between stress and performance have been largely unsuccessful, due primarily to intra- and inter-individual differences in the way in which people respond to stress (Cerin, Szabo, Hunt, & Williams, 2000). Consequently, transactional models of stress that account for cognitive appraisal of the stressor (Lazarus, 1990), have become widely acknowledged. The biopsychosocial model of challenge and threat (BPSM; Blascovich, 2008) is one such model, and provides a theoretical framework for understanding reactions to stress. According to the BPSM, how an individual responds in a stressful situation is determined by their evaluations of situational demands and personal coping resources. If the individual determines that resources are sufficient to meet the demands of the situation, then it is evaluated as a challenge; conversely, if resources are judged to be insufficient, then the situation is evaluated as a threat (see Seery, 2011, for a review). Critically, a consistent body of evidence has recently emerged, demonstrating that a challenge state (and underlying demand and resource evaluations) predicts superior performance compared to a threat state in academic (Seery, Weisbuch, Hetenyi, & Blascovich, 2010), sporting (e.g., Moore, Wilson, Vine, Coussens, & Freeman, 2013), and surgical (e.g., Vine, Freeman, Moore, Chandra-Ramanan, & Wilson, 2013) tasks. However, whether challenge and threat states predict task performance in highly stressful applied settings, such as aviation, has yet to be examined.

While challenge and threat states can be objectively determined via distinct cardiovascular responses (see Blascovich, 2008), they can also be indexed accurately using subjective measures that assess evaluated demands and resources (e.g., cognitive appraisal ratio; Tomaka, Blascovich, Kelsey, & Leitten, 1993). Importantly, these measures have been shown to corroborate closely with cardiovascular indexes of challenge and threat and have strong predictive validity for performance outcomes (Moore, Vine, Wilson, & Freeman, 2012; Vine et al., 2013; Zanstra, Johnston, & Rasbash, 2010). Subjective measures of challenge and threat evaluations are therefore an expedient and practical way to assess reactivity to stress in applied settings. This is important, because there is a paucity of research examining challenge and threat states in ecologically valid settings, where stress is meaningful (see Moore et al., 2013, for an exception). If research is to better understand performance variability under stress and ultimately inform human operator training and assessment, then such methodological approaches need to be examined further.

An additional limitation of previous research is that few studies have examined the possible mechanisms through which challenge and threat evaluations might influence performance. This lack of research is despite suggestions from several authors that impaired attentional control might be an important underlying mechanism (Blascovich, Seery, Mugridge, Norris, & Weisbuch, 2004; Jones, Meijen, McCarthy, & Sheffield, 2009). Recent research has supported this assertion and has shown that a threat state (and underlying demand and resource evaluations) is associated with disrupted gaze control during the performance of both sporting (Moore, Vine, Wilson, & Freeman, 2012; Moore et al., 2013) and surgical (Vine et al., 2013) tasks. For example, Vine and colleagues (2013) found that evaluating a stressful surgical task as a threat was associated with a sub-optimal gaze strategy consisting of more fixations of a short duration directed to the surgical tool rather than the targets to be moved. Such measures of in-vivo gaze control reveal interesting differences in the focus of attention between challenge and threat states that resonate with the predictions of a recent theoretical development of the anxiety-performance relationship; Attentional Control Theory (ACT; Eysenck, Derakshan, Santos, & Calvo, 2007).

ACT predicts that anxiety causes a diversion of available processing resources from task-relevant to task-irrelevant stimuli. The authors relate this impairment of attentional control to a disruption in the balance of two attentional systems; a goal-directed (top down) system and a stimulus-driven (bottom up) system. According to ACT, anxiety increases the sensitivity of the stimulus-driven system, making individuals more distractible, and less able to maintain focused, goal-directed control (Eysenck et al., 2007). These predictions have been supported in sporting and surgical environments where disruptions to goal-directed attention (gaze) have been associated with performance impairments (see Wilson, 2012, for a recent review). Generally, anxious individuals use more, shorter fixations to a variety of locations, and are unable to maintain the long, target-focused fixations important for the planning and control of movement (Wilson, 2012). For example, Allsop and Gray (2014) found that increased anxiety caused an increase in entropy (a measure of the randomness of visual scanning) in an aviation task, which they attributed to an increase in the influence of the stimulus-driven attentional system (Allsop & Gray, 2014). Importantly, as described above, recent research has shown that individuals experiencing a threat state also demonstrate such disruptions to attentional (gaze) control (e.g., Moore et al., 2012; 2013; Vine et al., 2013).

The aim of the present study was to advance our understanding of the individualistic way in which stress influences human performance, in an ecologically-valid setting. We report novel data which supports and builds upon existing research findings. Specifically, we examined reactions to stress (challenge and threat) and disruptions to gaze control (using mobile eye tracking technology) in a highly stressful simulated aviation scenario with experienced and qualified pilots. We predicted that evaluating the stressful aviation scenario as more of a threat (i.e., situation demands outweigh resources) would be associated with greater disruptions to attentional control (indexed by disrupted gaze behaviours) and poorer performance (reduced manual control of the aircraft).

## **Methods**

**Participants:** Sixteen active and qualified pilots (14 male, 2 female; *M* age = 34.8 years, *SD* = 8.1 years) were recruited through a regional commercial airline. All participants signed informed consent prior to the start of study procedures. The experiment was approved by an institutional ethics committee.

**Task:** Participants performed a flight in a Bombardier Dash-8 Q400 flight simulator (Flight Safety International) as part of their bi-annual license competency checks (line operation flight evaluations; LOEs). The LOE is an industry wide quality and performance assurance check. The importance of the LOE for both the operating airline, and for the pilot, can make it a highly stressful experience. This provides a unique opportunity to examine reactions to stress and changes to performance in a safe, yet meaningful environment.

***The scenario*****:** Pilots were required to execute routine pre-flight checks, and then take off. At a consistent point during takeoff (just after wheels clear the runway) the simulator was programmed to initiate an engine failure (left engine). Due to the low altitude, slow airspeed, and restricted time period to act upon the emergency, an engine failure is considered one of the most stressful situations a pilot can experience. Participants were required to deal with the engine failure appropriately and land the plane. All pilots were familiar with the flight simulator and the type of scenario they were asked to execute.

**Measures:**

***Demand and resource evaluations*****:** Demand and resource evaluations were assessed using two items from the cognitive appraisal ratio (Tomaka et al., 1993) so that challenge or threat responses to the flight scenario could be determined. Demand evaluations were assessed by asking: "How demanding do you expect the task to be?" and resource evaluations by asking: "How able are you to cope with the demands of the task?" These items are rated using a 6-point Likert scale anchored between 1 (not at all) and 6 (extremely). A Demand Resource Evaluation Score (DRES) was calculated by subtracting demands from resources, with a more positive score reflecting the task being evaluated as more of a challenge and less of a threat[1] (as Moore et al., 2013; Vine et al., 2013).

***Gaze Control:*** Gaze was recorded using an Applied Science Laboratories (ASL; Bedford, MA, USA) Mobile Eye Tracker. Data was analysed in a frame-by-frame manner using GazeTracker (Eye Response Technologies, Charlottesville, VA, USA) video analysis software. Look zones were created around relevant areas in the scene and maintained in place by the experimenter as the video progressed. The software then provided data regarding the duration and frequency of fixations occurring within each area of interest. We were able to capture useable eye tracking data for 12 of the 16 pilots tested (75%). From the data provided by gaze tracker we computed the following metrics that have recently been found to be sensitive to the effects of anxiety and relate to the predictions of ACT. First, search rate, a measure of the rate of visual scanning, was calculated by dividing the number of fixations by the mean fixation duration (as Wilson, Smith, Chattington, Ford, & Marple-Horvat, 2006; Wilson, Vine, & Wood, 2009). Second, the difference between the percentage of fixations to regions of importance (ROIs) and regions of unimportance (ROUs) was calculated to reflect changes in the influence of the stimulus-driven attentional system. ROIs were classified as providing information relating to controlling the plane (i.e., the cockpit window, and the primary flight display), whereas ROUs included the ‘engine management system’ display and the ‘emergency warning panel’ (which indicated that an engine failure had occurred). All other displays within the cockpit that were not of relevanceto the engine failure or the control of the aircraft (e.g. radar) were coded as ‘other’ and included as a

[1] While challenge and threat *states* are used to describe reactions to stress, these states represent the end points of a continuum.

ROU[2]. Finally, entropy, the randomness of the scanning behaviours of the pilot, was determined. First the order in which fixations entered the ROI and ROU (lookzones) was manually coded by an experimenter. In order to calculate the conditional entropy for each participant we then computed the following; (1) p(i) - the zero order probability of fixating upon the i-th ‘look zone' based on the percentage of time spent fixating upon it, and (2) p(j|i) - the conditional probability of viewing ‘look zone' j based on a current dwell on ‘look zone’ i. These probabilities were then used to calculate entropy in an identical way to Allsop & Gray, 2014 (see also Ellis and Stark, 1986).

***Performance:*** Performance was assessed both subjectively (by a flight instructor who assessed the pilot and was naïve to the purpose of this project) and objectively (via parameters provided by the simulator software). The subjective performance constitutes a 16-point assessment developed specifically for the purpose of this project by experienced flight instructors at the airline. This assessment measured performance in five dimensions: directional control during rotation, anticipated roll control, communication, speed control, and rudder control. Importantly, a greater evaluation rating from the flight instructor reflected better flying performance from the pilot. The objective performance provided by the simulator constitutes information about the speed and heading of the plane, and calculates deviation from expected values (errors; speed deviation and heading deviation). Such performance metrics are routinely used by flight instructors to assess a pilot’s flying performance with greater deviations reflective of poorer performance.

**Procedure:** Participants were made aware of the adaptation to their LOE prior to arriving at the testing centre, and were at this stage able to withdraw from the study. For those who agreed to

[2] These areas of importance / unimportance were determined through discussion with experienced flight instructors and pilots at the airline training academy. ROIs reflect the fact that pilots should focus on cues related to flying the plane while the co-pilot continues to monitor the ‘threat’ stimuli relating to the engine failure (ROUs).

participate, on arrival at the flight simulator they provided informed consent, and received further written and verbal information about the study. They were then fitted with the eye tracker. Pilots were then instructed to ready the plane for takeoff (pre-flight checks) before the flight instructor described the specific scenario (take off and engine failure) that they would undertake (see above). Self-report measures (demand and resource evaluations) were then taken to assess challenge and threat evaluations in response to the instructions. Eye tracking data were recorded continuously during the scenario. The instructors assessing the LOE were asked to record (on paper) their subjective assessment of performance throughout the flight, and objective performance metrics were downloaded from the simulator software at the end of the session.

**Statistical analysis:** To examine the extent to which demand and resource evaluations (DRES) predicted performance, a series of hierarchical regression analyses were performed. Performance measures (instructor's evaluation, speed deviation, and heading deviation) were entered into separate models as dependent variables; age and years of flying experience were entered as independent variables at step one and two, and DRES was entered as an independent variable at step three.

To examine the extent to which DRES predicted the gaze control of the pilots, a further series of hierarchical regression analyses were performed. Gaze control measures (search rate, stimulus-driven attention, and entropy) were entered into separate models as the dependent variable; age and years of flying experience were entered as independent variables at step one and two, and DRES was entered as an independent variable at step three.

To examine the extent to which the gaze control measures predicted performance a series of simple regression analyses were performed. In separate models the gaze control measures (search rate, stimulus-driven attention, and entropy) were entered as independent variables and performance (instructor's evaluation, speed deviation, and heading deviation) were entered as dependent variables.

## Results

### Hierarchical regression analyses

***DRES and performance:*** Hierarchical regression analysis revealed that DRES significantly predicted the instructor's evaluation ($\Delta R^2 = 0.61$), over and above the effects of the pilot's age ($R^2 = 0.05$), and years of flying experience ($R^2 = 0.12$). DRES also significantly predicted heading deviation ($\Delta R^2 = 0.33$), over and above the effects of the pilot's age ($R^2 = 0.02$), and years of flying experience ($R^2 = 0.15$). Finally, DRES significantly predicted speed deviation ($\Delta R^2 = 0.21$), over and above the effects of the pilot's age ($R^2 = 0.05$), and years of flying experience ($R^2 = 0.30$; see Table 1).

***DRES and gaze control:*** Hierarchical regression analysis revealed that DRES significantly predicted search rate ($\Delta R^2 = 0.68$), over and above the effects of the pilot's age ($R^2 = 0.08$), and years of flying experience ($R^2 = 0.09$). DRES also significantly predicted stimulus-driven attention ($\Delta R^2 = 0.23$), over and above the effects of the pilot's age ($R^2 = 0.43$), and years of flying experience ($R^2 = 0.52$). Finally, DRES predicted entropy ($\Delta R^2 = 0.32$), over and above the effects of the pilot's age ($R^2 = 0.09$), and years of flying experience ($R^2 = 0.26$), although this only approached significance ($p = 0.06$; see Table 1).

### Simple regression analyses

***Gaze control and performance:*** Simple regression analysis revealed that search rate significantly predicted both the instructor's evaluation ($R^2 = 0.67$), and heading deviation ($R^2 =$

0.46), but did not significantly predict speed deviation ($R^2$ = 0.14). Regression analysis also revealed that stimulus-driven attention significantly predicted both instructor's evaluation ($R^2$ = 0.50), and heading deviation ($R^2$ = 0.51), but did not significantly predict speed deviation ($R^2$ = 0.44). Finally, regression analysis revealed that entropy did not significantly predict instructor's evaluation ($R^2$ = 0.31), heading deviation ($R^2$ = 0.00), or speed deviation ($R^2$ = 0.09). For all simple regression analyses see Table 2.

## Discussion

Given that high levels of stress are a prominent cause of errors in safety critical industries such as aviation and emergency medicine, it is critical to gain a better understanding of how individuals perform in stressful environments. This is particularly pertinent within the field of aviation, where human error is now the leading cause of accidents (Causse et al., 2013; Nall, 2011). Thus, the aim of the present study was to investigate experienced and qualified pilot's reactions to a simulated stressful incident (engine failure), and to further probe the influence of these reactions (challenge vs. threat) on attentional control and motor (flying) performance.

The findings support previous research demonstrating that challenge and threat states and the underlying demand and resource evaluations predict subsequent task performance (e.g., Moore et al., 2013; Vine et al., 2013). The pilot's self-reported evaluations of situational demands and personal coping resources predicted performance in terms of the control of the aircraft, as indexed both subjectively by an instructor's evaluation, and objectively by the simulator (i.e., heading deviation). Importantly, the current findings suggest that such simple measures can predict performance in stressful situations above and beyond other relevant factors (e.g., years of flying experience). These results therefore have important implications for safety and error avoidance in safety critical industries (e.g., aviation, surgery, and driving), and for improved performance in stressful applied environments (e.g., sport and military). While more complex psychophysiological indices of challenge and threat states may reflect subconscious evaluations that are free from reporter bias to be assessed (e.g., Blascovich et al., 2004; Moore et al., 2012; Turner, Jones, Sheffield, & Cross, 2012; Turner, Jones, Sheffield, Slater, Barker, & Bell, 2013), the current study provides further support for the validity of expedient self-report measures that can be easily collected in applied environments.

The findings of the current study also shed further light on some of the processes through which stress influences performance. A greater threat reaction to stress was associated with increased disruptions to attentional control, as indexed by the gaze control of the pilots. Specifically, pilots who evaluated the scenario as more of a threat displayed higher search rates, increased randomness in scanning behaviour (entropy), and a reduced ability to inhibit distraction from threatening or irrelevant stimuli (i.e., greater stimulus-driven attention). Although entropy failed to predict performance (cf. Allsop & Gray, 2014), this may be due to the relatively larger distances involved between the regions of interest in the current study. Whereas the flight instruments in Allsop and Gray's (2014) study were presented on a single computer screen, the simulator cockpit necessitated larger head and trunk movements to fixate some locations of interest; potentially reducing the sensitivity of the entropy measure. Nevertheless, the findings support previous studies (Wilson et al., 2009; Allsop & Gray, 2013, 2014), and suggest that gaze disruptions reflect disturbances to the attentional control of the pilots, in line with the predictions of ACT (Eysenck et al., 2007; Vine et al., 2013).

Importantly, the disrupted gaze control exhibited by pilots who adopted a threat response to stress was associated with poorer performance. The inability to maintain control of attention, and to focus on regions of importance for flying the plane (out of the cockpit window, and the primary flight display), were associated with poorer manual control of the aircraft and lower flight instructor's subjective assessment. These findings are therefore in keeping with previous research highlighting the important role of top down attentional control in enforcing the necessary spatial and temporal co-alignment of the gaze and motor systems for accurate performance in visually guided tasks (see Land, 2009; Vickers, 2007; Vine, Moore, & Wilson, 2014)

Despite the encouraging findings, the present study is not without its limitations. First, it is not clear whether the positive findings would translate from the simulated test environment to the real world, where stressors may differ (e.g., distractions etc.; Barnes & Monan, 1990). Second, while mobile eye trackers allow researchers to collect data in ecologically valid settings, more controlled methodologies (e.g., the anti-saccade paradigm, Derakshan et al., 2009) may be required to examine the specific functions of working memory responsible for effective attentional control under pressure (e.g., the inhibition and shifting functions, see Miyake, Friedman, Emerson, Witzki, Howerter & Wager, 2000). Finally, while gaze and attention have been shown to be inextricably linked in goal-directed tasks (Henderson, 2003), covert shifts in attention, or 'look but don't see' errors in judgement cannot be assessed using eye tracking technology (Vickers, 2007).

## Conclusion

To conclude, the results of the current study add to the body of research demonstrating that an individual's evaluation of the relationship between environmental demands and personal coping resources predicts subsequent performance in a meaningful and stressful situation. A threat response to stress (demands outweighing resources) predicted poorer performance than a challenge response (resources outweigh demands). Furthermore, a threat response was associated with disrupted attentional control (as indexed by increases in search rate, stimulus-driven attention, and entropy of scanning). These findings unite the predictions of two prominent theories (the BPSM;

Blascovich, 2008, and ACT; Eysenck et al., 2007) and further our understanding of the processes that underpin individual reactions to stress.

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**Table 1:** Hierarchical regression analyses, reporting the variance in performance and attentional control explained by pilots' stress evaluation (demand resource evaluation score; DRES) over and above their age and flying experience.

| Dependent variable | Step | Independent variable | B | SE B | *t* | *F* |
|---|---|---|---|---|---|---|
| Instructors evaluation | 1 | Age | -0.10 | 0.06 | -1.72 | 0.72 |
| | 2 | Years of flying | 0.08 | 0.06 | 1.25 | 0.88 |
| | 3 | DRES | 1.26 | 0.25 | 5.15 | 10.56** |
| Heading deviation | 1 | Age | 1.27 | 2.45 | 0.52 | 0.24 |
| | 2 | Years of flying | 0.06 | 2.47 | 0.02 | 1.15 |
| | 3 | DRES | -28.26 | 10.19 | -2.78 | 3.73* |
| Speed deviation | 1 | Age | -0.09 | 0.19 | -0.44 | 0.76 |
| | 2 | Years of flying | 0.17 | 0.20 | 0.86 | 2.73 |
| | 3 | DRES | -1.84 | 0.81 | -2.27 | 4.11* |
| Search rate | 1 | Age | 10.55 | 4.62 | 2.29 | 0.88 |
| | 2 | Years of flying | -8.20 | 6.00 | -1.37 | 0.45 |
| | 3 | DRES | -83.84 | 17.42 | -4.81 | 8.74** |
| Stimulus-driven attention | 1 | Age | 1.28 | 1.51 | 0.85 | 7.44* |
| | 2 | Years of flying | -1.10 | 1.96 | -0.56 | 4.91* |
| | 3 | DRES | 15.23 | 5.70 | 2.67 | 7.90** |
| Entropy | 1 | Age | -0.09 | 0.19 | -0.44 | 0.92 |
| | 2 | Years of flying | -0.17 | 0.20 | 0.86 | 1.61 |
| | 3 | DRES | -1.84 | -0.62 | -2.27 | 3.69^ |

*Note: * = p < .05; ** = p < .01; *** = p < .001; ^ = p = .06.*

**Table 2**: Simple regression analyses, reporting the variance in performance explained by the three measures of attentional control.

| Dependent Variable | Independent variable | B | SE B | *t* | *F* |
|---|---|---|---|---|---|
| Instructors evaluation | Search rate | -0.01 | 0.00 | 4.51 | 20.31** |
| Heading deviation | Search rate | 0.35 | 0.68 | 2.90 | 8.43* |
| Speed deviation | Search rate | 0.02 | 0.01 | 1.26 | 1.59 |
| Instructors evaluation | Stimulus-driven attention | 0.04 | 0.01 | 3.17 | 10.04* |
| Heading deviation | Stimulus-driven attention | -1.16 | 0.36 | -3.23 | 10.44** |
| Speed deviation | Stimulus-driven attention | -0.09 | 0.03 | -2.79 | 7.79* |
| Instructors evaluation | Entropy | -6.24 | 2.20 | -2.10 | 4.39^ |
| Heading deviation | Entropy | -5.12 | 105.17 | -0.05 | 0.00 |
| Speed deviation | Entropy | 7.95 | 8.10 | 0.98 | 0.96 |

*Note:* * = $p < .05$; ** = $p < .01$; *** = $p < .001$; ^ = $p = .06$