PSYCHOMOTOR MECHANISMS UNDERPINNING PERFORMANCE CHANGES IN HIGH-PRESSURE SITUATIONS

by

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A thesis submitted to the

University of Birmingham

for the degree of

DOCTOR OF PHILOSOPHY

School of Sport, Exercise and Rehabilitation Sciences

College of Life and Environmental Sciences

The University of Birmingham

August 2015

ABSTRACT

Pressurised situations have the potential to influence the performance of visual-motor tasks. The aim of this thesis was to investigate psychomotor mechanisms that may be responsible for such performance changes. A series of experimental studies were conducted in order to examine kinematic (Chapter 2) and attentional (Chapters 3 - 5) mechanisms. Performance pressure was successfully manipulated in all studies but performance was consistently maintained at a group-level. In the first experiment, individual differences in performance responses to pressure were found to correlate with kinematic changes, with decreases in movement amplitudes correlating with poorer performances. In the second experiment, pressure led to attentional narrowing as indicated by impaired performance of a useful field of view task. Pressure-induced changes in useful field of view correlated with performance changes. The third and fourth experiments demonstrated that pressure-induced changes in cognitive anxiety positively correlated with changes in the randomness of gaze behavior, which suggested that pressure has the potential to impact attentional control.

ACKNOWLEDGEMENTS

This PhD thesis would not have been possible without encouragement and support from a number of people. Firstly, I would like to thank Dr Rob Gray for the advice, patience and considerable guidance that you have given throughout the process. I am especially grateful that you encouraged me to pursue my own research questions and fostered my interests in developing skills in more technical areas. I would also like to thank Professor Chris Ring for your input at various stages throughout this endeavor. Your insights, knowledge and thoughts were gratefully received. To both of you, thank you for making this PhD an enjoyable and rewarding process.

There are a number of other people who have been involved in this thesis that I would like to thank. Thank you to Dr Sarah Williams for your involvement in early parts of the thesis. I am also grateful for the opportunity and comments provided by both Dr Lewis Chuang and Professor Heinrich Bülthoff in relation to the latter parts of the thesis. To the technical staff - Steve Allen, Andy Benham and especially Dr David McIntyre, thank you for supporting this research by helping to solve various issues and building some of the necessary pieces of equipment.

To the lunch-club members, office-mates, journal club members, Christmas pub-crawlers and other members of the postgraduate community - it was great to share the experiences of PhD life with such a great bunch of people. The many laughs along the way will be remembered for a very long time. Also, thanks to my Tübingen friends for making my stay immensely enjoyable. Thanks must also go to my friends outside of university, for the welcome escape, and for providing me with various pearls of wisdom, such as, "Pressure is what you put in tyres". Special thanks to Siobháin for the laughs and support – you're a good 'un.

Saving the most important until last - thank you to my Mom, Dad & Brother, along with the rest of my family, for the unconditional support, love and encouragement you have provided throughout.

LIST OF PAPERS

The following papers are included in this thesis:

Gray, R., Allsop, J., & Williams, S. (2013). Changes in putting kinematics associated with choking and excelling under pressure. *International Journal of Sport Psychology*, *44*, 387-407.

Allsop, J., & Gray, R. (In preparation). Effects of Performance Pressure on the Useful Field of View: Attentional Narrowing and Putting Performance.

Allsop, J., & Gray, R. (2014). Flying under pressure: effects of anxiety on attention and gaze behavior in aviation. *Journal of Applied Research in Memory and Cognition*, *3,* 63-71

Allsop, J., Gray, R., Bülthoff, H.H., & Chuang, L.L. (In preparation). Effects of anxiety and cognitive load on gaze behavior in an aviation task.

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CHAPTER ONE

General Introduction

The ability to successfully perform visual-motor tasks in high pressure situations is essential for success in many different domains, ranging from sport to surgical medicine. Whilst people can sometimes rise to the occasion in a seemingly 'ice-cool' manner, other times people can crumble or 'choke'. Rory McIlroy's performance in the final round of the 2011 US Masters golf tournament provides a prominent example of the latter outcome in sport. Before commencing the final round, McIlroy had amassed a four stroke lead over his nearest competitors. By the end of the round, he had dropped to a tie for 15th place, trailing the winner by 10 strokes after attaining his worst 18-hole score of the whole year. He later said when interviewed, "I hate using the word choke but that's exactly what happened" (Donegan, 2011). This thesis examines the psychomotor mechanisms that underlie performance changes in pressure situations. The aim of this chapter is to provide an introduction to the topic, and in doing so, provide a backdrop for the rest of the thesis. Core constructs are defined and the influence of pressure on visual-motor skills in the real-world is investigated. A number of attentional and behavioral mechanisms are then outlined and supporting evidence is critically explored. Next, limitations of previous research are pinpointed and linked to subsequent experimental chapters.

The constructs pressure, choking, stress, and anxiety are commonly used in sport and performance psychology, however, definitions for each of these terms vary therefore clarification is warranted. Pressure can be defined as any single factor, or combination of factors, that increases the perceived importance of performing optimally in a particular situation (Baumeister, 1984; Baumeister & Showers, 1986), with Beilock & Carr (2001) similarly defining pressure as the "anxious desire to perform at a high level in a given situation" (p. 701). Inherent within these definitions is that the individual's perception of the situation is key, what may be perceived to be a pressure situation to one performer may not be perceived as pressure by another performer. Baumeister and Showers (1986) provided a number of factors that were suggested to potentially elicit pressure in an additive manner, these included: performance contingent rewards or punishments, competition, the presence of an audience, and how performance may reflect on important features of the person's self.

Based on this definition, 'choking under pressure' can be characterised by a decrease in performance that occurs due to any pressure-inducing factor, with a commonly employed definition being "the occurrence of inferior performance despite striving and incentives for superior performance" (Baumeister & Showers, 1986, p. 361). Importantly, choking is therefore not just poor performance, it is a decrease in performance when compared to a baseline or expected level which specifically occurs due to pressure (Beilock & Gray, 2007). While this definition has been commonly adopted, other researchers have advocated definitions that encapsulate the extreme magnitude of performance deterioration commonly associated with choking (Gucciardi and Dimmock, 2008; Mesagno & Hill, 2013). However, Jackson (2013) expressed caution towards definitions that include a specific magnitude threshold. Firstly, he argued that it is difficult to establish what level this threshold should be. Secondly, he argued that it is unclear whether this approach is necessary if the goal of the research is to understand the reasons why performance can change under pressure. This uncertainty stems from the lack of evidence, or theorising, to suggest that the mechanisms causing small performance deteriorations are any different to the mechanisms that underpin large, dramatic, performance deteriorations. Related to the individual differences in the perception of high pressure situations described above, at the opposite end of the performance change continuum is clutch performance, which has been antithetically defined as the occurrence of superior performance in pressure situations (Otten, 2009). Similar to the disagreement surrounding the definition of choking, being "clutch" under pressure is sometimes meant to indicate performing above one's expected level while in other instances it refers to maintaining one's typical level of performance in the face pressure, in other words, being clutch means not choking (Beilock & Gray, 2007). While the bulk of the statistical evidence supports the latter definition (e.g., Palmer, 1985; 1990), the former is likely perpetuated due to the availability bias in memory for successful performances under pressure. Regardless of definition, as will be discussed in detail below, recent research has shown that performance under pressure can be determined by how an individual appraises the stress associated with high pressure situations (Moore, Wilson, Vine, Coussens, Freeman, 2013).

Stress has been defined in a multitude of ways (Linden, 1974; Staal, 2004). Stimulus-based approaches suggest that certain conditions or situations are stressful, with examples of stressors being workload, heat, cold or time pressure. On the other hand, response based approaches focus on the behavioral and cognitive outcomes that occur due to a stressor. Both approaches neglect the role of individual differences in perceptions of stressors and resultant responses. However, transactional approaches (e.g., Lazarus & Folkman, 1984) suggest that stress is an interactive process whereby the magnitude of the stress response is determined by a combination of the details of the stressor, appraisals of the stressor, and availability of coping resources. This process can lead to differing responses to stressors, with anxiety being an emotional response that is likely to occur if the stressor outweighs the perceived coping abilities (Woodman & Hardy, 2001; Spielberger 1989).

Finally, anxiety can be defined as a negative and unpleasant emotion characterised by "consciously perceived feelings of tension and apprehension" (Spielberger, 1966, p. 17). It consists of two components, a cognitive component and a somatic component (Martens, Vealey & Burton, 1990). The cognitive component consists of concerns and worrying thoughts about the ability to perform, whereas the somatic component refers to the perceptions of physiological symptoms such as increased heart rate, sweaty palms (Martens et al., 1990). In the majority of research in this area, anxiety in high pressure situations is assessed, rather than specifically measuring perceived pressure. Previous studies that have measured both suggest that cognitive anxiety and perceived pressure are overlapping constructs (Cooke, Kavussanu, McIntyre, Boardley & Ring, 2011; Balk, Adriannse, de Ridder & Evers, 2013). Therefore, in this thesis, I will follow the common research convention of considering the anxiety-performance, rather than perceived pressure-performance relationship. With these key terms defined, I next turn to a more detailed examination of the phenomenon of choking under pressure.

Incidence of Choking in Naturalistic Contexts

Statistical analyses performed on large archival datasets suggest that pressure does tend to have a negative effect on performance in real-world sport competitions (Baumeister & Steinhilber, 1984; Cao, Price & Stone, 2011; Hickman & Metz, 2015; Wells & Skowronski, 2012). For instance, Baumeister and Steinhilber (1984) found that in both basketball and baseball, the home team tended to win the first two games but lose the last (and decisive) game in these series. In support of the notion that the home team was choking in these games, they found that in baseball that the incidence of fielding errors for the home team increased in the final games while in basketball free throw percentage decreased in the final games. More recently, in an analysis of 2009 PGA Tour data, Wells & Skowronski (2012) found that professional golfers' scores were higher (i.e., worse) in the final round of a tournament in comparison to the penultimate round. Furthermore, larger performance decrements were found for players who were closer to the top of the leaderboard immediately prior to commencing their final round. In a larger and more fine-grained analysis, Hickman & Metz (2015) examined the influence of pressure on the performance of over 23,500 golf putts that were performed on the final hole of US PGA Tour events between 2004 and 2012. Pressure was operationalised by the magnitude of monetary reward or loss that was dependant on whether the final putt was made or missed. Analyses again revealed that pressure negatively impacted performance; the regression coefficient indicated that, on average, players were 1% less likely to make a putt when the outcome determined the gain or loss of $56035 (~£36000) in prize money, all other things being equal. Larger effects were found for certain putt distances, with $20000 (~£13000) equating to a 1% reduction in the likelihood of successfully holing out from putt distances between 5 and 10 feet.

These may not seem like large effects, however, it should be noted that the prize money available at each PGA Tour event is many times more than either of these amounts. To illustrate, the average prize money for tournament winners in the 2014-2015 season was approximately $1.1 million (~£710 thousand), with the average total prize money available at each tournament being approximately $6 million (~£3.86 million). Other archival studies have found that performance responses can vary across individuals (González-Díaz, Gossner & Rogers, 2012).

González-Díaz and colleagues (2012) conducted a point-by-point analysis of all men's US Open tennis matches taking place between 2004 and 2012. They calculated the importance of each point in determining the outcome of each match, with highly important points assumed to invoke pressure. Results revealed individual differences in behavioral responses to important points, certain players consistently underperformed in highly important points whereas others excelled. Furthermore, the ability to consistently excel during important points was positively correlated with traditional tennis ratings and rankings, showing that this ability was important for career success. Taken together, these studies offer real-world evidence to suggest that pressure can influence performance. They also emphasise the importance of being able to robustly perform visual-motor skills in high-pressure situations.

A limitation of the aforementioned archival studies is that pressure was inferred rather than actually measured. Greater insight into the effects of pressure on performance may be gained from the considerable number of field studies that have examined the relationship between cognitive anxiety and performance in real-world competitive sport environments. A number of studies have suggested a positive relationship between cognitive anxiety and performance (e.g., Taylor, 1987), while others have suggested a negative relationship (e.g., Burton, 1988; Terry & Slade, 1995), and still others have found no relationship (e.g., Maynard & Cotton, 1993). Meta-analyses attempting to elucidate the nature of the relationship have also produced mixed results (Craft, Magyar, Becker & Feltz, 2003; Woodman & Hardy, 2003). Specifically, Woodman & Hardy (2003) found a small, negative overall relationship between cognitive anxiety and sport performance when analysing the results of 46 studies, whereas Craft et al. (2003) found no overall relationship. Both meta-analyses did however find that the examined effect sizes were heterogonous, indicating a significant variation in the direction of the relationship between cognitive anxiety and performance across studies. This suggests that the nature of the relationship between pressure and performance is complex – an effect that is encapsulated in models such as the inverted-U hypothesis and catastrophe theory (Hardy & Parfitt, 1991; Yerkes & Dodson, 1908). As the primary goal of this thesis was not to add to this literature on the pressure-performance relationship a detailed discussion of these theories is outside the scope of this thesis. Instead, I next turn to the main interest of this thesis: understanding the processes that underlie pressure-performance effects.

Attentional Mechanisms

Attentional theories detail how pressure can change the cognitive and attentional processes that underlie visual-motor performance (Beilock & Gray, 2007). The theories presented here offer differing and sometimes conflicting views on how pressure can influence performance. The particularly contentious issue that distinguishes these theories is whether pressure serves to turn attention inwards, towards the body and skill execution, or outwards, towards the environment and irrelevant stimuli.

Attentional Control Theory

Attentional control theory (ACT; Eysenck, Derakshan, Santos & Calvo, 2007) offers a comprehensive theoretical framework that aims to explain the effects of anxiety on performance. While its scope was primarily limited to trait anxiety and cognitive task performance, it has readily been applied to explain the effects of both state anxiety and visual-motor performance. Two major predictions made by its precursor, processing efficiency theory (PET; Eysenck & Calvo, 1992), are subsumed within ACT. Firstly, like other interference theories (c.f. Sarason, 1988; Wine 1971), ACT assumes that anxiety occupies a portion of limited cognitive resources that are then less available for task-relevant activities. This dissipation of resources can lead to impaired overall performance. Secondly however, ACT also predicts that anxiety can act as a motivational function initiated by concerns over substandard performance. This has the potential to lead to an increase in on-task effort, potentially maintaining or even increasing performance. The discrepancy between performance outcome and invested effort is a key facet of ACT (and previously PET). Specifically, ACT predicts that processing efficiency, which is the ratio between invested effort and the performance outcome, is impaired to a greater extent than the effectiveness of performance. ACT builds on its predecessor's predictions by taking a more precise stance on the specific mechanisms involved.

The central tenets of ACT are positioned within evidence for the existence of two attentional sub-systems: a goal-directed system and a stimulus-driven system. For instance, in an influential review, Corbetta and Shulman (2002) propose that parts of the frontal cortex and dorsal posterior parietal are responsible for top-down attentional control. This sub-system directs attention based on expectations, experience and task-knowledge. Its counterpart, located within areas of the temporoparietal and ventral frontal cortex, is responsible for bottom-up control and directs attention based on sensory events, particularly when they are unattended and salient. ACT suggests that anxiety leads to a disruption in the balance of these two systems, with the stimulus-driven system exerting increased control over attention than the goal-directed system. This overarching imbalance underpins a number of more specific predictions. Firstly, it is predicted that anxiety reduces inhibitory control, potentially causing attention to be directed towards prepotent or task-irrelevant stimuli, particularly if they are threatening. These task-irrelevant stimuli may either be internal (e.g., worrisome thoughts) or external (e.g., environmental distractions). Secondly, anxiety is predicted to impair the ability to efficiently shift attention between different tasks or operations within a single-task. Finally, anxiety is predicted to reduce the ability to update and monitor information in working memory.

Numerous studies within the cognitive psychology domain offer support for the predicted effects of anxiety on processing efficiency. High- and low-trait anxiety individuals have been shown to be capable of achieving similar levels of performance on cognitive tasks, but at the expense of lower processing efficiency (e.g., Calvo & Carreiras, 1993; Calvo, Eysenck, Ramos & Ramos & Jiménez, 1994). For example, overall reading comprehension performance has previously been shown to be unaffected by trait anxiety, however, high-trait individuals required more reading regressions (re-reading of sentences) to achieve this comparable performance (Calvo et al., 1994). Considerable evidence for anxiety-induced processing efficiency deficits have also been shown in visual-motor tasks (for a comprehensive review, see Wilson, 2008) where processing efficiency has been operationalised in various ways. For instance, self-report ratings of mental effort have been shown to be higher for trait anxiety individuals where visual-motor performance was similar (e.g., Smith, Bellamy, Collins, Newell, 2001; Wilson, Smith & Holmes, 2007). Psychophysiological indices such as pupil dilation (Wilson, Smith, Chattington, Ford & Marple-Horvat, 2006) and event related potentials (Murray and Janelle, 2007) have also offered more objective evidence in support of impaired processing efficiency.

Changes to gaze behavior have been unitised by a number of studies as a more direct measure of processing efficiency. For instance, studies have shown that anxiety leads to less efficient search strategies as indexed by an increase in search rate, which is defined as the total number of fixations divided by the average fixation duration (e.g., Murray and Janelle, 2003; Nieuwenhuys, Pijpers, Oudejans & Bakker, 2008; Williams, Vickers & Rodrigues, 2002; Wilson, et al., 2006). For example, Wilson and colleagues (2006) asked participants to perform a simulated rally driving task in neutral and anxiety conditions while wearing an eye-tracker. Trait anxiety scores were used to categorise participants into low- or high-trait anxious groups based on a median split approach. Anxiety was also manipulated experimentally using a combination of monetary incentives and ego threatening instructions. Overall, performance suffered in anxiety conditions, with a larger decrease in performance being found for the high trait anxiety group. In support of processing efficiency deficits, search rate was significantly higher for the high-trait individuals, although experimentally manipulated state anxiety had no effect. A number of visual-motor studies have also utilised gaze behavior metrics to test other predictions of ACT.

According to ACT, anxiety results in a disruption in the balance between the goal-driven and stimulus-driven attentional systems. Simple laboratory tasks (e.g., antisaccade task) have supported this overarching prediction (e.g., Derakshan, Ansari, Hansard, Shoker, & Eysenck, 2009; Derakshan, Smyth, & Eysenck, 2009). In more complex visual-motor tasks, two lines of anxiety-induced effects have provided support: disruptions to ordinarily long fixations known as the 'quiet eye', and increased allocation of visual attention towards salient or goal-threatening stimuli.

The quiet eye (QE) period has been defined as the duration of the final fixation on a location in the environment, that occurs before movement initiation (Vickers, 1996) and that lasts at least 100 ms; although more refined definitions have since been employed (c.f. Vine, Lee, Moore & Wilson, 2013). Briefly, the QE duration has been robustly linked to visual-motor expertise in a wide range of sport tasks (Mann, Williams, Ward & Janelle, 2007), and interventionally increasing its duration has been linked with expedited skill acquisition (e.g., Moore, Vine, Cooke, Ring, & Wilson, 2012) and refinement (e.g., Vine, Moore, & Wilson, 2011). Importantly in relation to ACT, the QE has been used as an index of effective attentional control, partially based on this link with skilled visual-motor performance. Specifically, a longer QE duration has been suggested by a number of authors (e.g., Causer, Holmes, Smith & Williams, 2011; Wilson, Vine, & Wood, 2009) to minimise distraction from task-irrelevant cues (stimulus-driven control), and allow extended movement programming (goal-directed control). An impressive body of evidence has shown that naturally occurring QE durations (i.e., without any explicit QE instructions) are consistently diminished in anxious conditions (e.g., Behan & Wilson, 2008; Causer et al., 2011; Moore et al., 2012; Nibbeling, Oudejans & Daanen, 2012; Vickers & Williams, 2007; Vine et al., 2013; Vine & Wilson, 2010; Vine & Wilson, 2011; Wilson, et al., 2009). This reduction has been used as confirmatory evidence for an increased influence of the stimulus-driven attentional system as predicted by ACT (Causer et al., 2011; Wilson et al., 2009). Changes to attentional allocation also support this prediction.

A small number of studies have examined whether anxiety leads to changes in the allocation of visual attention within a scene (e.g., Wood & Wilson, 2010; Wilson, Wood, & Vine, 2009). For example, Wilson et al. (2009) asked university level footballers to complete a penalty kick task in neutral and anxiety conditions while wearing a head-mounted eye-tracker. A goal-keeper stood in a standardised body position in the centre of the goal at the start of each trial. The objective was to score the penalty, with the goal-keeper representing a naturalistic, threatening stimulus. Results showed that in anxious conditions, visual attention was directed towards the goal-keeper both earlier, and for a longer duration. This research suggests that salient or goal-threatening stimuli capture attention to a greater extent in anxious conditions. A limitation of this research is that it has mainly focused on self-paced tasks, with little research examining the contemporary predictions of ACT in continuous visual-motor tasks.

Lapses in attentional control may be particularly evident in complex continuous visual-motor tasks, such as driving or flying an aircraft, due to the complexity, variety and speed of stimuli in the visual scene. For example, a person driving on a busy city street has to monitor other vehicles to avoid a collision, while also locating and reading street signs and paying attention to traffic. Likewise, a pilot flying in foggy conditions has to extract information from relevant cockpit instruments in order to maintain or adjust the orientation of the aircraft, while also ignoring information presented on irreverent instruments. Due to the complexity of these situations, it is likely that effective attentional control (i.e., shifting, inhibiting, updating) is even more crucial for successful performance that in self-paced tasks like golf putting where maintaining attentional focus on particular areas seems to be critical. This suggests that the breakdown in attentional control under pressure predicted by ACT may result in even larger performance decrements for continuous visual-motor tasks.

Examining gaze behavior in continuous visual-motor tasks offers a greater opportunity to examine not only changes to attentional allocation as a result of anxiety, but disruptions in the sequencing of visual attention. As stated previously, visual-motor ACT research has focused on scan rate, however, the rate of visual-scanning could be influenced by other concomitant factors that accompany anxiety, such as mental effort or arousal. So while its use as a general measure of inefficiency is valid, greater insight may be gleaned by examining the randomness of gaze behavior. To illustrate, imagine a tracking task that requires the use of a number of instruments, with each providing separate information on the state of the task. Rate measures, such as transition rate (i.e., number of gaze transitions between the instruments per second), simply indicate how quickly visual attention is being cycled through the instruments. However, measures of randomness indicate how predictable the next instrument to be attended is. In such a task, low randomness would be indicative of predictable, stereotyped gaze behavior (Ellis & Starks, 1986; Harris, Glover & Spady, 1984). Therefore in relation to ACT, anxiety-induced obstructions to goal-directed control should be evidenced by less predictable transitions. The reasoning behind this suggestion is that the goal-directed attentional system will be predominantly responsible for predictable scanning, as it dictates which instrument will be attended next based on knowledge of the task and expectations of future changes.

Attentional Narrowing

In a seminal review article, Easterbrook (1959) proposed cue utilisation theory, which hypothesised that arousal or stress can lead to a reduction in the breadth of cues that can be utilised. Specifically, the theory predicted an inverse relationship between stress or arousal and the ability to use peripheral cues, due to "a shrinkage of the perceptive field" (Easterbrook, 1959, p. 189). 'Attentional narrowing' has therefore become a more generic and commonly used term that encompasses Easterbrook's idea. Based on the theory's predictions, performance on tasks which require a large breadth of cues should suffer in stressful conditions. On the other hand, performance may be maintained or improved in tasks which require a narrow breadth of cues. Early supportive evidence came from continuous tracking experiments (e.g., Bahrick, Fitts and Rankin, 1952; Bursill, 1958). For example, Bursill (1958) found that heat stress reduced participants' ability to detect the intermittent onset of peripheral lights while performing a centrally located pursuit tracking task. In a similar experiment, Bahrick et al. (1952) found that stress, in the form of monetary incentives, decreased the detection of peripheral stimuli. More recently, a small number of studies have investigated the effects of pressure-induced attentional narrowing in more complex visual-motor tasks.

Janelle, Singer & Williams (1999) investigated attentional narrowing in a simulated indy-car racing task. The view from the simulated cockpit was displayed on a projector screen and coloured peripheral lights were positioned on the screen at the extremities of each participants' peripheral vision. Participants were instructed to drive as fast as possible while wearing a head-mounted eye-tracker. They were also required to indicate when certain peripheral lights illuminated by pressing a push-button. It was emphasised that both the driving and peripheral detection tasks were of equal importance. Following acclimatisation trials, pressure was induced using monetary incentives. Results were generally indicative of attentional narrowing effects, with pressure reducing the ability to accurately respond to peripheral stimuli. A greater number of saccades towards the peripheral stimuli were observed, suggesting that peripheral vision alone was no longer able to accurately detect the stimuli.

Studies that lend support for attentional narrowing effects commonly employ infrequent, less salient stimuli in order to assess peripheral vision, while a salient, continuous task is performed in central vision (Eysenck et al., 2007). Eysenck and colleagues (2007) argue that attentional narrowing effects may simply occur due to salience differences, with anxiety leading to a prioritisation of the salient continuous task at the expense of the less-salient peripheral task. The previously mentioned research cannot determine whether attentional narrowing effects are found in tasks which require the processing of central and peripheral stimuli of similar salience. A more direct test for attentional narrowing effects may be found using techniques employed in a separate, but related, body of research which has examined the effects of various factors on the 'functional' or 'useful' field of view.

Ironic Processes of Mental Control

Wegner's (1994) theory of ironic processes of mental control proposes that ironic performance errors are more likely to occur when cognitive load or anxiety is high. To illustrate, a golfer leading a tournament, standing with an out-of-bounds fence to their left, may desperately want to avoid jeopardising their lead by hitting a leftwards shot and losing the ball. Ironically, they may hit a bad shot that achieves precisely that outcome. The theory suggests that mental control results from the interaction of two processes: an operating process and a monitoring process. The intentional operating process searches for mental contents that will produce a desired goal or state. Its counterpart, the monitoring process, unconsciously searches for mental contents that signal a failure to achieve this outcome. If failure signals are detected, attempts are made to reinitiate the operating process. Of most relevance to the current thesis, anxiety is suggested to consume the cognitive resources needed by the operating process. This then leads the monitoring process to gain mental control, meaning that mental contents indicating a failure are brought to the forefront.

Numerous thought (e.g., Wegner & Erber, 1992; Wegner, Schneider, Carter & White, 1987) and emotional suppression (e.g., Dalgleish, Yiend, Schweizer & Dunn, 2009; Wegner, Eber & Zanaoks, 1993) studies offer support for Wegner's theory. In general, these studies show that participants are less able to supress specific target words, phrases, images (e.g., "don't think about a white bear"), or emotions, when cognitive resources are pre-occupied. Other studies have found support for anxiety-induced ironic performance errors in visual-motor tasks such as golf putting (e.g., Wegner, Ansfield & Pilloff, 1998; Woodman & Davis, 2008) and football penalty kicks (e.g., Bakker, Oudejans, Binsch & Van der Kamp, 2006; Binsch, Oudejans, Bakker & Savelsbergh, 2010).

Woodman & Davis (2008) hypothesised that individuals with a repressive coping style (i.e., low self-reported anxiety but high psychophysiological indications) would be most prone to ironic errors in anxious conditions, as this coping style has been shown to require more cognitive resources. Novice participants performed a golf putting task on a flat surface, the objective was to putt a golf ball so that it landed on an 11cm diameter target circle positioned two metres away. After completing baseline putts, they were then asked to perform one putt in high-anxiety conditions, with the additional instruction to “be particularly careful not to hit the ball past the target”. Anxiety was manipulated using a monetary incentive, with every participant being given the chance to instantly win £50 if the ball landed on the target - a design choice that perhaps indicates the researchers’ confidence in the manipulation. Results supported their hypotheses, with a higher average ironic error being found for individuals exhibiting a repressive coping style. Penalty kick studies have also found evidence for ironic performance errors, with the added finding that ironic errors were accompanied by a reduced final fixation duration on the desired target area and either longer duration, or a higher frequency of, fixations on the to-be-avoided goalkeeper (Binsch et al., 2010).

While the aforementioned studies offer support for Wegner’s theory, most have used explicit instructions on what performance outcome is to be avoided, therefore it is unclear how well the findings generalise to environments where explicit avoidance instructions are not provided. Also, it has been acknowledged that truly ironic errors in high-level sport are probably quite rare, and it is often difficult to distinguish between a generic error and ironic error *per se* (Woodman & Davis, 2008; Woodman, Barlow & Gorgulu, In Press). Finally, and as noted by Binsch et al. (2010), the results of a portion of these studies may equally be explained by Eysenck and colleagues’ ACT (outlined previously). Specifically, allocating an area of the visual scene as ‘to be avoided’ is essentially turning that area into a threating stimulus - the avoidance instruction emphasises a threat (e.g., the goalkeeper) to achieving a specific outcome (i.e., scoring a penalty). Therefore in line with ACT, it is possible that attention becomes more directed towards this threatening stimulus as a result of a disruption between goal-directed and stimulus-driven attentional subsystems.

It should be noted that both ACT and the ironic processes of mental control theory proposed that the primary mechanism through which pressure has its's effect on performance is by reducing the cognitive resources available. Inherent in this prediction are two suggestions that have not been directly tested in previous ironic effects research. First, the effects of pressure should be similar in nature to the effect of increasing cognitive load (e.g., the addition of an unrelated secondary task). Second, the effects of pressure and cognitive load may be additive.

Self-Focus Theories

Self-focus theories are collectively predicated on the view that pressure increases self-consciousness (e.g., Baumeister, 1984), which leads focus of attention to be directed onto oneself and can in-turn impair learned movement patterns. Two of the most prominent theories, the theory of reinvestment and the explicit monitoring hypothesis, are reviewed here. It is worth noting that although these theories do overlap, their differences will be delineated.

Theory of Reinvestment

The theory of reinvestment was proposed by Masters (1992) and it suggests that pressure can cause individuals to attempt to control their movements using previously learnt rules or instructions, which in-turn leads to performance decreases. To illustrate, an expert golfer who is leading a tournament may begin to re-think about previously learnt rules or tips on how to execute their backswing (e.g., how far apart to place their feet, how their fingers should be positioned). They 'reinvest' in their knowledge base. In doing so however, they are interrupting or breaking-down a previously well-learnt movement pattern, which leads them to hit a poor shot. Reinvestment theory is closely aligned with cognitive theories of skill acquisition.

Cognitive theories of skill acquisition (Anderson, 1987; Fitts & Posner, 1967) are based around the distinction between two forms of knowledge. Explicit or declarative knowledge, is knowledge that can be articulated and manipulated within working memory. Its counterpart, implicit or procedural knowledge, is knowledge that is known but cannot be articulated. According to these theories, learners progress from the declarative knowledge stage to the procedural stage. The declarative stage is characterised by effortful, slow and poor performance, whereas the procedural stage is characterised by effortless, fast and superior performance (Hardy, Mullen & Jones, 1996). As stated previously, the crux of reinvestment theory is that performance will be impaired if individuals in the procedural stage begin to 'reinvest' in previous explicit knowledge about the task. Reinvestment has therefore been formerly defined as the 'manipulation of conscious, explicit, rule based knowledge, by working memory, to control the mechanics of one's movements during motor output' (Masters & Maxwell, 2004, p. 208). The theory suggests that reinvestment is likely to occur in pressure situations as people realise the consequences of their actions and begin to control the process of performing (Masters & Maxwell, 2008). In order to test this viewpoint, a number of studies have investigated whether preventing the accumulation of explicit knowledge reduces the likelihood of failing under pressure.

Masters' (1992) original study investigated the role of explicit knowledge in choking under pressure in a golf-putting task. Participants were randomised into a number of groups, all of which completed 400 acquisition putts. Of central interest are the explicit and implicit groups; the explicit group were given instructions on the mechanics of the putting stroke, whereas the implicit group were asked to generate and vocalise random letters while putting in order to prevent the self-generation of explicit knowledge. At the end of learning, these groups completed a number of putts in pressurised conditions. Results showed that the explicit group outperformed the implicit group across acquisition, as expected, they also accrued more explicit rules about the task. However, in pressure conditions the explicit group's performance plateaued whereas the implicit group continued to improve. This study has been replicated and scrutinised a number of times (e.g., Hardy et al., 1996; Bright and Freedman, 1998; Mullen, Hardy, Oldham, 2007), and overall, the results show a similar pattern. In relation to choking under pressure, it is slightly problematic that pressure only caused performance of the explicit group to plateau rather than decrease. Specifically, it was expected that the explicit group's performance would deteriorate under pressure if reinvesting in explicit knowledge is indeed a mechanism responsible for choking. It was however noted that the levels of pressure may not have been sufficient to invoke choking (Mullen et al., 2007).

Taken together, these studies do seem to suggest a trade-off: choosing explicit learning gives superior performance that is potentially maintained under pressure, whereas implicit learning gives inferior performance which does however continue to improve under pressure. Other learning techniques (i.e., analogy instructions) have since been shown to provide the performance benefits of explicit learning without accruement of explicit rules, while also providing the pressure resistive benefits of implicit learning (c.f. Liao and Masters, 2001). These studies used acquisition paradigms where novices learn how to perform a task. The effects of specifically utilising explicit cues during pressure situations has however also been investigated using performance paradigms with skilled performers.

It has been recognised that the accumulation of explicit knowledge does not necessarily lead to choking under pressure in itself, rather, the *use of* explicit knowledge under pressure is likely more critical (Jackson & Wilson, 1999). A number of studies have investigated whether utilising explicit cues is detrimental to skilled sportspeople's performance in pressure situations, with some studies supporting the link (e.g., Hardy, Mullen & Martin, 2001; Gucciardi & Dimmock, 2008), whereas others do not (e.g., Mullen & Hardy, 2000, 2010; Mullen, Hardy & Tatersall, 2005). For example, Gucciardi and Dimmock (2008) asked experienced golfers to perform a putting task in low and high pressure conditions, while either focusing on a number of explicit coaching points, task-irrelevant words or a swing thought ('smooth'). The results showed that explicit cues caused participants to choke under pressure, whereas the task irrelevant words and swing thought condition led to performance improvements. In a similar study, Mullen & Hardy (2010) again found that one 'holistic' swing cue resulted in improved performance under pressure, however one explicit cue led to performance being maintained rather than deteriorating. The authors accounted for these discrepant findings by suggesting that the number of explicit cues utilised may be a crucial and overlooked factor in the previous literature. Specifically, the utilisation of more than one explicit cue may be the cause of performance decreases in previous studies. Interestingly, certain individuals may be dispositionally more likely to reinvest in explicit knowledge, and in-turn choke under pressure.

Individuals' propensity to reinvest in their movements has been measured using the reinvestment scale (Masters, Polman & Hammond, 1993; Orell, Masters & Eves, 2009), which in its most recent revision encompasses two factors. Conscious motor processing, reveals the tendency to monitory and control movements, while movement self-consciousness, reveals the tendency to be concerned with one's movement style. Research has consistently shown dispositional reinvestment to be positively associated with poor performance under pressure (e.g., Chell, Graydon, Crowley, & Child, 2003; Jackson, Ashford & Norsworthy, 2006; Maxwell, Masters & Poolton, 2006). While this research is persuasive and suggests that 'high-reinvesters' are more likely to choke under pressure, it is not without its limitations. By definition, reinvestment refers to the use of the explicit, rule-based knowledge. However, when examining the content validity of the measure, it does not specifically assess whether explicit knowledge is involved in movement control. Instead, the subscales reflect a general propensity to monitor and think about movements. For example, the conscious motor processing scale contains items such as "I am aware of the way my mind and body works when I am carrying out a movement". Accordingly, the previously mentioned studies are, at least partially, suggesting that merely monitoring movements is detrimental to performance under pressure. This point leads to the second self-focus theory which is reviewed below.

Explicit Monitoring Hypothesis

The explicit monitoring hypothesis (Beilock & Carr, 2001) again suggests that pressure increases self-consciousness about correctly performing visual-motor tasks (Baumeister, 1984). However, in contrast to reinvestment theory, it is suggested that pressure will more likely lead to heightened *monitoring* of movements, as opposed to stimulating the use of explicit rules in an attempt to *control* them. While subtle, this is an important distinction. A number of studies have explicitly manipulated attentional focus in order to investigate the effects of monitoring movements on performance.

Attentional manipulations designed to promote movement monitoring have been shown to impair experts' performance in a number of different visual-motor tasks, including golf putting (e.g., Beilock, Carr, MacMahon & Starkes, 2002; Beilock & Gray, 2012), baseball batting (Gray, 2004), hockey (Jackson et al., 2006) and soccer dribbling (Ford, Hodges & Williams, 2005). For example, Beilock et al., (2002) asked novice and expert footballers to complete a soccer dribbling task, while simultaneously performing either: a word-monitoring task, or a skill-monitoring task which required them to report the side of the foot that last made contact with the ball. Results showed that expert performance was impaired during the skill-monitoring task, whereas novice performance was impaired by the word-monitoring task. In a related body of research, Wulf and colleagues (reviewed in Wulf, 2007, 2013; Wulf & Prinz, 2001) have shown that focusing attention on the effects of movements on the environment (i.e., an external attentional focus) enhances the learning of visual-motor tasks in comparison to more internal foci of attention. These studies support the view that focusing on movements may impair performance, however the relation with pressure was not manipulated.

Gray (2004, Experiment 3) more directly examined the effects of pressure on movement monitoring expert baseball batters. A dual-task paradigm was employed where participants were required to perform a batting task at the same time as either a skill-focused or extraneous secondary task. In the skill-focused task, participants were required to indicate whether their bat was moving up or down at the onset of a response prompt. Accuracy on this secondary task therefore provided an index of the participants' awareness of their movements. In the dual-task condition they had to judge the pitch of an auditory tone. Pressure significantly impaired performance and this choking effect was accompanied by a significant improvement in response accuracy for the skill-focused secondary task. This finding provided direct evidence to suggest that pressure can lead to increased movement monitoring, which can in-turn impair performance.

Behavioral Mechanisms

Initial research investigating the effects of pressure on visual-motor tasks focused on performance outcomes, such as holing or missing golf putts, or scoring or missing penalty kicks in football. However, performance outcomes result from movement execution, therefore in order to empirically understand the mechanisms underlying choking under pressure it is important to examine how movements are affected (Beilock & Gray, 2007). A greater understanding may also help to stimulate possible interventions – if specific movement tendencies emerge under pressure, these may be guarded against in training (Gray, 2011). A number of kinematic changes have been proposed and observed in a variety of tasks. In this section, evidence for freezing degrees of freedom will firstly be explored, then changes to movement variability will be examined. For a number of possible reasons, a considerable amount of research has examined the effects of pressure specifically on golf-putting kinematics, this research will be examined last.

Freezing Degrees of Freedom

Bernstein (1967) suggested that stress or pressure may result in the freezing, or coupling of, degrees of freedom in order to simplify movement execution. Bernstein highlighted the extremely high degree of complexity that the motor system successfully and efficiently manages when performing any movement. For instance, the seemingly simple act of striking a nail with a hammer involves many joints, each with several degrees of freedom, all of which must be coordinated in order to successfully achieve the movement objective. When learning a new skill, attempts may be made to simplify the movement solution by restricting, or freezing, degrees of freedom or by coupling them into larger coordinated units. Throughout learning, the restriction or coupling of these degrees of freedom is relinquished. Vereijken, van Emmerik, Whiting & Newell (1992) examined the movement kinematics of participants learning a ski slalom task over a number of days. In support of Bernstein's ideas, a restriction in joint angle ranges was found early in learning. Furthermore, cross correlations between certain joint angles were initially high and decreased throughout practice, indicating a gradual decoupling of different degrees of freedom. A small number of experiments have examined whether pressure leads to a reversal of these processes (Collins, Jones, Fairweather, Doolan & Priestly, 2001; Higuchi, Imanaka, Hatayama, 2002).

Collins et al. (2001) examined the performance and movements of Olympic weight lifters in neutral and competitive conditions. They found that certain individuals choked under pressure, and that this performance effect was accompanied by an increase in the cross correlation between the hip and neck joint in competition, for certain individuals. Higuchi et al. (2002) offer further evidence for a coupling of degrees of freedom. The authors asked participants to learn a simple batting task, which involved controlling a virtual bat shown on a screen using a manipulandum. Initially, the timing of certain kinematic events (e.g., movement initiation, backswing peak velocity, foreswing peak velocity) were highly correlated, which the authors argued was indicative of a coupling of degrees of freedom. Throughout learning, the timing of kinematic events became decoupled but then became relatively more coupled during the stress condition. However, performance was not affected by the stress manipulation. It is possible that the freezing degrees of freedom process may emerge in an attempt to reduce movement variability, the results of Higuchi and colleagues study partially support this view as spatial variability was marginally lower in the stress condition than the previous block. However, no performance effects were found, and no attempts were made to relate kinematic measures to performance. Therefore it is unclear how these findings relate to performance changes under pressure. However, other studies have examined the possibility that pressure may specifically influence movement variability.

Movement Variability

Skilled performance is often associated with repeatable (i.e., low variability), consistent movement timing and spatial positioning (e.g., Franks, Weicker & Robertson, 1985; McDonald, van Emmerik & Newell, 1989). Performance changes under pressure might therefore be accompanied by changes in movement variability, with a number of studies supporting this view (e.g., Beuter & Duda, 1985, Beuter, Duda & Widule, 1989; Causer et al., 2011; Gray, 2004; Higuchi, 2000; Wilson et al., 2006). For example, Causer and colleagues (2011) asked elite level skeet shooters to perform a shooting task in counterbalanced low and high pressure conditions. Performance significantly deteriorated under pressure with less skeets being successfully hit. Analysis of movements revealed a tendency for faster, larger amplitude and more variable lateral gun movements under pressure. In a simulated baseball batting task, Gray (2004) found that expert baseball batters choked in a pressure conditions, and this was accompanied by an increased variability in the relative timing of different stages of their swing. Both these studies focused on discrete movements, however Wilson et al. (2006) found that pressure-induced performance decrements in continuous rally driving task were accompanied by more variable steering wheel and accelerator pedal displacements. Further insights into the underlying effects of pressure on performance have been determined by examining variability throughout different stages of the movement.

Fast target-directed limb movements involve two control 'phases': a ballistic, pre-planned phase, and an online control phase, where available visual and proprioceptive input is utilised for guidance (e.g., Elliott, Hansen, Grierson, Lyons, Bennett & Hayes, 2010; Woodworth, 1899). The operation of these two control processes can be inferred by examining the variability of movement trajectories at different stages of the movement (c.f. Khan, Franks, Elliott, Lawrence, Chua, Bernier, Hansen & Weeks, 2006). Lawrence, Khan & Hardy (2012) exploited this analysis technique and found that anxiety specifically affected the online control phase of movement execution. Specifically, in comparison to neutral conditions, anxiety led to both a decrease in outcome performance, and an increase in movement variability in the latter portion (i.e., online control phase) of movement trajectories. This provides the most direct evidence to suggest that anxiety affects the online control of movements, a finding which relates to the previously mentioned self-focus theories. As alluded to previously, a common criticism of this study, and many of the previously mentioned studies in this section, is the absence of any analyses to relate choking under pressure to specific kinematic parameters. Although performance changes under pressure were accompanied by kinematic changes, this does not mean that these changes were related.

Golf-Putting Kinematics

A significant number of studies have examined the effects of pressure on golf-putting kinematics. It is unclear why there is a continued especial focus on golf-putting kinematics specifically, or indeed golf-putting as an experimental task more generally. The interest may be partially attributed to pragmatic reasons, such as the relative ease of data collection, and more recently, the accessibility of affordable and accurate measurement techniques, such as multi-axial accelerometers. Regardless, an important contribution of this research has been the identification of a number of kinematic parameters that may be related to performance changes under pressure.

The first study to examine the effects of pressure on golf-putting kinematics was conducted by Mullen and Hardy (2000), who performed kinematic analyses in an exploratory manner. They asked experienced golfers with mid-level handicaps (range 12-18) to putt along an inclined surface to a standard sized golf hole from a distance of 3m in neutral and pressure conditions. The golf handicapping system gives a general index of golf performance, therefore putting performance can vary widely between golfers with the same handicap. As a consequence, participants were further divided into high and low putting skill groups based on a median split of baseline putting performance. Movement kinematics were measured and analysed using a camera system. In pressure conditions, the time to peak speed in the downswing occurred earlier. A number of other kinematic parameters were also analysed but no significant differences were found and pressure had no overall effect on performance.

More recently, a number of studies have employed similar methodologies and kinematic measurement techniques and found preliminary evidence to suggest that pressure leads to a reduction in: movement time, backswing displacement and downswing displacement (Tanaka & Sekiya, 2010; 2011). For instance, Tanaka & Sekiya (2011) asked novice golfers to learn a putting task that resembled Mullen and Hardy's. Participants were transferred to a pressure condition after acquisition. Although manipulation checks were only partially validated (heart rate increased, but self-reported anxiety did not), kinematic analyses revealed that the angular displacement of the clubhead and arm decreased in both the backswing and downswing, while the average acceleration in the downswing increased. However, pressure again had no effect on performance and these kinematic changes were not correlated with performance change from pre-test to pressure conditions.

Establishing the kinematic changes that correlate with pressure-induced performance changes in golf putting has proved somewhat difficult. Triaxial accelerometer based studies with novice golfers (i.e., no golf handicap and no formal playing experience) have been the most successful (e.g., Cooke, Kavussanu, McIntyre & Ring, 2010; Moore, Vine, Wilson & Freeman, 2012). Cooke et al. (2010) asked novice participants to putt from three different distances in low, medium and high pressure conditions. The medium and high pressure conditions led to a reduction in the number of putts holed. Analyses showed that side-to-side acceleration of the clubhead (acceleration of clubhead movement in the sagittal plane of the golfer) increased under high-pressure and that this change partially mediated the performance effects.

Moore and colleagues (2012) also asked novice golfers to perform putts from one set distance in pressurised conditions. Participants were first randomly assigned to one of two groups where the experimental instructions were designed to frame the task as either a challenge or a threat. The threat group achieved a significantly higher average error, and also reported significantly higher cognitive anxiety. Mediation analyses revealed that club head acceleration in all three axes, as well as the first order derivative of acceleration in the backswing-downswing axis (clubhead movement in the coronal plane of the golfer), was responsible for this performance difference. This seems to indicate that the movements of the threat group were all-together poorer than the challenge group, and this was responsible for the observed performance differences. However, similar studies investigating expert or experienced golfers have not been as successful in establishing kinematic variables that are responsible for performance changes under pressure (e.g., Cooke, Kavussanu, Gallicchio, Willoughby, McIntyre & Ring, 2014), even when significant outcome performance differences have been found (e.g., Moore et al., 2013).

An important limitation of this previous research is that all putts were commonly made from a constant distance, apart from Cooke and colleagues (2010) who did not report any analyses with putt distance as a factor. Previous research has shown that expert and novice golfers differ in the way they adjust their putting stroke to suit different putt distances (Delay, Nougier, Orliaguet & Coello, 1997). Specifically, expert golfers control the club head velocity at impact across different distances by substantially varying the downswing amplitude, whereas novices employ similar amplitude movements and vary other aspects of their swing. Previous related research (Beilock & Gray, 2012) has shown that attentional manipulations have the potential to influence the relationship between downswing amplitude and putt distance. Therefore it is possible that the relationship between putt distance and downswing amplitude could be an important kinematic parameter that may be affected by pressure. This is particularly important given the null findings specifically in expert populations.

Synopsis of Thesis

Understanding why performance pressure can cause changes to visual-motor performance is important from both a practical and theoretical viewpoint. For instance, from a practical point of view, achieving clarity on the mechanisms that lead to performance changes may help to inform interventions aimed at maximising performance under pressure. The current thesis investigates kinematic (chapter two) and attentional (chapters three, four and five) mechanisms that may underpin performance changes under pressure. Otten (2007) has previously suggested that the occurrence of both performance improvements, and deteriorations, under pressure could result in a lack of any group-level effects. Therefore, throughout each experimental study in this thesis, performance changes under pressure are correlated with changes in specific mechanistic variables in order to account for the possibility that responses to pressure may vary across individuals. Other specific limitations of previous research have been presented previously, these are now linked with the subsequent experimental chapters.

Study one (chapter two) examined the effects of pressure on golf-putting kinematics in expert golfers. In order to remedy limitations of previous research, putt distance was manipulated and inherently included in the analysis procedure. A novel analysis approach was used in order to investigate the relationship between movement amplitude and putt distance. It was predicted that the strength of the relationship between movement amplitude and putt would weaken under pressure for certain individuals, and that the change in relationship may correlate with performance changes.

Study two (chapter 3) investigated attentional narrowing during a golf-putting task. Limitations of previous research are accounted for by utilising a novel useful field of view task that was performed separately from the golf-putting task. The useful-field of view task also purposely presented equally salient stimuli to central and peripheral vision. Taken together, if evidence for attentional narrowing is found using this methodology, it is less likely to be due to an imbalance in salience of visual stimuli. It was predicted that pressure would lead to a reduction in the useful field of view and that this would be correlated with performance changes under pressure.

Study three (chapter 4) investigated the effects of cognitive anxiety on attentional control. In order to remedy a limitation of previous ACT research, the contemporary predictions of ACT were examined in a continuous visual-motor task. Specifically, participants were asked to perform an aviation instrument landing task in which several instruments were required in order to achieve optimal task performance. A novel measure, scanning entropy, was utilised as an index of attentional control. Based on the predictions of ACT, it was therefore hypothesised that anxiety would lead to an increase in scanning entropy and that this would correlate with performance changes under pressure.

Study four (chapter 5) aimed to replicate and extend upon the results of study three, and test the predicted links between pressure, cognitive load and performance described above. The study therefore examined the effects of both cognitive anxiety and cognitive load in the previously utilised aviation instrument landing task. It was predicted that the effects of cognitive anxiety on attentional control would be exacerbated when cognitive load was high. If this was the case, evidence should be found for an interaction between cognitive load and anxiety on scanning entropy.

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CHAPTER TWO

Changes in Putting Kinematics Associated with Choking and Excelling Under Pressure

The effects of performance pressure on the putting kinematics of 13 expert golfers was investigated. Golfers varied substantially in their response to pressure, with three having significantly increased putting errors (i.e., choking), three having significantly decreased putting errors (i.e., clutch performance) and the remainder showing no significant effect of pressure. Putting performance was significantly related to several kinematic variables. In particular, the relationship between downswing amplitude (DA) and putting distance was weaker for those golfers that choked under pressure as compared to clutch performers. The change in the DA-distance relationship associated with the introduction of pressure was significantly correlated with the change in accuracy (r = -0.58). These effects of pressure on putting kinematics are qualitively similar to the effects produced by directing attention to skill execution with a secondary task (Beilock & Gray, 2012) and thus provide support for the explicit monitoring theory of choking under pressure.

Introduction

Over the past 30 years the question of why some athletes fail under pressure while others thrive has remained one of the most popular research topics in sports science. Choking under pressure (i.e., "choking") is defined here as performing more poorly than expected given one's skill level i.e., a significant decrease in performance relative to pre-pressure levels (Masters, 1992). For a discussion of alternative definitions of "choking" see Mesagno & Hill (2013). As reviewed in Beilock and Gray (2007), the phenomenon of choking has been studied from multiple different angles investigating mechanisms including attentional control, biomechanics and kinematics, anxiety, effort, and social threat. Despite this considerable body of research, an understanding of exactly how pressure exerts its effects on performance in terms of how the perceptual-motor control of the performer changes in high pressure situations is still lacking (Gray, 2011).

How does pressure change the movements and kinematics associated with complex motor skills? As discussed in detail by Gray (2011), there are important theoretical and practical reasons for investigating this largely unresolved question. Previous research examining the effect of pressure on performance has primarily measured performance outcomes. While performance effects are obviously the most immediate concern of an athlete or coach, movement effects may provide a more reliable and direct index. Anyone who has participated regularly in sport knows that good execution does not always lead to a successful outcome (and poor execution does not always lead to failure). There are many additional variables (e.g., the reactions of opponents and environmental conditions) which determine whether the execution of a sports skill will be successful. Therefore, measurement of movement effects and kinematic changes (which are more directly influenced by attention than performance effect) are key to developing a theoretical account of skilled motor action.

It is also of practical importance. Identifying problems at the level of movement execution will improve the ability of a coach to help an athlete remedy performance failures - one can only get so far by instructing a performer to “stop trying too hard” when faced with a pressure situation. The focus of the present study was golf putting therefore we next review previous research that has investigated the pressure-kinematics relationship in this context.

The Effects of Pressure on Putting Kinematics

Mullen and Hardy (2000) conducted the first exploratory analysis of the effects of pressure on kinematics in golf putting for high and low skill golfers (as defined by a median split based on baseline putting data). Golfers ranged in handicap from 12-18 and it was noted that in a pilot study golfers with a handicap lower than 12 showed no effect of the pressure manipulations used (a combination of monetary reward for performance and telling participants their performance would be evaluated by a golf professional). Putts were always made from a distance of 3m. The only significant effect of anxiety on putting kinematics was that under pressure conditions the time to peak speed (TTPS) of the putter head occurred earlier in the downswing as compared to the pre-test condition. There were no significant effects of pressure on any of the other kinematic variables measured which included range of motion, velocity and acceleration variables. However, it should also be noted that the pressure manipulation used in the study did not have a significant effect on putting performance.

Cooke, Kavussanu, McIntyre and Ring (2010) examined the effect of pressure on the putting kinematics of 48 novice golfers. The putting distances were 1.2, 1.8 and 2.4m, pressure was induced via monetary rewards for performance and socially evaluative instructions. Anxiety ratings were significantly higher, and the number of putts holed was significantly lower under pressure. In terms of kinematics, there was an increase in the lateral acceleration of the putter head during the downswing which led to an associated increase in the variability of the putter face angle at the point of contact.

Tanaka and Sekiya (2010) investigated the effects of pressure on the kinematics of six professional golfers and five novices. Following a training period, pressure was induced via the presence of a small audience and a cash prize for performance. All putts were made from a distance of 4m. Although there were no significant changes in state anxiety or putting performance as a result of pressure, there were some significant kinematic effects. For both novices and experts the amplitude of backswing and downswing was significantly smaller and the velocity of the downswing was significantly slower under pressure. The authors propose that these changes reflect a general motor strategy used to increase the accuracy movements, that is moving a shorter distance and at a slower velocity (Schmidt, Zelaznik, Hawkins, Frank & Quinn, 1979).

In a follow up study, Tanaka and Sekiya (2011) asked 20 novice golfers to perform under pressure conditions in which they either received a cash reward or cash punishment for performance. All putts were made from a distance of 1.5m and a 3-D kinematic analysis was used. There were again no significant changes in performance or state anxiety associated with the pressure manipulations, however there was a significant increase in heart rate (HR). Consistent with their previous findings of reduced amplitudes of the backswing and downswing, this study found that pressure led to significantly decreased rotational movements (i.e., pronation-supination of wrists). It also reported increased acceleration of the elbows during the downswing (DS) phase, and decreased movement time during the backswing (BS) and DS phases of the pressure test. In other words, participants who showed greater increases in HR exhibited short, quick and rigid putting strokes as opposed to the long smooth strokes used by the other participants.

An important limitation of these previous studies is that all putts were made from a constant distance, apart from Cooke et al. (2010) who did not report any analyses with putt distance as a factor. Previous research has shown that the manner in which a golfer adapts their putting stroke to different putting distances is one of the key characteristics that distinguish expert from novice golfers. As first proposed by Delay, Nougier, Orliaguet and Coello (1997), expert golfers achieve the optimal force at putter head/ball contact by programming the movement amplitude of the backswing (and the resulting downswing) according to the hole distance. In other words, to putt the ball further experts substantially increase the length of their putting stroke while keeping the velocity of the movement roughly constant across distance (see also Sim & Kim, 2010). Less skilled golfers, on the other hand, do not show this tight coupling between swing amplitude and putting distance and instead vary other aspects of the backswing and downswing (either movement time or velocity). Noted golf instructor Dave Pelz (2000) explains the disadvantage associated with the strategy used by less-skilled golfers.

> We tested the putting stroke of some 150 amateurs at the DuPont World Amateur Tournament. The averaged results show that the length of their backswings varied only about 6 inches, while the length of the putts produced varied 6 to 30 feet. This means their backswing, the power generator of the putting stroke, varied only 6 inches for 24 feet...Think of the pressure that puts on every putt. These amateurs must be able to sense and feel a difference of less than one inch to produce putts of 12 and 15 feet, respectively. (p. 117)

He further explains the advantage of the expert putting strategy observed by Delay and colleagues: “backswings change to control the distance our putts roll....This means that there is more room for adjustments when producing putts of different lengths." (Pelz, 2000, p. 120).

Given that this downswing amplitude/putting distance relationship is a characteristic difference between elite and novice performers it might also be one that changes under pressure. We have recently provided evidence consistent with this idea in a study examining the effects of attentional control on putting kinematics (Beilock & Gray, 2012). In this study, attentional control was manipulated via two different secondary tasks: a *dual-task condition,* in which participants judged the frequency of a tone presented during their stroke and a *skill-focused condition,* in which participants judged whether the tone occurred closer to the starting or end point of the swing segment in which the tone was presented. For experts, putting performance decreased in the skill-focused condition relative to baseline and the dual-task condition. This decline in accuracy was significantly mediated by a reduction in the strength of the relationship between downswing amplitude (DA) and distance (and a significant increase in the strength of the relationship between movement time and distance). In other words, when attention was directed to skill execution, experts switched to using the novice motor control strategy for putting from different distances.

It is suggested that similar effects may occur in pressure situations. This is anticipated because one of the primary theories of "choking" is that pressure prompts skilled performers to shift their attention inwards so that the focus is on movement execution, in much the same manner as the skill-focused task described above. These "self-focus" theories have been proposed in various forms by many authors (e.g., Baumeister, 1984; "Reinvestment Theory" Masters, 1992; "The Constrained Action Hypothesis" reviewed in Wulf & Prinz, 2001) and supported by abundant evidence (e.g., Beilock, Carr, MacMahon & Starkes, 2002).

Unfortunately, because putting distance was not varied or examined in previous research, the effect of pressure on the DA/putting distance relationship cannot be evaluated.

Another limitation of previous research in this area is that, with the exception of the Cooke et al. (2010) study, the pressure manipulations used have not led to significant changes in putting performance. Therefore, it is difficult to determine whether the reported kinematic changes under pressure actually underlie the phenomenon of "choking" or are just irrelevant changes. As proposed by Craig, Delay, Grealy, and Lee (2000), for experts the downswing movement of the club is continuously adjusted in response to the value of the optical variable $\tau_{departure}$ where this variable is defined as the optical angle between the current club head location and the location of the end of the swing (i.e., final follow-through position of the club head) divided by the rate of change of this angle. Perhaps the majority of kinematic changes observed in previous studies are simply variations in the putting stroke that are corrected in this final continuous control phase of the stroke. The lack of effect on the actual putting error or number of putts holed suggests that this is likely the case. Previous research on perceptual-motor control in sports has demonstrated that variations early in the execution of movements are frequently irrelevant to performance outcomes because they can be compensated for by subsequent online corrections (e.g., Bootsma & van Wieringen, 1990; Lee, Lishman & Thompson, 1982).

Another possible explanation for the lack of performance effects in this previous research is that performance changes are masked by individual differences in the effects of pressure. It is well known to anyone who watches sports regularly that not all athletes respond in the same way to performance pressure: while some 'choke', defined as "performance decrements under pressure situations" (Baumeister, 1984, p. 610), others seem to excel or be 'clutch', defined as "superior performance that occurs under pressure circumstances" (Otten, 2009, p. 584). Perhaps if participants were separated on the basis of their performance outcome under pressure, different kinematic effects will be observed for those that fail and those that succeed. This may allow the identification of more relevant kinematic changes.

Aims of the Present Study

The goal of the present study was to investigate the effect of pressure on the ability of expert golfers to modulate the force of their stroke appropriately for putts made from different distances. In particular, we sought to test the prediction described above that pressure would serve to decrease the strength of the relationship between downswing amplitude and putting distance, that is it would cause a change in the perceptual-motor control strategy. We also sought to investigate individual differences in pressure-performance outcomes.

Method

Participants

A total of 13 (11M, 2F) golfers enrolled in the Applied Golf Management Studies degree at the University of Birmingham participated in the study. Their mean age, mean handicap and mean number of years competitive playing experience were 20.7 (*SE* = 0.5) years, 3.3 (*SE* = 0.5) strokes, and 7.6 (*SE* = 0.7) years respectively.

Apparatus

A McGregor M220™ 35 inch (88.9 cm) right handed putter and Wilson Ultra™ golf balls (diameter 4.27 cm) were used. The artificial putting mat had a width of 1.4 m and a length of 4.6 m. The putting task required participants to putt a golf ball as accurately as possible to a red square-shaped target (10.5 cm^2) marked on the surface of the green, on which the ball was supposed to stop. A target on the green surface, rather than a standard hole, was used in order to gain a continuous measure of putting error rather than a dichotomous "hit/miss" score. Previous research has demonstrated similar performance outcomes using either a target or a hole (Beilock & Carr, 2001). Putts were made from distances of 2, 2.5 and 3 m to a target 1.03 m from the end of the putting surface. The x/y/z location and angle of the putter head was recorded by mounting a Fastrak (Polhemus™) position tracker sensor weighing 10g on the back side of the putter.

Anxiety Questionnaire Measure

The Immediate Anxiety Measures Scale (IAMS; Thomas, Hanton & Jones, 2002) assessed participants' intensity and direction of cognitive anxiety, somatic anxiety and self-confidence. The questionnaire is composed of three items measuring the extent to which participants feel cognitively anxious (*I was cognitively anxious*), somatically anxious (*I was somatically anxious*), and self-confident (*I was self-confident*). Responses are made on a 7-point Likert-type scale ranging from 1 (*not at all*) to 7 (*extremely*). Participants then indicate whether they regard this anxiety and self-confidence as helpful or hurtful to performance with ratings made from -3 (*very debilitative/hurtful*) to +3 (*very facilitative/helpful*). To ensure responses are reflective of each state, the IAMS provides participant friendly definitions of each construct to enable individuals to fully understand the meaning of each one. Thomas et al. (2002) demonstrated the IAMS to be a valid and reliable measure of anxiety and self-confidence with the items significantly correlating with the corresponding subscales of the Competitive State Anxiety Inventory-2 (CSAI-2; Martens, Burton, Vealey, Bump, & Smith, 1990). Consequently, the IAMS has now become a frequently used measure of state anxiety and self-confidence within studies due to being quick and easy to administer (e.g., Williams & Cumming, 2012).

Procedure

The experiment was divided into three phases: practice, pre-pressure and pressure. In the practice phase, participants made 24 practice putts (eight from each distance following the distance progression 2, 2.5, 3, 2.5, 2…). The distance from the centre of the marker to the ball was recorded after each putt, before the ball was returned to the participant for their next putt. After a 10 minute break, participants next completed 18 putts (following the same progression in distance) that were used to evaluate pre-pressure performance. After another 10 minute break participants completed the pressure phase which was comprised of the same 18 putts. Prior to beginning putting, participants were next read the following script:

> We're now moving into a competition phase. Your objective in the competition is still to putt the ball as close to the marker as possible. However, throughout the experiment you have so far accumulated 180 points. A small ring will be placed around the marker on the green. For every putt that finishes outside the ring, you will lose 10 points. Your point total (and that of the top participants in the study) will be displayed on a leader board that will be updated after each putt. Prize money of £50, £25 and £10 is up for grabs, for 1st, 2nd and 3rd Place. How many points you manage to hold on to determines your position on the leader board. All the results will be e-mailed out to everyone who takes part in the study, and will be displayed on the notice board in the school atrium. So everyone will know how everyone else performs. No pressure then<<said sarcastically>>..........good luck![1]

[1]As suggested by one reviewer our inclusion of the expression "no pressure" in the pressure block script may have indicated to participants that they should feel pressure rather than allowing them to subjectively interpret our pressure manipulation. It will be important for future research to determine whether similar effects occur when this "priming" phrase is not used.

In the pressure condition, a 16.5 cm diameter ring was placed around the target. The leader board was displayed on a 61 cm (24") computer monitor positioned beside the putting green. For every participant, the leader board displayed the names and scores of four fictitious players. The point scores were 150, 130, 90 and 50 points. The participant's last name and point total of 180 appeared at the top of the leader board at the beginning of the pressure phase and was dropped down as their point total fell below the other players listed. No matter how they performed the participant never fell below 5th place on the leader board.

Upon completion of the 18-putt pre-pressure phase and the 18-putt pressure phase, participants completed the IAMS.

Data Analysis

Questionnaire responses. Intensity and direction data from each of the IAMS subscales were submitted to separate paired sample t-tests.

Putting accuracy. The mean distance from the target for each participant (averaged across the six repeats) were submitted to a 2 (block: pre-pressure, pressure), x 3 (putting distance: 2, 2.5 and 3 m) repeated measures ANOVA.

Putting kinematics. As described above, our main dependent variable of interest for putter movement was the relationship between downswing amplitude (DA) and putting distance. Mean values of DA were submitted to a 2 (pre-pressure, pressure), x 3 (putting distance: 2, 2.5 and 3 m) repeated measures ANOVA.

We also analysed several other movement variables including backswing MT (BMT), downswing velocity (DSV), time to peak speed (TTPS), and velocity at impact (VI) using 2x3 repeated measures ANOVAs. These particular variables were chosen because previous research has shown that they were the primary variables which distinguished novice and expert performance (Delay et al., 1997) and/or were significantly influenced by attention manipulations (Beilock & Gray, 2012; Mullen & Hardy, 2000).

Results

Manipulation Check

A paired samples t-test revealed a significant difference in cognitive anxiety ratings between pre-pressure (M = 2.31, SE = .37) and pressure (M = 3.23, SE = .48) conditions; $t(12) = - 2.65$, $p = .021$. Similarly, a significant difference was found for ratings of somatic anxiety between pre-pressure (M = 1.92, SE = .31) and pressure conditions (M = 3.15, SE = .45); $t(12) = -2.70$, $p = .019$. Confidence ratings did not significantly differ ($p = .42$) between pre-pressure (M = 4.46, SE = .42) and pressure conditions (M = 4.77, SE = .47). All analyses on directional aspects of cognitive anxiety, somatic anxiety and self-confidence were non-significant (p all > .3) and are therefore not reported.

Putting Accuracy

The 2x3 repeated measures ANOVA revealed non-significant main effects of block and putting distance (p both > 0.5). The Block x Distance interaction was also not significant. As illustrated below and as expected (see above), further inspection of the data indicated that this lack of significant effects was due to the fact that the different participants in the study responded very differently to the pressure. Therefore, we chose to analyse the data at the level of individual participants.

Since each participant performed the identical set of 18 putts in the pre-pressure and pressure blocks we first calculated the difference in putting error for each of the 18 putts for each golfer. We next scaled these differences by the distance of each putt. Figure 2.1A shows the mean pre-pressure to pressure difference for each of the 13 participants. To analyse these data we next performed separate paired samples t-tests for each golfer using Bonferroni correction for type I error (critical $p = 0.004$). These t-tests revealed that putting errors were significantly larger under pressure for participants 1 [$t(17) = -4.03$, $p < 0.001$], 3 [$t(17) = -3.4$, $p < 0.004$], and 7 [$t(17) = -3.6$, $p < 0.004$] and were significantly lower under pressure for participants 6 [$t(17) = 3.4$, $p < 0.004$], 8 [$t(17) = 3.4$, $p < 0.004$], and 11 [$t(17) = 3.6$, $p < 0.004$]. For the remaining participants there were no significant differences between putting errors pre-pressure to pressure (p all > 0.004).

As an additional means of quantifying performance we calculated the number of putts that stopped inside the ring in the pressure block for each golfer. Figure 2.1B plots the means of this variable. Across participants there was a significant negative correlation between the number of putts inside the ring and the pre-pressure to pressure difference in putting error: $r = -0.57$, $t(11) = -2.3$, $p < 0.05$.

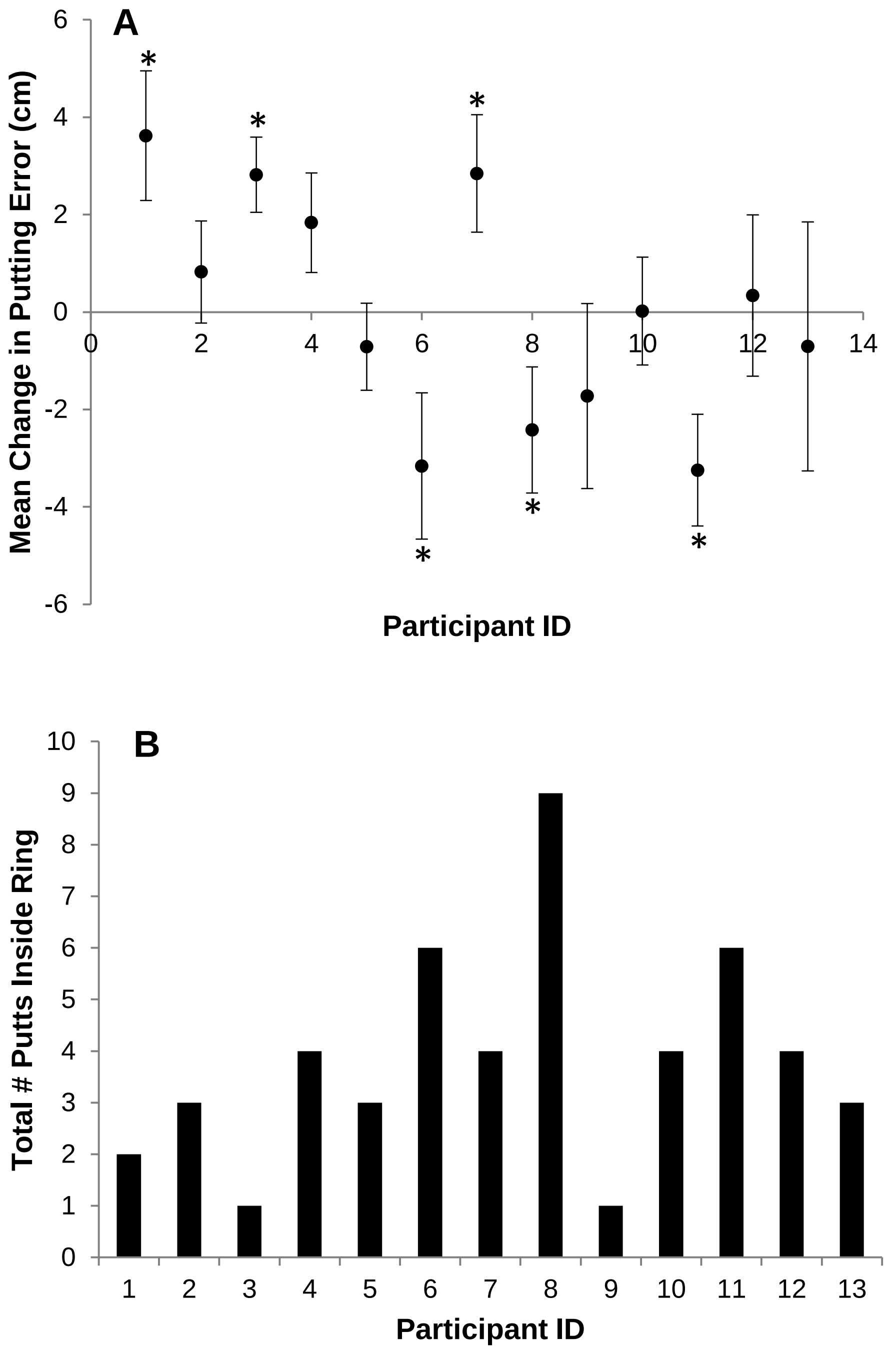

Figure 2.1. Putting performance for each participant. (A) Change in mean putting error (pressure – pre-test) for each participant. Data are averages for the three putting distances. Error bars are standard errors. (B) Total number of putts in which the ball stopped inside the 16.5cm diameter ring in the pressure condition.

Putting Kinematics

As described above, our main dependent variable of interest for putter movements was the downswing amplitude (DA), in particular how it varied as a function of putting distance. For each golfer we first plotted the DA as a function of putting distance, fit a linear function, and then calculated the slope. This was done separately for the pre-pressure and pressure data. Thus, a total of 26 plots were analysed (13 golfers x 2 blocks). In Figure 2.2, example plots are shown for participants at each of the performance continuum: a golfer that "choked" under pressure (Figure 2.2A, Participant 3) and a golfer that was "clutch" under pressure (Figure 2.2B, Participant 6).

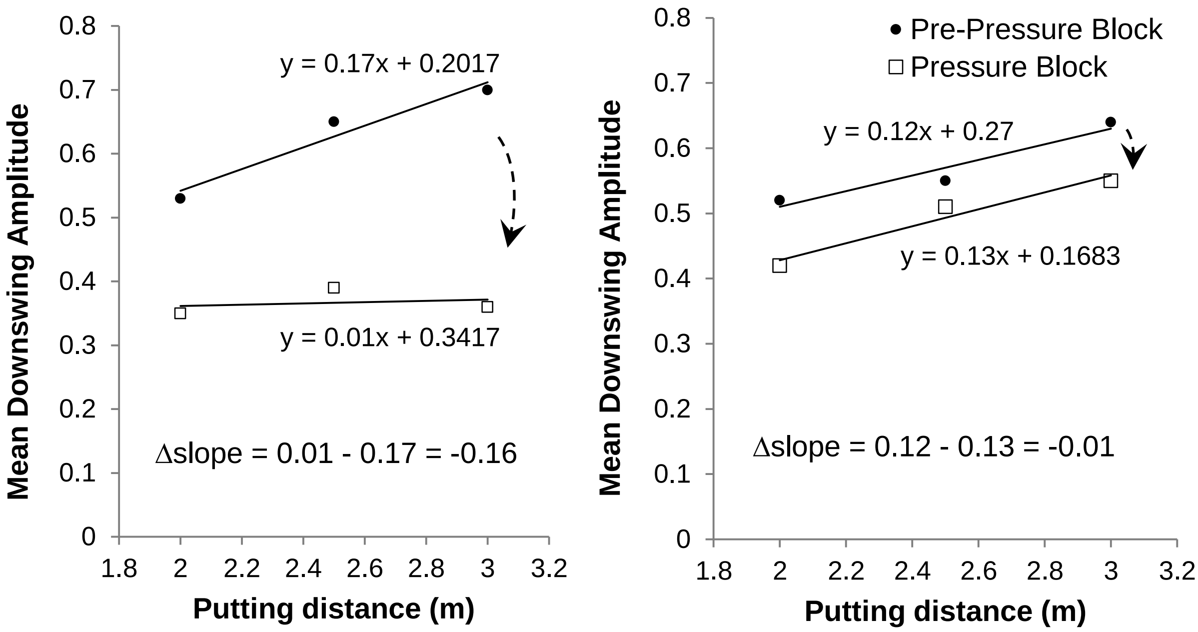

Figure 2.2. Calculation of change in downswing amplitude x distance slopes. Left Panel: DA x distance functions for a participant that "choked" under pressure (participant 3). Right Panel: DA x distance functions for a participant that was "clutch" under pressure (participant 6).

Finally, we calculated the change in slope from the pre-pressure to pressure block for each participant (see Figure 2.2 for example calculations). Figure 2.3A plots the change in DA x Distance Slope as a function of change in putting error. Note that a negative change indicates a decrease in the DA/distance slope. Note that a steep DA/distance slope is typically seen for expert golfers whereas a shallow slope is typical of novice golfers (Beilock & Gray, 2012; Delay et al., 1997), therefore a decrease in the DA/distance slope can be seen as a regression towards novice performance. There was a significant negative correlation between these variables: $r = -0.58$, $t(11) = -2.36$, $p < 0.05$. There was also a significant relationship between the change in DA/distance slope and the number of putts that ended inside the ring as shown in Figure 2.3B, $r = 0.69$, $t(11) = 3.1$, $p < 0.01$.

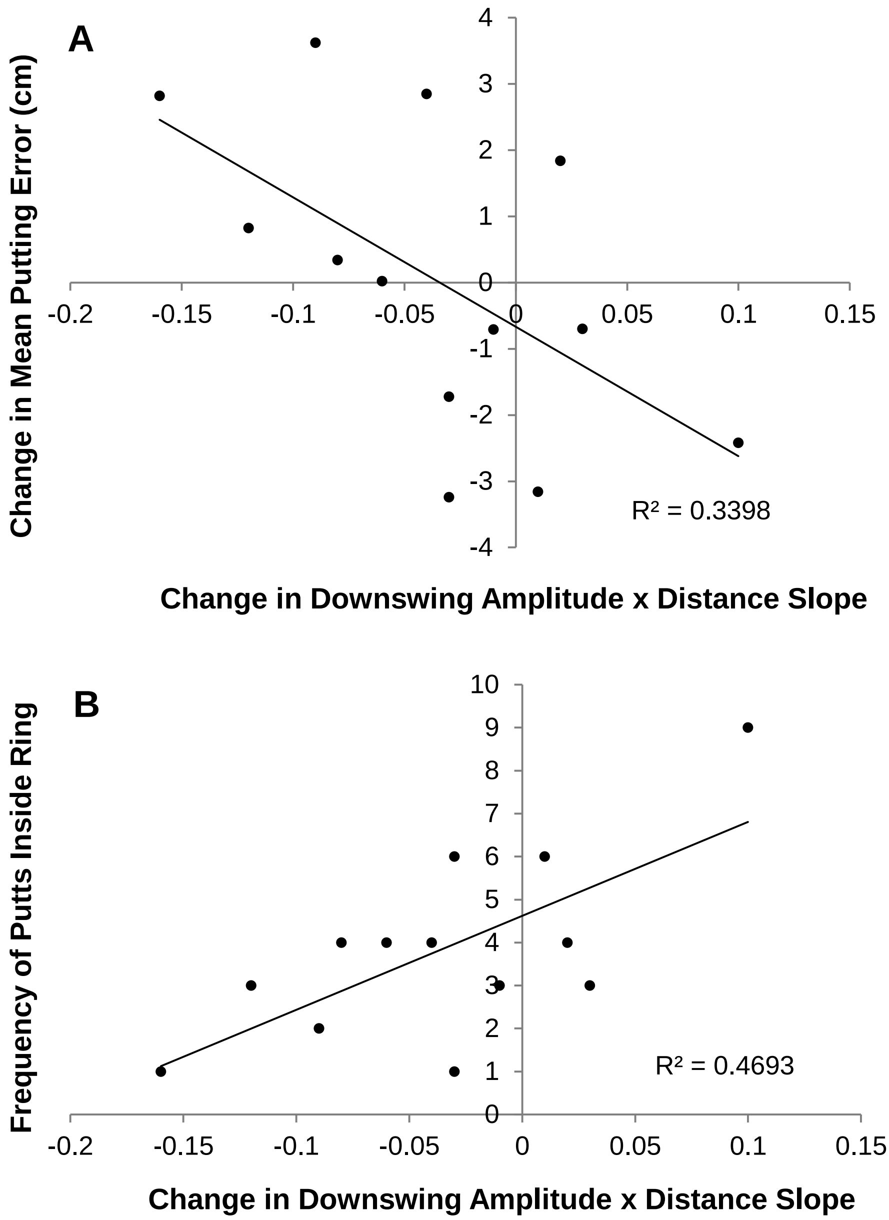

Figure 2.3. Relationship between change in downswing amplitude x distance slope and putting performance. (A) Change in slope vs. mean change in putting error. (B) Change in slope vs. total number of putts for which the ball stopped inside the ring in the pressure condition.

We also found significant relationships between putting performance under pressure and two other kinematics variables. Figure 2.4A shows the change in the backswing movement time (BSMT) from the pre-pressure block to the pressure block, as a function of the mean change in putting error. There was a significant negative correlation between BSMT vs. putting error, $r = -0.60$, $t(11) = -2.5$, $p < 0.05$. The correlation between change in BSMT and number of putts in the ring was marginally significant: $r = 0.50$, $t(11) = -1.9$, $p = 0.07$. Figure 2.4B shows the change in the club-head velocity at impact (VI) from pre-pressure to pressure block as a function of the mean change in putting error. There was a significant positive correlation between change in VI and change in putting error: $r = 0.74$, $t(11) = 3.6$, $p < 0.01$. Note that novice golfers typically exhibit higher VI values than experts because they contact the ball at the point of maximum velocity in the putting stroke whereas the club head is still accelerating at the point of contact for expert golfers (Delay et al., 1997). Therefore, an increase in VI under pressure can be thought of as a regression to novice performance levels. The relationship between change in VI and the number of putts in the ring was not significant: $r = -0.49$, $t(11) = -1.8$, $p = 0.09$. Figure 2.4C shows the change in the time to peak speed (TTPS) from the pre-pressure block to the pressure block, as a function of the mean change in putting error. There was a significant negative correlation between change in TTPS and change in mean putting error, $r = -0.57$, $t(11) = -2.3$, $p < 0.05$, and a significant negative correlation between change in TTPS and change in number of putts in the ring $r = 0.64$, $t(11) = -2.8$, $p < 0.01$. There were no significant correlations between the change in DSV and putting performance under pressure (p both > 0.2).

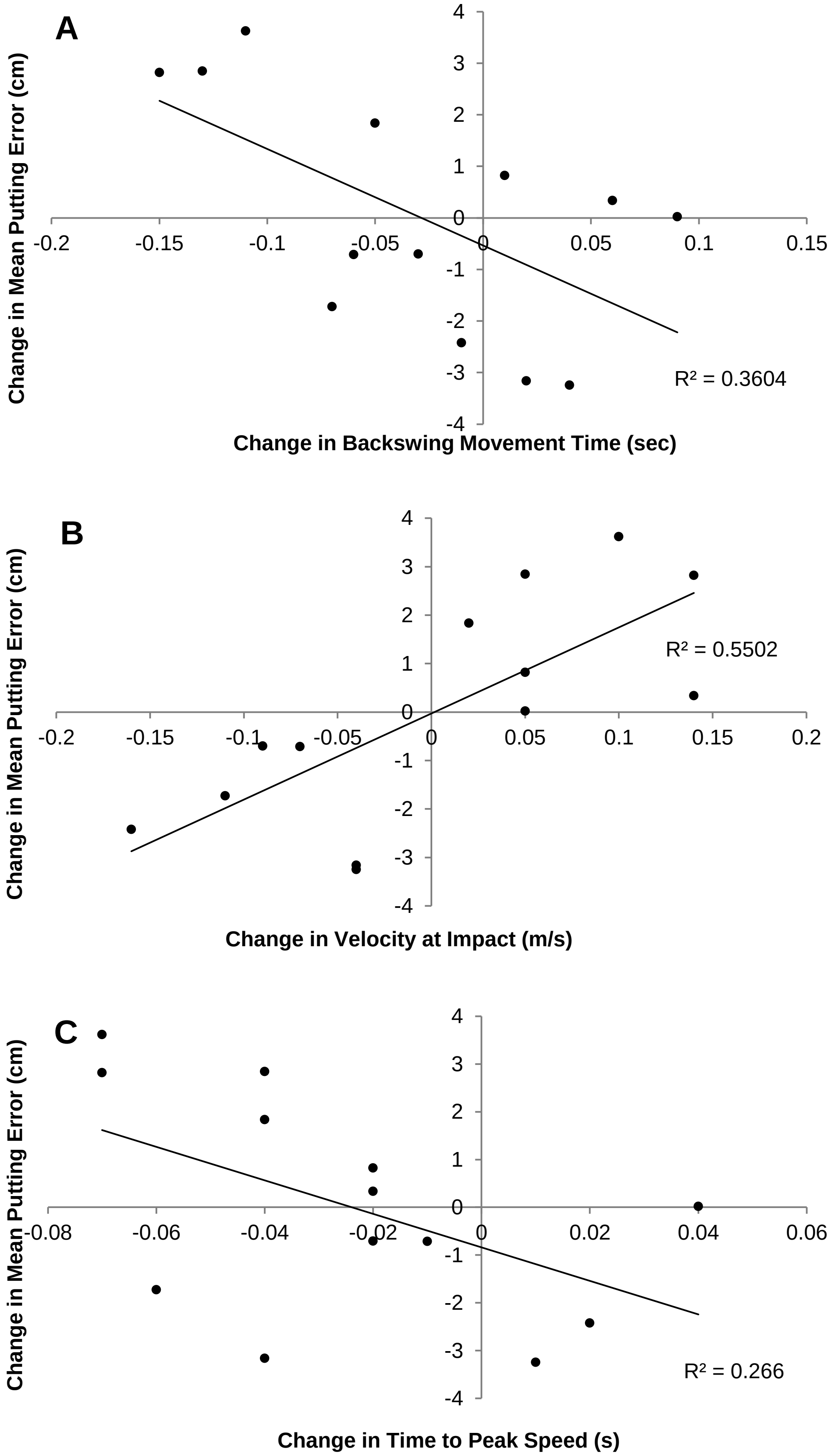

Figure 2.4. (A) Relationships between change in BSMT vs. mean change in putting error. (B) Change in VI vs. mean change in putting error. (C) TTPS vs. mean change in putting error

Discussion

An understanding of the specific mechanisms through which attention influences skilled motor performance is needed to better inform individuals how to perform optimally and to protect against performance breakdowns under pressure (i.e., choking). The goal of the present research was to examine how pressure changes putting kinematics (i.e., the motion of the club during the putting stroke) and how these changes are related to the performance under pressure of individual golfers. To extend previous research on this topic we investigated how pressure changes the manner in which golfers regulate their putting stroke for different hole distances.

As predicted, the addition of pressure resulted in a significant decrease in the strength of the relationship between DS amplitude and putting distance overall. In other words, under pressure golfers in the present study used a smaller range of stroke amplitudes to putt over the same range of distances – an effect identical to the difference between highly-skilled and less skilled golfers described in the quotation by golf coach Dave Pelz presented above (see also Delay et al., 1997). This effect of pressure is highly similar to the effect of directing attention to skill execution (via the addition of a skill-focused secondary task) on the DS amplitude/distance relationship (Beilock & Gray, 2012). Taken together these findings provide further support for explicit monitoring (and related) theories of choking under pressure in which it is proposed that attention serves to cause inward shift in attention towards skill execution resulting a perceptual-motor control strategy typical of an earlier stage of skill acquisition.

It should be noted that evidence in support of the explicit monitoring theory can be weaker when skills are studied outside of the laboratory in more ecological contexts. For example, in a study involving a questionnaire given to athletes in a variety of sports Oudejans, Kuijpers, Kooijman and Bakker (2011) found that the frequency of skill-focus thoughts is actually quite low. Therefore, it will be important for future studies to examine pressure-induced changes in putting kinematics in more naturalistic settings, possibly using portable motion tracking technology.

Unlike the majority of pressure-related kinematic changes reported in previous research on golf putting (e.g., Tanaka & Sekiya, 2010; 2011), in the present study we found significant relationships between the changes in the strength of the DS amplitude/distance relationship and putting performance. Overall, golfers that had a greater decrease in this relationship under pressure had significantly larger putting errors and had significantly fewer putts that stopped in the target ring as compared to golfers who had a lesser decrease in this relationship. This is evidenced by significant correlations between these performance variables and the DS amplitude/distance slopes (see Figure 2). Furthermore, the three players in our study that were ‘clutch’, actually showed increases in the DS amplitude/distance slope under pressure. Conversely, the three golfers that showed a significantly “choking” effect had decreased slopes. Taken together these findings suggest that performance failures under pressure in golf putting are mediated by changes in the way in which golfers control the force of their stroke by programming DS amplitude (Delay et al., 1997).

If golfers are not using swing amplitude to vary stroke force, which motor control strategy are they using? Consistent with some previous research findings (Mullen & Hardy, 2000; Tanaka & Sekiya, 2011) the results of the present study suggest that this is achieved by varying backswing movement times and by using a more symmetrical putting stroke in which the peak speed occurs earlier in the stroke (see Figure 3). Why might golfers revert to a more “novice” control strategy for regulating putting force under pressure? Unlike typical “reinvestment” type effects (Masters, 1992) it is not the case that the behavior observed under pressure (i.e., the symmetrical putting stroke with variable movement times) is taught at early stage of learning to putt (Pelz, 2000). One possibility is that it could be an attempt by the golfer to avoid leaving putts short of the hole. Anecdotal evidence suggests that this is a common concern in pressure situations. For example, under the extreme pressure of having a 10 foot putt to record the first score of 59 in the history of the PGA tour, Al Geiberger thoughts were “whatever you do, don’t leave it short” (Cohn, 2001, p. 51). As described by Pelz, one of the problems associated with learning to use large amplitude putting strokes is that initially it feels to the golfer as if they have no power: “When you first try it, you will probably feel insecure, as if you can’t get the ball to the hole, so you will probably leave every putt short” (Pelz, 2000, pg. 118). Therefore, perhaps the observed changes in movement kinematics are an attempt to prevent an ironic error under pressure. An ironic error in this instance would be telling oneself to not leave the putt short, but then proceeding to leave the putt short (Wegner, Ansfield & Pilloff, 1998). Participants may therefore be overcompensating (see Binsch, Oudejans, Bakker & Savelsbergh, 2009; De La Pena, Murray & Janelle, 2008), by changing their putting technique, in order to avoid these ironic effects.

Increased muscular tension may offer an alternative explanation for the observed kinematic changes. Increases in electromyographic (EMG) activity have previously been reported when performing motor tasks under pressure (e.g., Cooke et al., 2010; Weinberg & Hunt, 1976; Yoshi, Kudo, Murakoshi & Ohtsuki, 2009). For example, Cooke et al. (2010) showed that novice golfers exhibit elevated extensor carpi radialis activity when performing a similar golf putting task under pressure, with this change partially mediating a deterioration in performance. In a separate but related body of literature, changes to a performer’s focus of attention have also been shown to influence EMG activity, with an internal focus of attention being associated with higher levels of muscle activity in comparison to an external focus (e.g., Lohse, Shewrood & Healy, 2010; Vance, Wulf, Töllner, McNevin & Mercer, 2004; Zachry, Wulf, Mercer & Bezodis, 2005).

It has been suggested that the decreased EMG activity associated with an external focus of attention may be related to greater movement amplitudes (Zachry et al., 2005). Therefore using a similar line of reasoning, an internal focus of attention may be associated with increased muscle activity and reduced movement amplitudes. This suggestion dovetails well with the observed decrease in downswing amplitudes found as a result of both attentional focus manipulations (Beilock & Gray, 2012) and the current pressure manipulation. While we did not measure EMG activity, tentative support for this suggestion lies within the IAMS somatic anxiety subscale in which "tense muscles" is a component of its definition provided to participants. The increase in somatic anxiety scores may therefore partially reflect increased EMG activity in muscles associated with the stroke. An obvious direction for future research would be to explicitly examine whether the changes in downswing amplitude found in the current study are a result of a direct effect of pressure on muscle activity, or an indirect effect of pressure mediated by an inward focus of attention (as suggested by explicit monitoring theories).

Two alternative explanations for decreased movement amplitudes centre around changes in strategy in order to maximise certain inherent features of perceptual-motor control. Firstly, in agreement with suggestions made by Tanaka et al. (2010) it is possible that participants may seek to reduce movement amplitudes in order to reduce movement variability in accordance with Schmidt and colleagues' impulse variability model (Schmidt, Zelaznik, Hawkins & Frank, 1978; Schmidt et al., 1979). Secondly, current theories of motor control in golf putting suggest that the backswing of a golf putt is pre-programmed, whereas the downswing movement is continually adjusted on the basis of visual information during movement execution (Coello, Delay, Nougier & Orliaguet, 2000; Craig et al., 2000). Reflexive online control processes that are responsible for the visual regulation of limb movements have recently been shown to be impaired in anxious conditions, leading to decrements in overall task performance (Lawrence, Khan, & Hardy, 2012). Therefore experts who have a dispositional tendency towards choking under pressure, may pre-program shorter backswing amplitudes under pressure in an attempt to reduce the reliance on online control processes during the downswing movement of the putt.

This study further highlights the importance in considering the level of analysis when examining performance under pressure (see Beilock & Gray, 2007). To illustrate, previous between-subjects analyses of archival final round scores for PGA tour players resulted in a lack of evidence to suggest that choking under pressure actually occurs (Clark, 2002). However, Wells and Skowronski (2012) found clear choking effects when conducting within-subject analyses on similar PGA tour data, by examining individual differences between third and fourth round scores. The strength of the choking effect was related to the position on the leaderboard, that is being closer to the lead was associated with larger choking effect. In the current study, no effects were found when examining performance across all individuals. Analysis at the individual level however clearly showed that this was caused by the occurrence of both clutch and choking performances, thus nullifying each other. Future research may benefit from examining choking in a similar fashion to the current study. Alternatively, techniques that allow the concurrent examination of different levels of analysis may be employed, such as hierarchical linear modelling (e.g., Beattie, Lief, Adamoulas & Oliver, 2011). Regardless of the method employed, by continuing to investigate performance under pressure at a group level, researchers may be missing the factors that separate 'chokers' and 'clutch' individuals.

There are some important limitations of the present study. First, in employing the IAMS as a manipulation check we only used single items to assess cognitive and somatic anxiety. It will be important for future research to provide a more complete assessment of the effects of pressure in our conditions using a multiple-item assessment of state anxiety such as the Competitive State Anxiety Inventory-2 (CSAI-2; Martens et al., 1990). Second, the present study involved a relatively small and highly homogeneous (in terms of age, gender, and playing experience) group of participants. It will be important for future studies to investigate whether similar effects occur for golfers with a wider range of demographics.

Third, it is possible that the utilised repeated measures experimental design may have led to the masking of pressure induced performance effects as a result of learning. In other words, practice effects may have counteracted the negative effects of pressure on performance, thus leading to a null effect. Whilst this possibility cannot be ruled out, it is suggested that learning effects should have been relatively low for the homogenous group of expert participants used in the current experiment. However, it is acknowledged that either a counterbalanced repeated-measures design, or a between-subjects design would allow a stronger rebuttal of this potential limitation in future studies. Finally, the putting tasks used in the present study (putting to a small target or ring on the green) have some distinct differences from normal putting. Therefore, it will be important for future research to determine whether similar effects are observed when putting into a hole.

In conclusion, the present study extended previous work that has explored the effects of performance pressure on putting kinematics by examining the kinematic changes that occur across different putting distances. We have shown that the relationship between downswing amplitude and putting distance was weaker for golfers who experienced "choking" when compared to clutch performances. While the specific mechanisms are yet to be explored, the changes to movement kinematics suggest a regression to earlier levels of skill. By relating the current findings to evidence suggesting that similar effects occur as a result of directing attention to skill execution with a secondary task, we suggest that the results are consistent with the explicit monitoring theory of choking under pressure.

The findings from the current experimental chapter suggest that pressure influences the relationship between putt distance and downswing amplitude. Visual information has previously been shown to be a crucial factor in the regulation of the downswing portion of the putting stroke (Refs). Interestingly, the visual, 'online', regulation of limb movements has recently been shown to be negatively affected by pressure (Lawrence, Khan & Hardy, 2012). It is possible that changes in the ability to utilise visual information may have led to the changes in putting performance and downswing amplitude observed in the present study. The proceeding experimental chapter therefore aims to examine if changes to indices of visual attention may be related to putting performance under pressure.

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CHAPTER THREE

Effects of Performance Pressure on the Useful Field of View: Attentional Narrowing and Putting Performance

Performance pressure can negatively influence the execution of visual-motor skills. The current study examined changes to the useful field of view as a potential underlying mechanism behind performance changes under pressure. Twenty four participants performed a golf-putting task in neutral conditions, with interleaved pauses in order to undertake a computer-based useful field of view (UFOV) tests. Half the participants then performed the putting task in conditions designed to induce performance pressure, while the other half continued in neutral conditions. Results indicated that the size of the UFOV significantly reduced when under pressure. Furthermore, changes in UFOV were significantly correlated with changes in putting performance. These results extend previous research by suggesting that pressure may have a general effect on the ability to use peripheral stimuli.

Introduction

The ability to perform visual-motor skills in high pressure situations is critical for success in many different domains, ranging from sport to aviation. In competitive sport, performing below one's level of expertise in such situations is obviously an unwanted outcome that is commonly termed 'choking under pressure'. "Choking" has defined as suboptimal performance, despite strong performance-contingent incentives that are of personal importance (Baumeister, 1984; Beilock and Gray, 2007). Several theories of the underlying causes of have been proposed including; explicit monitoring theory (Beilock & Carr, 2001), reinvestment theory (Masters, 1992) or attentional control theory (Eysenck, Derakshan, Santos & Calvo, 2007). While these particular theories have been applied to sport in several recent studies (reviewed in Beilock & Gray, 2007 and Nieuwenhuys & Oudejans, 2012), the concept of attentional narrowing (Easterbrook, 1959) has received surprisingly little research attention in sport (Janelle, Singer & Williams, 1999).

Attentional narrowing effects were first compiled in a seminal review article by Easterbrook (1959). Easterbrook proposed that arousal or stress causes a reduction in the breadth of cues that can be utilised. Specifically, as the level of stress increases, the ability to use peripheral cues decreases, due to "a shrinkage of the perceptive field" (Easterbrook, 1959, p. 189). Errors are therefore likely to occur when tasks require a wide range of cues to be utilized. This effect can however allow the performance of central tasks to be improved or maintained, until the level of stress reaches a certain threshold. In other words, performance may actually benefit from attentional narrowing effects when tasks do not necessarily require the use of peripheral stimuli (Mendl, 1999). One line of evidence that provided initial support for these propositions came from continuous tracking experiments (e.g., Bahrick, Fitts and Rankin, 1952; Bursill, 1958). Bahrick et al. (1952) for example, asked participants to follow a moving target using a stylus, while attempting to correctly identify when randomly presented peripheral stimuli were activated (i.e., illumination of lights, or movement of an instrument needle). Monetary bonuses were offered at certain points throughout the experiment. Overall, results showed that monetary incentives decreased the detection of peripheral stimuli, which was seen as evidence for a stress-induced attentional narrowing effect. More recently, a small number of studies have investigated pressure-induced attentional narrowing effects in more complex sensorimotor tasks.

Janelle et al. (1999) investigated attentional narrowing in a simulated indy-car racing task. Coloured LEDs served as peripheral stimuli, and were first positioned around the edge of the simulator screen at locations customised for each individual. Their positions were set by determining the maximum visual angle at which five accurate colour discriminations could occur consecutively. Overall performance was based on both the average driving speed around a circuit, and the speed and accuracy of responses to randomly presented peripheral stimuli. Following acclimatisation sessions, pressure was induced via monetary incentives. Results were generally supportive of attentional narrowing effects, with pressure causing a reduction in the ability to accurately respond to the peripheral stimuli. Furthermore, an increase in the number of saccades to these stimuli was observed, as peripheral vision alone no longer allowed accurate discriminations (for similar results see Murray & Janelle, 2003).

One limitation of the aforementioned studies is that they involved presentation of infrequent and less salient stimuli to peripheral vision, while a continuous, cognitively demanding and more salient task is performed in central vision (Eysenck et al., 2007). Eysenck et al. (2007) have argued that this salience difference can explain the previous results which appeared to support attentional narrowing effects. Specifically, the authors suggest that anxiety causes participants to direct attention to the continuous, salient task (in central vision) at the expense of the less-salient task (in peripheral vision). Whether attentional narrowing effects would occur in situations in which the processing of central and peripheral stimuli is of similar importance cannot be addressed from this previous research. However, a separate but related research area has examined the predictors and correlates of the ‘functional’ or ‘useful field of view’, and may offer an alternative methodology to assess attentional narrowing while resolving this limitation.

The useful field of view (UFOV) is defined as the total visual field area in which information can be obtained in a single glance without eye or head movements (Ball, Beard, Roenker, Miller and Griggs, 1988; Sanders, 1970). It is distinct from clinical measures of the visual field which ascertain the *physical capabilities* of the retina to detect stimuli, in terms of luminance sensitivity at maximum visual angles (Ball, Owsley & Beard, 1990; Williams, Davids and Davids, 1999). The UFOV is instead a measure of the ability to accurately detect, identify and localise, rapidly presented suprathreshold targets (Ball et al., 1990). This tests the ability to process and use peripheral visual information, rather than merely detect its presence. Therefore, while the UFOV will be partially based on physical limitations (e.g., Ball & Keeton, 1995), it is also a measure of higher-order visual processing skills (Das, Bennet, & Dutton, 2007). As many activities rely on these processing skills, it is unsurprising that UFOV has been associated with the performance of such visual-motor tasks.

Measures of the UFOV have been consistently linked to both simulated (e.g., Belanger, Gagnon, Yamin, 2010) and real-world driving performance (e.g., Ball, Owsley, Sloane, Roaenker and Bruni, 1993; Ross, Vance, Ball, Cak, Ackerman, Benz & Ball, 2011; Wood, Chaparro, Lacherez, Hickson, 2011). A recent meta-analysis investigated the cumulative relationship between UFOV and various driving performance outcomes, such as at-fault crashes and instructor ratings (see Clay, Wadley, Edwards, Roth, Roenker & Ball, 2005). A large combined effect size was found (Cohen's d = 0.945), with poorer driving outcomes being consistently linked to poorer UFOV scores across different laboratories. Poorer UFOV scores have also been linked to increases in bumps while walking, even after adjusting for tests of visual acuity, standard visual field tests and other attention tests (Broman, Westm Munoz, Bandeen-Roche, Rubin and Turano, 2004).

Despite its potential applicability, UFOV has been left relatively unexplored in sport (see Alves, Voss, Root, Deslandes, Cossich, Salles & Kramer, 2013). To our knowledge, there have been only two studies that have investigated the UFOV in sporting contexts. Appelbaum, Schroeder, Cain, and Mitroff (2011) recently demonstrated that sport-specific visual training (using stroboscopic eyewear) resulted in a significant improvement in the divided attention component of the UFOV test. Gray, Cumming, Quinton and Wilkins (submitted) examined the relationship between the UFOV and sports performance (soccer and basketball) in young athletes. It was found that, the divided attention and processing speed components of a novel sport UFOV test explained a significant amount of variance in the performance of soccer dribbling/passing tests, while the selective attention and processing speed components were significantly related to basketball dribbling performance.

The preceding discussion highlights the link between UFOV and the performance of both complex (i.e., driving and sport) and less complex (i.e., walking) visual-motor skills. Of central interest to the current study however, Mackworth (1965) proposed that the area of the UFOV can change based on a number of factors, which is a suggestion closely aligned with attentional narrowing. The size of the UFOV has been shown to be influenced by a number of acute factors, including, the cognitive or visual complexity of tasks presented to central vision (e.g., Ikeda & Takeuchi, 1975; Murata, 2004; Salvemini, Stewart & Purcell, 1996; Reynolds, 1993; Williams, 1988, 1995) and sleep deprivation (e.g., Ho & Wang, 2010). For example, Murata (2004) presented numerical calculations of varying complexity levels to participants' foveal vision. At the same time, a stimulus was presented for two seconds to a random location in peripheral vision. Results showed that increasing calculation complexity led to decreases in peripheral detection. The specific methodology used to assess the UFOV has however differed between studies, with a wide variance in the central and peripheral stimuli employed (Williams, 1988). Recently, standardised UFOV tests are available for use on personal computers (Edwards, Vance, Wadley, Cissel, Roenker & Ball, 2005), and involve the simultaneous presentation of *equally salient* stimuli, to both foveal and peripheral vision. Foveal stimuli are presented in all subsets of these tests, however different subsets also present one peripheral stimulus alone (divided attention subset), or embed a stimulus within distracters (selective attention subset). The task is performed using binocular vision, with peripheral targets being presented at various azimuth and elevations from the central target. The characteristics of these tests therefore seem to be a promising, alternate and unexplored method in which to detect attentional narrowing effects under pressure.

The present study investigated the effects of pressure on UFOV in a sporting context, using a golf-putting task to create competitive pressure. In accordance with Easterbrook's (1965) attentional narrowing hypothesis, we predicted that competitive pressure would decrease the UFOV.

Method

Participants

Twenty four (17 male, 7 female) self-reported right-handed adults (mean age 23.3, *SD* = 2.78) completed the study. All participants were considered novice golfers as they did not have an official golf handicap or any history of formal putting experience (Cooke, Kavussanu, McIntyre & Ring, 2010). Written informed consent was gained from all.

Apparatus

Putting Task

A McGregor M220™ 35 inch (88.9 cm) right handed putter and Wilson Ultra™ golf balls (diameter 4.27 cm) were used. The artificial putting mat had a width of 1.4 m and a length of 4.6 m. The putting task required participants to putt a golf ball as accurately as possible to a red square-shaped target (10.5 cm^2) marked on the surface of the green, on which the ball was supposed to stop. A target on the green surface, rather than a standard hole, was used in order to gain a continuous measure of putting error rather than a dichotomous "hit/miss" score. Previous research has demonstrated similar performance outcomes using either a target or a hole (Beilock & Carr, 2001). Putts were made from distances of 2.0, 2.5, 3.0, 3.0 m to a target 1.03 m from the end of the putting surface. Absolute radial error from the position the ball stopped after each putt to the centre of the target square served as a measure of putting performance.

Sport-specific UFOV Task

The UFOV test used custom-designed software and was displayed on a 28-inch (71cm) TFT monitor from a viewing distance of 57 cm. It was a modified version of the sport-specific UFOV test developed by Gray et al. (Submitted). The test was comprised of two separate subtests corresponding to the divided and selective attention components of the commercially available UFOV test (Edwards et al., 2005). Both subtests began with the presentation of a fixation cross for 1.5 sec. After a 200ms delay an image of a golf hole including a small portion of the green and the flag (size 3.6 x 2.7 degrees) was displayed in the centre of the screen (central task). The image had two possible alternatives (a green sloped to the left as shown in Figure 3.1A or to the right as shown in Figure 3.1B), chosen randomly on each trial. The display time for the central target was determined using a staircase procedure described below. Participants were required to make a forced choice judgment about the green slope direction by pressing one of two keys on the keyboard. The two subtests of the test were as follows:

Divided attention subtest. In this subtest, a black flag was presented on the screen at the same time (and for the same duration) as the central target. The flag could appear at one of 24 different locations on the screen representing all possible combinations of 3 eccentricities (10, 15 or 20 degrees measured from the centre of the display) and 8 directions (N, NE, E, SE, S, SW, W, and NW). As shown in Figure 3.1A, peripheral flags were presented in small black squares that were located on radial arms extending from the centre of the display

Participants were asked to make two judgments on every trial: a 2AFC judgment about the slope direction of the central target using the keyboard and to use the computer mouse to click on the location of the peripheral flag. There were informed that they should make always make the judgment about the central target first followed by peripheral judgment. The presentation duration was varied according to the staircase procedure used in the UFOV test developed by Ball et al. (1993). Namely, after two correct responses, stimulus presentation time for the next trial was shortened, whereas stimulus presentation time for the next trial was lengthened if the response was incorrect. This was continued until six reversals occurred. The threshold presentation time (equivalent to 75% correct) was calculated by taking the mean of the final four reversals. Correct responses for both the central and peripheral tasks were required before the duration was shortened. Three separate staircases (corresponding to the 3 peripheral target eccentricities were randomly interleaved). Peripheral target direction was chosen randomly on each trial. The test was completed once a minimum of six reversals occurred for each of the three staircases. The initial presentation duration for each staircase was 150 ms. The initial step size was 10ms and was halved after the first two reversals.

Selective attention subtests. The second subtest was exactly the same as the first except that, as illustrated in Figure 3.1B, two distracters (white flags) were added to the display. The eccentricity and direction of the distracters was varied randomly from trial to trial. The initial presentation duration for each staircase was 200 ms.

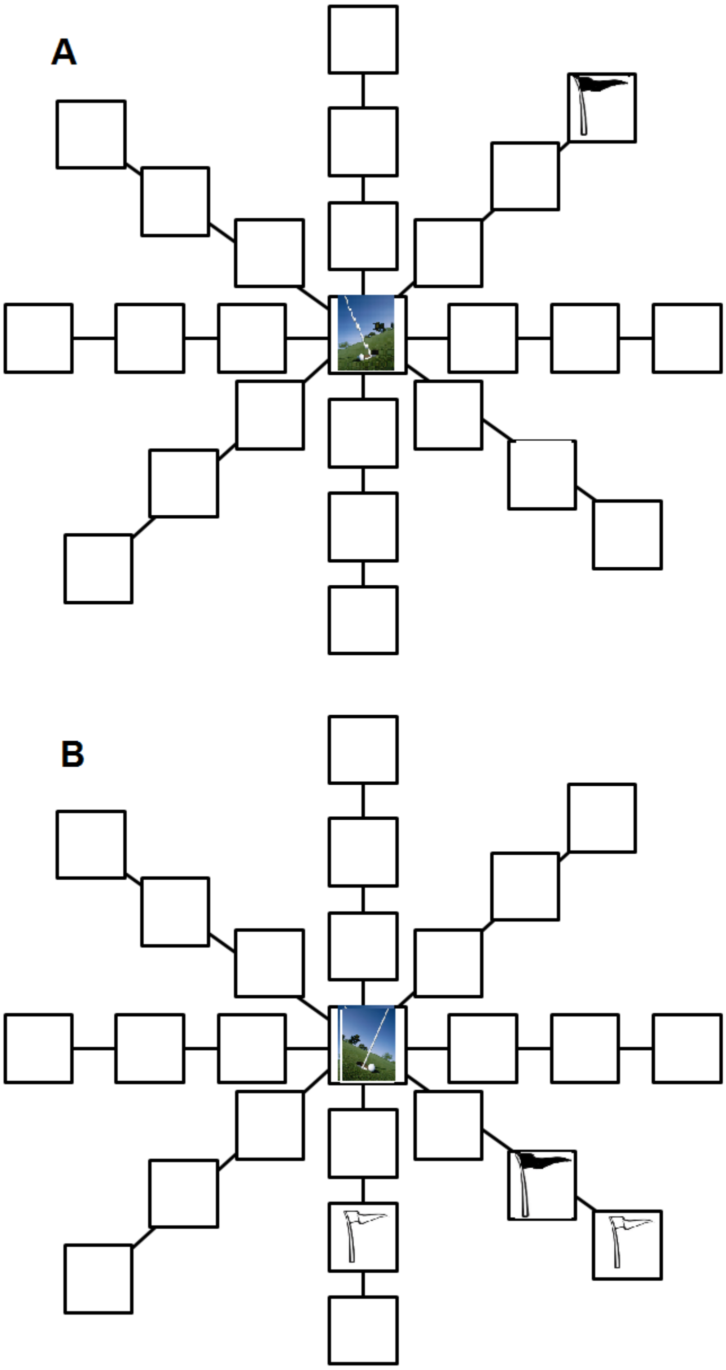

Figure 3.1. UFOV subtests. (A) Divided attention. (B) Selective attention.

Immediate Anxiety Measures Scale (IAMS)

Cognitive and somatic state anxiety was measured using the Immediate Anxiety Measures Scale (IAMS; Thomas, Hanton & Jones, 2002). The scale assesses both the intensity and directional interpretation of each anxiety construct. A definition of cognitive and somatic anxiety is provided. Participants then rate the intensity of their anxiety symptoms on a 7 point likert scale anchored at the extremes by 1(*Not at all*) and 7(*Extremely*). They subsequently indicate whether they regard their level of anxiety to be debilitative or facilitative to performance on a 7 point likert scale ranging from -3(*Very debilitative*) to +3(*Very facilitative*). The IAMS has been used previously in similar research (e.g., Moore, Vine, Wilson & Freeeman, 2012), with Thomas and colleagues (2002) providing initial validation of the scale as an expedient tool for assessing anxiety before and during competition.

Procedure

The experiment was divided into three phases: practice, pre-pressure and pressure. In all phases, participants were asked to putt to the target square from three different distances in the following recurring order: 2.0, 2.5, 3.0, 3.0, 2.5, 2.0 m. In the practice phase, participants completed two blocks of 18 practice putts. After the twelfth putt in each block, the UFOV tests were performed. The data collection procedure was identical for both the pre-pressure and pressure phase. 18 putts were performed, with participants completing the IAMS and both subsets of the UFOV after 6 and 12 putts. These data collection points are entitled pre-pressure one, pre-pressure two, pressure one and pressure two.

To ensure that any changes to UFOV were the result of pressure rather than repetitive testing, participants were randomised into an experimental group or a control group upon entering the lab. In the pressure phase, the control group continued to putt as normal. For the experimental group, the pressure phase began with the experimenter reading the following script:

> We're now moving into a competition phase. Your objective in the competition is still to putt the ball as close to the marker as possible. However,

> throughout the experiment you have so far accumulated 180 points. A small ring will be placed around the marker on the green. For every putt that finishes outside the ring, you will lose 10 points. Your point total (and that of the top participants in the study) will be displayed on a leader board that will be updated after each putt. Prize money of £50, £25 and £10 is up for grabs, for 1st, 2nd and 3rd Place. How many points you manage to hold on to determines your position on the leader board. All the results will be e-mailed out to everyone who takes part in the study, and will be displayed on the notice board in the school atrium. So everyone will know how everyone else performs. No pressure then (said sarcastically)..........good luck!

A 16.5 cm diameter ring was placed around the target. An interactive leader board was presented on a 61cm computer monitor, which was positioned conspicuously next to the putting mat. Four fictitious players were displayed on the leader board, whose scores were: 150, 130, 90 and 50 points. The participant's last name was displayed at the top of the leaderboard with next to a point total of 180. As indicated in the script above, 10 points were lost for every putt that landed outside the ring. Their name fell down the leader board when based on their new point total. Note that we previously used an identical manipulation in a study investigating the effect of pressure on putting kinematics (Gray, Allsop & Williams, 2013).

Data Analysis

In order to examine the effectiveness of the pressure manipulation, both the intensity and directional components of the cognitive and somatic anxiety data were submitted to separate 2 group (Experimental and Control) x 4 phase (Pre-test one, Pre-test two, Pressure one and Pressure two) ANOVAs with repeated measures on the second factor. To examine the effects of performance pressure on UFOV performance, mean stimulus presentation data from both the divided and selective attention subsets were submitted to separate 2 group (Experimental and Control) x 4 phase (Pre-test one, Pre-test two, Pressure one and Pressure two) x 3 Peripheral target eccentricity (10, 15, 20 degrees) ANOVAs with repeated measures on the final two factors. Putting performance data was analysed using a 2 Group (Experimental, Control) x 2 Phase (Pre-test and Pressure) repeated measures ANOVA with repeated measures on the second factor.

Results

Manipulation Check

Cognitive anxiety

The ANOVA conducted on the cognitive anxiety intensity data revealed a significant main effect for phase, $F(3,66) = 19.7$, $p < .001$, $\eta_p^2 = .47$, and group, $F(1,22) = 12.0$, $p = .002$, $\eta_p^2 = .35$, however these effects were superseded by a significant Phase x Group interaction $F(3,66) = 20.4$, $p < .001$, $\eta_p^2 = .47$. Tukey's HSD tests showed that the intensity of cognitive anxiety symptoms increased for the experimental group between the pre-test phase and the pressure phase, whereas no change was found for the control group (See figure 3.2). No significant effects (all *p*'s > .16) were found for the direction component (Experimental group – Pre-test phase 1: 0.75, *SD* = 1.21; Pre-test phase 2: 0.67, *SD* = .89; Pressure phase 1: -0.83, *SD* = 2.02; Pressure phase 2: 0.1, *SD* = 2.04. Control group – Pre-test phase 1: 0.83, *SD* = 1.34; Pre-test phase 2: 1.0, *SD* = 1.12; Pressure phase 1: 0.82, *SD* = 1.19; Pressure phase 2: 1.08, *SD* = 1.08).

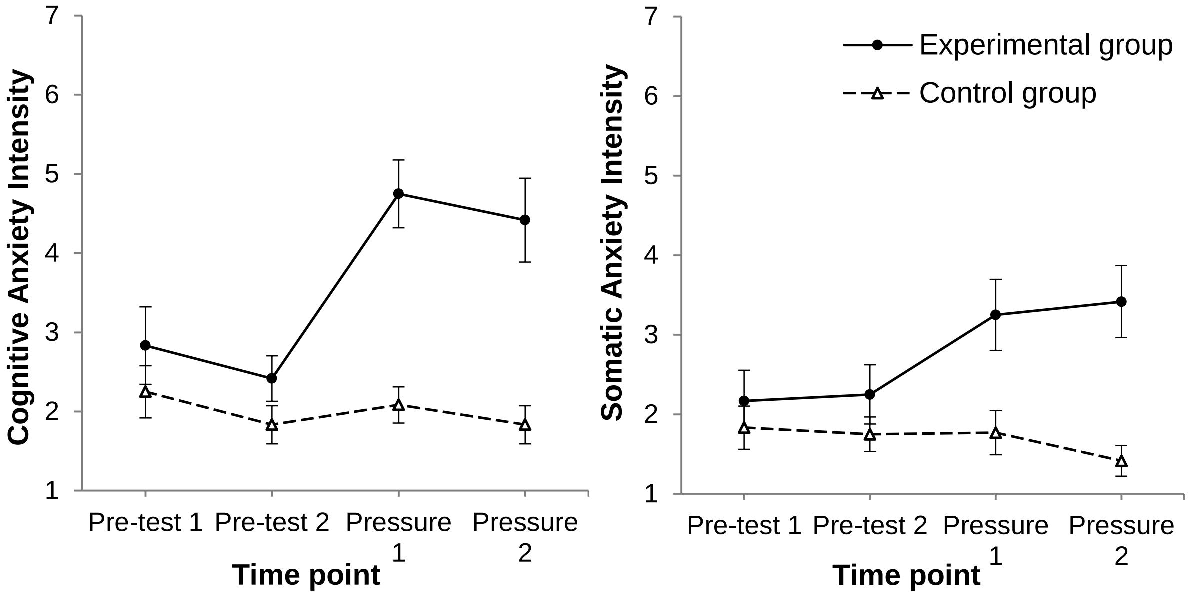

Figure 3.2. Cognitive (left panel) and somatic (right panel) anxiety intensity ratings across time points for the experimental (solid line) and control (dashed line) groups. Error bars represent standard errors of the mean.

Somatic anxiety

The ANOVA conducted on the somatic anxiety intensity data revealed significant main effects for phase $F(3,66) = 3.43$, $p = .022$, $\eta_p^2 = .14$, group, $F(1,22) = 6.94$, $p = .015$, $\eta_p^2 = .24$, and a Phase x Group interaction, $F(3,66) = 7.70$, $p < .001$, $\eta_p^2 = .26$. Breakdown of this interaction revealed that somatic anxiety increased for the experimental group from the pre-test to the pressure phase, whereas somatic anxiety intensity remained the same for the control group (See figure 3.2). The ANOVA conducted on the somatic anxiety direction data revealed non-significant main effects for phase, $F(3,66) = 1.66$, $p = .18$, $\eta_p^2 = .07$, and group, $F(1,22) = 1.60$, $p = .22$, $\eta_p^2 = .07$. There was however an interaction between phase and group, $F(3,66) = 3.04$, $p = .035$, $\eta_p^2 = .12$. Breakdown of this interaction using Tukey's HSD tests showed that the directional interpretation of somatic anxiety symptoms remained stable for the control group. For the experimental group however, a significant difference was found between pre-test phase 2 and pressure phase 2 (Experimental group - Pre-test phase 1: 0.33, *SD* = 1.15; Pre-test phase 2: 0.58, *SD* = 1.24; Pressure phase 1: -0.08, *SD* = 1.83; Pressure phase 2: -.33, *SD* = 1.56. Control group – Pre-test phase 1: .75, *SD* = 1.22; Pre-test phase 2: .67, *SD* = 1.23; Pressure phase 1: .76, *SD* = 1.20; Pressure phase 2: .83, *SD* = 1.15).

Useful Field of View

The ANOVA conducted on the divided attention subset of the UFOV test revealed a significant main effect for group, $F(1,22) = 40.1$, $p < .001$, $\eta_p^2 = .65$, phase, $F(3,66) = 5.89$, $p = .001$, $\eta_p^2 = .21$, and eccentricity, $F(2,44) = 80.6$, $p < .001$, $\eta_p^2 = .79$. These main effects were qualified however by significant phase x group $F(3, 66) = 10.6$, $p < 0.001$, $\eta_p^2 = .33$, eccentricity x group $F(2, 44) = 22.0$, $p < 0.001$, $\eta_p^2 = .5$, and the phase x eccentricity x group $F(6, 132) = 2.22$, $p = 0.04$, $\eta_p^2 = .1$ interactions. The phase x eccentricity interaction was marginally significant, $F(6, 132) = 2.1$, $p = 0.05$, $\eta_p^2 = .09$.

To further analyse the significant three-way phase x eccentricity x group interaction, for each eccentricity we performed separate 2x4 mixed ANOVAs with group and phase as factors. For an eccentricity of 20 degrees, there were significant main effects of group, $F(1, 22) = 46.5$, $p < 0.001$, $\eta_p^2 = .68$, and phase $F(3, 66) = 4.9$, p = 0.04, $\eta_p^2 = .18$, and a significant group x phase $F(3, 66) = 9.0$, $p < 0.001$, $\eta_p^2 = .29$ interaction. As can be seen in Figure 3.3, this significant interaction occurred because the UFOV time increased from the pre-test phase to the pressure phase for the experimental group, while no similar increases were found for the control group across the same period. For the 10 and 15 degrees eccentricities none of the main effects or interactions were significant (*p*'s all > 0.05).

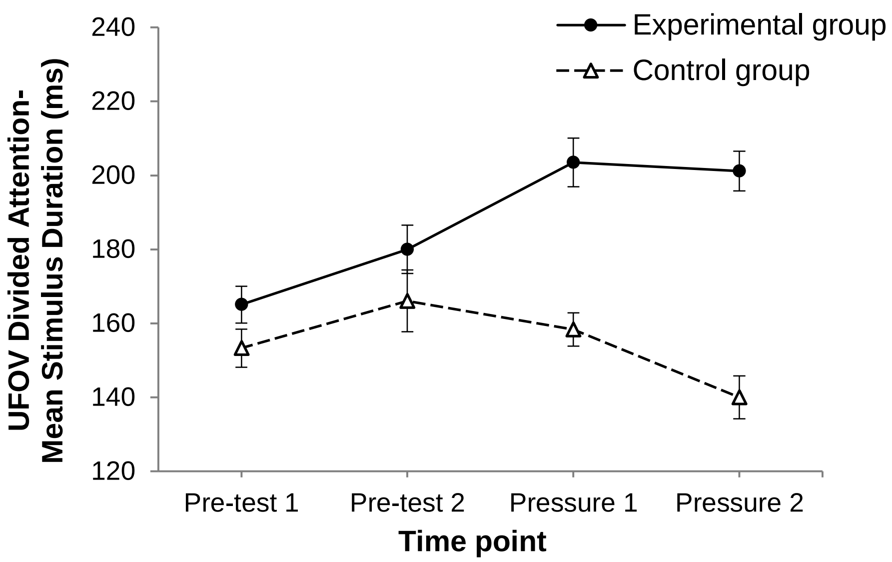

Figure 3.3. Mean stimulus duration (ms) for the divided attention subset of the UFOV test across time points for the experimental (solid line) and control groups (dashed line). Error bars represent standard errors of the mean.

Similar results were obtained for the selective attention UFOV subtest. The ANOVA conducted on these data revealed a significant main effect for group, $F(1,22) = 53.8$, $p < .001$, $\eta_p^2 = .99$, phase, $F(3,66) = 4.44$, $p = .007$, $\eta_p^2 = .17$, and eccentricity, $F(2,44) = 135.6$, $p < .001$, $\eta_p^2 = .86$. These main effects were qualified however by significant phase x group, $F(3, 66) = 8.1$, $p < 0.001$, $\eta_p^2 = .27$, eccentricity x group $F(2, 44) = 34.9$, $p < 0.001$, $\eta_p^2 = .61$, and the phase x eccentricity x group $F(6, 132) = 2.46$, $p = 0.02$, $\eta_p^2 = .1$ interactions. The phase x eccentricity interaction was not significant, $p = 0.33$.

To further analyse the significant three-way phase x eccentricity x group interaction, for each eccentricity we performed separate 2x4 mixed ANOVAs with group and phase as factors. For an eccentricity of 20 degrees, there were significant main effects of group $F(1, 22) = 112.2$, $p < 0.001$, $\eta_p^2 = .9$, and phase, $F(3, 66) = 10.3$, p = 0.04, $\eta_p^2 = .32$, and a significant group x phase interaction, $F(3, 66) = 43.3$, $p < 0.001$, $\eta_p^2 = .66$. As can be seen in Figure 3.4, this significant interaction occurred because the UFOV time increased from the pre-test phase to the pressure phase for the anxiety group, while no similar increases were found for the control group across the same period. For the 10 and 15 degrees eccentricities none of the main effects or interactions were significant (*p*'s all > 0.05).

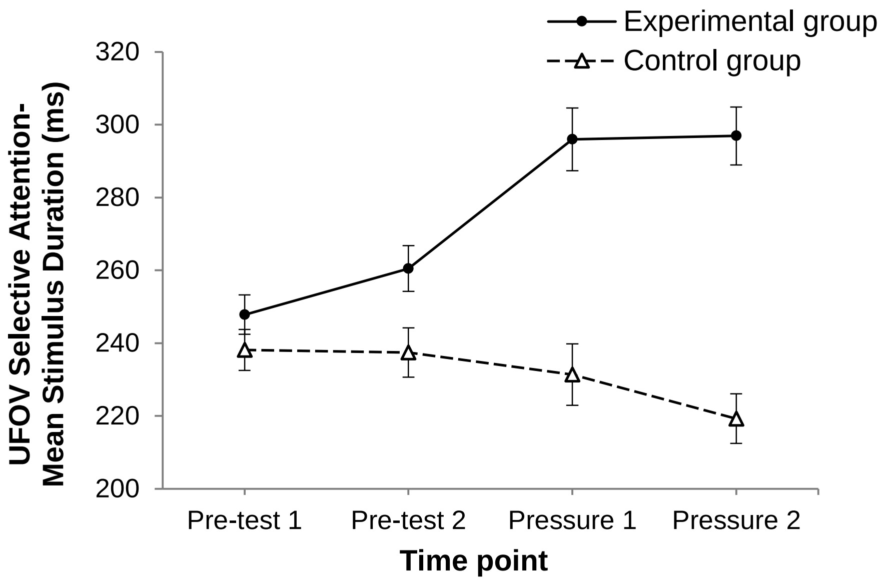

Figure 3.4. Mean stimulus duration (ms) for the selective attention subset of the UFOV test across time points for the experimental (solid line) and control (dashed line) groups. Error bars represent standard errors of the mean.

Putting Performance

The ANOVA conducted on the putting performance data (see Figure 3.5) revealed non-significant effects for phase, $F(1,22) = 1.01$, $p = .33$, $\eta_p^2 = .04$, group, $F(1,22) = 1.86$, $p = .19$, $\eta_p^2 = .08$, or an interaction between phase and group, $F(1,22) = 1.01$, $p = .19$, $\eta_p^2 = .01$. This suggests that when examined at a group level, putting performance for these novice golfers was not affected by the introduction of a pressure manipulation.

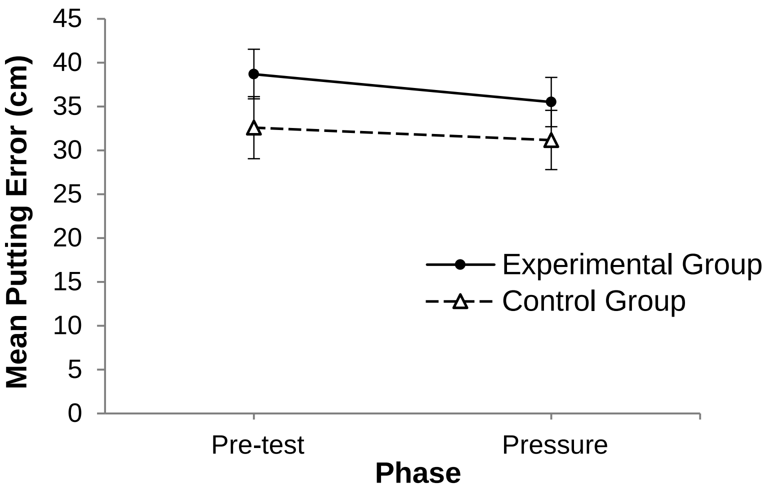

Figure 3.5. Mean putting error across experimental phases for experimental group (solid line) and the control (dashed line) groups. Error bars represent standard error of the mean.

As a supplementary analysis to examine individual responses to pressure (see Gray, Allsop & Williams, 2013), change scores were calculated for both putting performance and the two subsets (divided and selective attention) of the UFOV test. Note for the latter calculation we only used data for 20 degrees eccentricity. Specifically, we calculated the difference in mean putting error and mean stimulus duration from the pre-test phase to the pressure phase for each participant in the experimental group. Therefore a positive change in putting performance and UFOV score indicates poorer putting performance and poorer useful field of view performance respectively.

As shown in Figure 3.6, a significant positive correlation was found between change in putting performance and change UFOV score for the divided attention subset of the UFOV test, $r(10) = .60$, $p = .04$. However, the correlation between change in putting performance and mean stimulus duration for the selective attention subset of the UFOV test only approached significance, $r(10) = .53$, $p = .08$. These relationships suggest that participants who performed poorly under pressure (i.e., choked), had associated declines in divided attention performance at the large eccentricity. Identical correlations were non-significant

(p's > .4) when performed on the control group data, indicating that individual responses to pressure were most likely responsible for the development of these relationships.

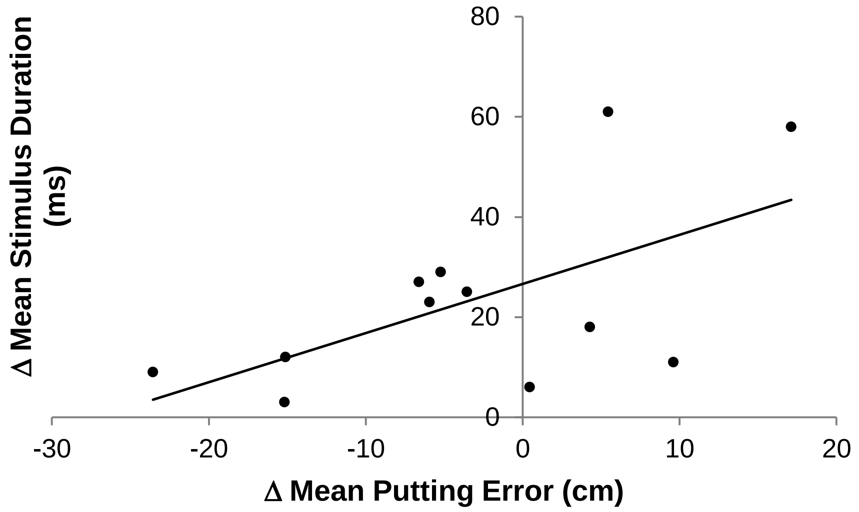

Figure 3.6. Experimental participants' change in mean stimulus duration (ms) for the divided attention subset of the UFOV test as a function of change in mean putting error (cm).

Control Experiment

For the UFOV data described so far participants were always required to perform the central task first. This is a potential limitation since it may have implied to the participant that the central task was more important than the peripheral task thus creating a difference in the saliency. To address this possibility we collected data for additional 12 participants with a reversed response order. All of these participants were subjected to the pressure manipulation. The results for this group of participants were highly similar to the experimental group described above. For 20 degrees eccentricity, there was a significant effect of block on UFOV score for both the divided attention, $F(3, 33) = 27.2$, $p < 0.001$, $\eta_p^2 = .61$, and selective attention, $F(3, 33) = 18.1$, $p < 0.001$, $\eta_p^2 = .41$, subtests. There were also significant correlations between the change in putting performance and change in UFOV scores for both subtests: divided attention, $r(10) = .59$, $p = 0.04$; selective attention, $r(10) = 0.63$, $p = 0.03$.

Discussion

The main aim of the present study was to investigate Easterbrook's (1959) attentional narrowing hypothesis in a sporting context. We extended upon previous research by measuring attentional narrowing using a sport-specific UFOV test. We predicted that competitive pressure would cause a reduction in the ability to use peripheral stimuli, as indicated by poorer UFOV performance (in particular for the largest peripheral target eccentricities). Competitive pressure was successfully manipulated. The intensity of both cognitive and somatic anxiety symptoms significantly increased according to self-report data from the IAMS. The interpretation of cognitive anxiety symptoms remained unaffected by the pressure manipulation, however somatic anxiety symptoms were interpreted as being more debilitative in the latter parts of the pressure phase.

In line with our hypothesis, UFOV performance significantly decreased under pressure. Specifically, the average presentation duration required to accurately detect, and locate a peripheral stimulus, was significantly higher in pressure conditions. This effect was found when the stimulus was presented both alone (divided attention UFOV subtest), or when embedded within distracters (selective attention UFOV subtest). It is also important to note that the introduction of pressure did not result in a general decline in these abilities (i.e., performance was maintained at small eccentricities). Unlike most previous studies investigating Easterbrook's (1959) hypothesis, the measure of attentional narrowing was performed separately to the main task (i.e., golf putting). Therefore, it cannot be argued that the reduction in the ability to use peripheral cues was due to participants directing attention to the task of central importance, at the expense of peripheral tasks. Furthermore, the UFOV test presents similar stimuli, concurrently to both central and peripheral vision and there was no significant effect of reversing task order. This suggests that the present results are unlikely to have occurred through the effect of stimuli salience. Comparable studies using central and peripheral stimuli of the same salience have produced differing results (Shapiro & Johnson, 1987; Shapiro & Lim, 1988).

Shapiro & Johnson (1987) asked participants to respond to either a peripheral or central stimulus as quickly as possible. The stimuli were identical small green circles and the peripheral stimulus was presented at 10 degrees of visual angle from the central stimulus. One group was given random electric shocks in order to manipulate arousal, while a control group simply performed the task. The control group consistently responded faster to the central stimulus, whereas this effect was attenuated for the arousal group. Similar effects were found when music (Stravinsky's 'The rite of Spring') was used to create anxiety (Shaprio & Lim, 1988). It is possible from an attentional narrowing point of view, that increased anxiety should have caused a bias towards the central stimulus. However, it is also possible that the visual angle was not great enough to detect such effects. This suggestion may explain the discrepancy of these studies with the current findings, as the visual angle for peripheral stimulus presentation in the UFOV test ranged from 10 – 20 degrees. Differences in the nature of the stress manipulation may also explain contradictory findings (Furst & Tenenbaum, 1985). However, it is suggested that the current results do support Easterbrook's (1959) proposal, with pressure causing a generalised reduction in the ability to process and use peripheral stimuli. This suggestion is supported by results from studies which have investigated Andersen & Williams' (1988) multicomponent stress-injury model.

In the stress-injury model attentional narrowing has been implicated as a mediating mechanism between life stress and athletic injury. Rogers, Alderman and Landers (2003) tested high-school American football players' peripheral vision using a perimeter test, both before a practice session and before a competitive game. Results showed that the field of vision significantly narrowed before a competitive game. Most interestingly however, individuals with high levels of positive life-event stress experienced significantly greater attentional narrowing than those with lower levels. Examples of positive life-stress include being given an award or a scholarship. It is therefore possible that these athletes experienced more pressure to perform well in front of their teammates during competitive games. Using a similar time-to-event paradigm, Rogers & Landers (2005) again showed that attentional narrowing occurred before a competitive game, with life stress producing greater narrowing effects. Attentional narrowing was also linked with the incidence of self-reported athletic injuries. These studies lend support to the idea of generalised attentional narrowing effects, and provide tentative evidence that these effects can influence athletic outcomes.

The current study also investigated the influence of competitive pressure on putting performance. When examined at a group level, putting performance was not influenced by the introduction of pressure. This is not surprising, as previous studies with novice golfers have also found null effects when using mean error as a performance outcome (Cooke et al., 2010). Therefore, similar to Gray et al. (2013), we performed supplementary analyses to examine individual responses to pressure. Interestingly, we found that changes in putting performance under pressure were positively related to changes in UFOV performance. Specifically, participants who had larger reductions in UFOV under pressure, performed worse under pressure than those who had smaller reductions. Examining the perceptual-motor processes that underpin the execution of the putting stroke may offer an explanation for this finding.

It has previously been shown that visual information is used to regulate the downswing of the stroke, in order to ensure the correct force is delivered to the ball for a given distance (Coello, Delay, Nougier, & Orliaguet, 2000; Craig, Delay, Grealy, & Lee, 2000). It has been proposed that this regulation is achieved based on the optical variable $\tau_{departure}$, which is the angle between the current putter-head location and the desired follow-through position, divided by its rate of change. It is possible that the observed disruptions to peripheral vision associated with the pressure manipulation in the present study may have impacted upon the quality of the visual information needed to regulate the stroke. These changes to the stroke would then obviously impact on outcome performance measures. Recent evidence supports this assertion, as anxiety has been shown to detrimentally influence the reflexive online-control processes responsible for visually regulating limb movements (Lawrence, Khan & Hardy, 2012). Further exploration could be achieved by measuring both UFOV and online control processes in pressure situations. Changes to the locus of attention under pressure may offer an alternative explanation for the correlation between pressure-induced changes in UFOV and performance.

The relationship between measures of visual attention and the performance of novel motor tasks has recently been shown to be moderated by locus of attention (Kasper, Elliott & Giesbrecht, 2012). Kasper et al. (2012) measured visual attention using the Attention Network Task (ANT; Fan et al., 2002), some aspects of the ANT correlate with measures of UFOV (Weaver, Bedard, McAuliffer and Parkkari, 2009). Before performing a novel golf putting task, participants were placed into either internal or external locus of attention groups. Participants in the internal group were given putting instructions directed towards their arms, while the external group were given instructions directed towards the club or the ball. Results showed that measures of visual attention only correlated with performance on the putting task when an external focus of attention was adopted. The authors suggest that an internal focus of attention may disrupt the processing of visual information. This would negate the possibility of relationships occurring between dispositional measures of visual attention and task performance. With relation to the current study, choking under pressure has been consistently linked with increases in skill focused (i.e., internal) attention (e.g., Beilock and Carr, 2001; Gray, 2004, Experiment 3). Therefore combining these lines of reasoning, it is possible that participants experiencing larger increases in pressure-induced internal attention experienced concomitant; decreases in visual processing (indicated by UFOV performance) and decreases in putting performance.

In summary, the current study aimed to investigate Easterbrook's (1959) attentional narrowing hypothesis using a previously unexplored methodology, the UFOV test. In line with this hypothesis, results showed that pressure causes a decrease in the ability to accurately detect and use peripheral stimuli. Furthermore, changes in UFOV performance under pressure correlated with changes in putting performance. The proceeding experimental chapter aims to again examine the effects of pressure on visual attention. The present, and previous, experimental chapters have attempted to elucidate the mechanisms behind pressure-induced performance changes in discrete golf putting tasks. Surprisingly less research has previously examined the effects of pressure on continuous tasks. Given the plethora of complex, but routine, visual-motor tasks that are continuous in nature (e.g., driving, cycling), understanding the relationship between pressure and performance during the performance of such tasks is, at least, of equal importance. Therefore, chapter four examines the effects of pressure during the performance of a continuous, as opposed to discrete, visual-motor task.

The results of the current chapter suggest that pressure negatively affected the UFOV, a specific index of visual attention. In continuous tasks, the timing and sequencing of gaze behaviour across the visual scene has previously been shown to be critical for task performance (Land, 2006). Based on the current chapter, it is expected that pressure will again negatively affect performance-critical indices of visual attention. specifically, this will be evidenced by a disruption in the sequencing of gaze behaviour.

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CHAPTER FOUR

Flying Under Pressure: Effects of Anxiety on Attention and Gaze Behavior in Aviation

Landing an aircraft is a complex task that requires effective attentional control in order to be successful. The present study examined how anxiety may influence gaze behavior during the performance of simulated landings. Participants undertook simulated landings in low visibility conditions which required the use of cockpit instruments in order to obtain guidance information. Landings were performed in either anxiety or control conditions, with anxiety being manipulated using a combination of ego-threatening instructions and monetary incentives. Results showed an increase in percentage dwell time towards the outside world in the anxiety conditions. Visual scanning entropy, which is the predictability of visual scanning behavior, showed an increase in the randomness of scanning behavior when anxious. Furthermore, change in scanning randomness from the pre-test to anxiety conditions positively correlated with both the change in cognitive anxiety and change in performance error. These results support the viewpoint that anxiety can negatively affect attentional control.

Introduction

A human operator's emotional state has been linked to performance outcomes in a range of dynamic systems, including aviation (e.g., Causse, Dehais, Peran, Sabtini, Pastor, 2013; Mortimer, 1995) and driving (e.g., Taylor, Deane, & Podd, 2008; Underwood, Chapman, Wright & Crundall, 1999). The inherent nature of these tasks means that the consequences for performance errors are high, often for both the operator and other individuals. Given the potential consequences, understanding the underlying changes that occur as a result of emotional fluctuations is of both practical and theoretical importance. Anxiety is an emotion that can be invoked by high-pressure or stressful situations (Staal, 2004). It has been defined as a negative emotional and motivational state that can occur when a current goal is under threat (Eysenck, Derakshan, Santos & Calvo, 2007), or when physical harm is perceived to be imminent (Stokes and Kite, 1997). Anxiety has been proposed to cause negative changes to attentional and psychomotor skills while performing such dynamic tasks, including aviation (e.g., Stokes and Kite, 1997). The negative changes in attentional control that can occur alongside adverse mental states have been linked to numerous aviation accidents, including "controlled flight into terrain" incidents (Shappell & Wiegman, 2003). However, relatively few studies have examined the specific influence of anxiety on visual attention during the control of complex, dynamic systems. This study aims to fill this research void by examining the attentional changes that occur when performing an aviation landing task in anxious conditions.

Attentional control theory (Eysenck et al., 2007) has recently outlined a number of specific attentional changes that may occur as a result of anxiety[1]. The central tenets of Attentional Control Theory (ACT) are based upon evidence for the existence of two attentional sub-systems: a goal-directed system and a stimulus-driven system (see Corbetta

& Shulman, 2002). The goal-directed system directs attention based upon task knowledge, expectations and current goals. In contrast to this 'top-down' control, the stimulus-driven or 'bottom-up' system is influenced by salient and (currently) unattended sensory events. In an aviation context, the goal-directed system will be influenced by a pilot's mental model, knowledge and phase of flight. The stimulus-driven system could be influenced by other aircraft coming into view, or flashing cockpit instruments. ACT proposes that anxiety disrupts the balance between these two sub-systems, with the stimulus-driven system taking precedence over the goal-directed system. This overarching imbalance underpins a number of more specific predictions that are made by ACT. Firstly, it is predicted that anxiety reduces *inhibitory control*, thereby causing attention to be directed towards prepotent responses or task-irrelevant stimuli. This effect is amplified when the irrelevant stimuli are threatening, or are perceived to threaten a current goal. Secondly, it is predicted that anxiety causes a reduction in the ability to *shift attention efficiently* between separate tasks. Since many real world tasks require the ability to shift attention or multi-task, this prediction seems particularly relevant in the current context. Thirdly, anxiety causes a reduction in the *ability to update and monitor information in working memory*. The final predictions are derived from processing efficiency theory (PET; Eysenck & Calvo, 1992) which is the predecessor to ACT.

ACT has subsumed the major predictions made by PET. Specifically, PET proposes that anxiety reduces the processing and storage capabilities of the working memory system. However, a key component of PET is that this reduction can be partially or fully offset by an increase in on-task effort. PET therefore predicts that anxiety is more detrimental to processing efficiency (i.e., the ratio between performance outcome and effort) than performance outcomes. A number of studies have provided support for the effort/outcome predictions made by PET, in both simple (e.g., Ikeda, Iwanaga & Seiwa, 1996), and more complex perceptual-motor tasks, such as driving (e.g., Murray & Janelle, 2003; Wilson, Smith, Chattington, Ford & Marple-Horvat, 2006). The associated predictions made by ACT (i.e., decrements in inhibition, attentional shifting and working memory capacity) have been examined in relatively simple laboratory tasks (e.g., Coombes, Higgins, Gamble, Cauraugh & Janelle, 2009; Derakshan, Smyth & Eysenck, 2009). For example, support for the deleterious influence of anxiety on inhibitory functions has been found in an anti-saccade task (Derakshan, Ansari, Hansard, Shoker & Eysenck, 2009). Briefly, this task requires a fixation upon a central location while peripheral stimuli are unexpectedly presented to either the left or right side in a random manner. When the stimulus appears, participants are required to quickly direct their gaze to the opposite side of the screen. In order to achieve this, precise top-down control is needed in order to inhibit a reflexive saccade towards the stimulus. Derakshan et al. (2009) found that the reaction time for saccades in the correct direction was slower for participants high in trait anxiety in comparison to their low anxiety counterparts, providing evidence for less efficient goal-directed control. It is acknowledged that such simple tasks allow a localised and process-pure approach to examining specific predictions (see Derakshan & Eysenck, 2009), however the overarching predictions have also been shown to be applicable to more complex real-world tasks (e.g., Causer, Holmes, Smith, & Williams, 2011; Wilson, Vine & Wood, 2009).

The goal of the present study was to expand previous PET and ACT research into the context of aviation. Aviation is a particularly relevant domain to explore attentional changes for two main reasons. Firstly, the effective orientating of visual attention is essential for adequate performance (Talleur & Wickens, 2003). Secondly, a precise mental model is needed in order to effectively master the complex inter-related flight dynamics (Wickens, 1999; Wickens, 2002). Specifically, fixed wing aircraft have three primary flight axes – pitch, roll and yaw, which are inter-related with three positional variables: altitude, lateral deviation from flight path and position along a flight path (Wickens, 2002). Their inter-related nature means that pilots must monitor multiple variables when making any input to the primary flight axes. For example, initiating a roll will cause a decrease in pitch, as a consequence of the change in direction of the lift vector. Secondly, when direct perception of the environment is unavailable (in low visibility conditions, termed instrument meteorological conditions) flying is a radically different and more challenging task (Gibb, Gray & Scharff, 2010; Schvaneveldt, Beringer, Lamonica, Tucker & Nance, 2000). In these conditions, pilots must derive the values of the aforementioned flight variables from discrete, spatially separated cockpit instruments. The pilot's mental model of the system (see Kieras & Bovair, 1984, or Rouse & Morris, 1985, for a discussion of the development of mental models) drives the visual scanning of these instruments in order to direct visual attention towards the correct instrument at the correct time, in order to obtain the required information (Bellenkes, Wickens & Kramer, 1997; Brown, Bautsch, Wetzel & Anderson, 2002). As mentioned previously, such control will require the goal-directed (top-down) system to take precedence over the stimulus-driven (bottom-up) system. It is proposed that that the sequencing of visual attention will be negatively affected if the stimulus-driven system is not subservient to the top-down control of the mental model. While previous aviation research has not explored the attentional changes that occur as a result of increased anxiety, a considerable number of studies from this body of research have investigated visual scanning and attentional control.

Bellenkes et al. (1997) examined differences in visual scanning between novice and expert pilots. The average instrument flight experience was one hour and 80 hours, for novice and experts, respectively. A desktop flight simulator task was employed that required participants to complete a number of flight maneuvers while wearing a head-mounted eye tracker. Results revealed that lateral axis control was similar for novice and expert pilots, whereas novices were less able to accurately control vertical and longitudinal flight parameters. The analysis of eye movement data revealed a number of interesting results. Specifically, novices tended to exhibit longer dwell durations on each instrument, whereas experts visited instruments more frequently. Tentative evidence for a more refined mental model in expert pilots was also found. In maneuvers where both a heading (roll) and altitude (pitch) change was required, experts exhibited more dwells to the vertical velocity indicator. This suggests that experts are more aware of the cross-coupling between roll and pitch. They therefore attempted to make early corrections to rectify the loss of lift brought about by initiating a roll. The authors also found that the sequencing of dwells was more homogenous for novices than experts; this finding will be expanded upon later. A large number of studies have examined the effect of increased workload, in the form of secondary tasks, on visual scanning and attentional control (e.g., Hameluck, 1990; Itoh, Hayashi, Tsukui & Saito, 1990; Tole, Stephens, Harris & Ephrath, 1982; Wickens, Hellenberg & Xu, 2002).

Tole et al (1982) asked pilots of varying skill level (specific demographic information was not provided) to perform a straight and level instrument flight task while performing an auditory secondary task. A particularly interesting finding in relation to the current study was that increases in workload (achieved by decreasing the inter-stimulus interval of a secondary task) were linked with increases in scanning randomness for some pilots. This suggests that the sequencing of fixations may be a viable way of assessing top-down attentional control in aviation. This is further supported by Ellis & Stark (1986), who investigated the sequencing of visual fixations in expert pilots. The pilots were asked to make judgments on the outcome of air-traffic encounters, which were viewed on a cockpit display of traffic information. The primary purpose of the study was to investigate whether the sequencing of visual fixations is statistically dependent. This was achieved by constructing a first-order Markov matrix for each pilot. Put simply, these provide the probabilities of transitioning to an area of interest (AOI) based on the AOI previously viewed. These probabilities were compared with models that were based on an alternative assumption, that the transitions probabilities were simply based on the percentage of time that each AOI was viewed, rather than being based on the previous fixation point. The comparison clearly showed that the sequencing of visual fixations was statistically dependent, thus suggesting that scanning behavior was driven by mental models detailing the relationships between different areas of interest. Task knowledge of this sort complements the goal-directed, top-down attentional subsystem. Changes in statistical dependencies may therefore be a valid way of examining changes in goal-directed control in anxious conditions. Specifically, if the goal-directed system is negatively affected by anxiety, it should be evidenced by less statistically dependent fixation sequences. Closely related to this point, Ellis & Stark (1986) suggested that "measures of statistical dependency….may provide useful indices of workload or stress" (p 431).

In summary, the present study aimed to examine how attentional control and performance are affected by anxiety. Participants were asked to perform a simulated aviation landing task in instrument meteorological conditions where visibility was low. Participants were then transferred to a condition in which one flight was performed in anxiety-inducing conditions. The study was designed to test the following hypotheses:

(1) In anxiety conditions there would be a significantly greater dwell time towards the external world, and consequently, reduced dwell time on the instrument panel. The rationale

here was that the external world is ordinarily the prepotent source of guidance information for navigating. However, in instrument meteorological conditions the external view contains very little task-relevant guidance information until the last moments of the approach. According to ACT, anxiety will lead to decreased inhibitory functioning with attention then being directed to prepotent responses, such as the external view.

(2) In anxiety conditions there would be a significant reduction in the statistical dependency of visual scanning (i.e., more random visual scanning transitions) as a result of less effective goal-directed attentional control and reduced ability to efficiently shift attention.

(3) There would be a positive relationship between the level of anxiety and scanning entropy on an individual level as represented by a significant correlation between these two variables.

Method

Apparatus

X-Plane version 9 (Laminar Research) was used to simulate all landings. Participants flew a Cirrus Vision SF50 with both the landing gear and flaps extended. The instrument panel was edited to display seven electromechanical style instruments (airspeed indicator, attitude indicator, altimeter, instrument landing system course deviation indicator, turn coordinator, heading indicator and vertical speed indicator), spaced in order to ensure accurate and expedient eye-tracker calibration (see Figure 4.1). The panel and external visual scene were displayed on a 24-inch (61 cm) TFT monitor (screen resolution 1920 x 1080). The monitor was positioned 1 m away from the participant and a chin-rest was employed to restrict head-movements.

Figure 4.1. Example screenshot of the instrument panel and the runway

Auto throttles maintained airspeed at 105 knots. A head-mounted eye tracking (Model 501, Applied Science Laboratory, USA) system was used to record participants' eye movements (precision < 0.5°). Horizontal and vertical point of gaze coordinates were recorded alongside flight data at a rate of 60 Hz. This was achieved via a custom-made Python plugin for X-plane, which interfaced between the simulator and the eye-tracking system via a serial link.

Dependent variables

Flight performance

As has been used in our previous studies (e.g., Gibb, Schvaneveldt & Gray; 2008; Gray et al., 2008) flying performance was operationalised by calculating the root mean square error (RMSE) of the vertical deviations of the aircraft from the ideal landing flight path called the glideslope. The glideslope is a 3° slope extending from the proximal end of the runway. RMSE was derived directly from data displayed on the instrument landing system course deviation instrument and was measured in dots. In X-plane, one glideslope dot represents a 0.28° error from the ideal vertical path.

Manipulation check

Cognitive anxiety was measured using the Competitive State Anxiety Inventory 2-revised (CSAI-2R; Cox, Martens & Russell, 2003) which was administered during the pre-test and anxiety phases of the experiment. The questionnaire has two subscales which provide typical thoughts and feelings associated with cognitive (5 items) and somatic anxiety (7 items). Given our research aims, only the cognitive anxiety scale was employed in the current study. An example item from the cognitive anxiety subscale is "I'm concerned about performing poorly". Participants are then asked to rate, on a scale of 1 (not at all) to 4 (very much so), whether each item is indicative of their thoughts and feelings. The cognitive anxiety score was obtained by summing item responses, dividing by the number of items, and multiplying by 10 (Cox et al., 2003).

Heart rate served as an index of sympathetic nervous system activity and was measured using a heart rate receiver unit (Polar Electro S625X, Polar CIC inc, USA), which was connected to a transmitter (Polar Electro coded 31, Polar CIC inc, USA) with moistened electrodes positioned across the lower-mid thorax. Average heart rate was calculated for the pre-test and anxiety phases.

Gaze behavior

Raw vertical and horizontal gaze coordinates were converted into fixations using custom-made software employing a dispersion-threshold identification algorithm (c.f. Salvucci & Goldberg, 2000). Dispersion based techniques employ a minimum threshold duration of between 100 and 200 ms, in order to alleviate equipment variability (Salvucci & Goldberg, 2000). The fixation threshold was therefore set to 150 ms, which is in accordance with similar visual scanning research (e.g., Heumer, Hayashi, Renema, Elkins, McCandless, McCann, 2005). This software also used participants' calibration data to allocate each fixation to one of six relevant AOIs; correct fixation allocation was also confirmed manually. These AOIs were: external view, attitude indicator, altimeter, instrument landing system course deviation indicator, heading indicator and vertical speed indicator. This enabled the derivation of dwell frequencies for each AOI, as used in similar flight simulation studies (e.g., Bellenkes et al., 1997). In order to examine whether there was a general change in attentional allocation between the external world and the instruments, the instrument AOIs were combined into a single instrument panel AOI. Percentage dwell time was calculated for this AOI and the external world AOI.

Transitions between the 6 AOIs were characterised by calculating first-order transition frequency matrices of p(i to j), where i represents the 'from' AOI and j represents the 'to' AOI. Separate matrices were calculated for each participant and for all flights performed in pre-test and anxiety phases. An average matrix of these separate matrices was created for the experimental group in order to provide a brief descriptive analysis of the three most frequently observed transitions in each of these phases. The separate transition frequency matrices were converted into conditional transition-probability matrices of $p(j|i)$, which gives a 1st order Markov process where the probability of fixating on the jth AOI is based on the current dwell on the ith AOI. As recommended by a number of authors (e.g., Ellis & Stark, 1986; Harris, Glover & Spady Jr, 1986; Holmqvist, Nystrom, Andersson, Dewhurst, Jarodzka & van de Weijer, 2011; Schieber & Gilland, 2008), scan behavior was quantified using an entropy metric originating from information theory (Shannon, 1948). When applied to the conditional transition-probability matrices, entropy indicates the randomness, or alternatively the predictability, of a participant's scan behavior (Harris et al., 1986). This measure is therefore highly applicable for identifying changes in scanning behavior as a result of anxiety. The observed entropy of the matrices was calculated using Stark and Ellis' (1986) adaptation of Brillouin's (1962) conditional information equation:

$$\text{Entropy} = -\sum_{i=1}^{n} \mathrm{p}(i)\left[\sum_{j=1}^{n} \mathrm{p}(j|i)\log_2 \mathrm{p}(j|i)\right], i \neq j$$

Where p(i) is the zero order probability of fixating upon the *i*th AOI based on the percentage of time spent fixating upon it, $\mathrm{p}(j|i)$ is the conditional probability of viewing AOI *j* based on a current dwell on AOI *i*, and n is the number of AOIs.

Participants

25 university students (20 male, 5 female; mean age = 20.2, *SD* = 1.99) voluntarily took part in the study. All participants were right handed, reported normal or corrected vision and had no previous experience of real or simulated flight. Participants were randomly assigned to an experimental group (n = 14) or a control group (n = 11). Ethical approval was granted by the university ethics committee and informed consent was gained from all.

Procedures

Flight Task

All flights began with the aircraft positioned 5.55 km (3 nautical miles) away from the simulated runway (for example, see Figure 1). Participants were required to achieve and maintain a flight path along the extended runway centerline and correct 3° glideslope. The task was performed in one of two meteorological conditions: visual meteorological conditions or instrument meteorological conditions. For visual meteorological conditions (VMC), simulator visibility was set to 40 km. For instrument meteorological conditions (IMC), visibility was set to 0.7 km. Wind speed and turbulence was set to zero across all conditions. The lateral and vertical starting location of the aircraft was varied throughout the experiment. Specifically, vertical and lateral locations both ranged between 1.6 dots above and below, and to the left and right, of the ideal glideslope and runway centerline, respectively. This variation was employed to ensure that participants had to use the information provided by the instruments, rather than simply adopting a similar movement strategy for each flight. The experiment was split into three phases which are detailed below.

Practice phase: The main aim of this phase was to develop the participants' ability to fly the aircraft along the ideal 3° glideslope using only the cockpit instruments in low visibility, IMC. This phase took place over three visits to the laboratory (each visit lasted approximately 1 hour) and required the completion of 57 landings; a similar number of visits have been employed in similar previous experiments (e.g., McKinely, McIntire, Schmidt, Repperger & Caldwell, 2011). The maximum duration allowed between visits was one week, and visual feedback of their flight profile was displayed on the monitor after each landing. At the start of the first session, participants were given an information sheet that gave details and pictorial representations of both the flight task and cockpit instruments. Participants then observed two demonstrations of the flight task, one in VMC and one in IMC. This was followed by a five-minute free-flight where participants were asked to execute a number of flight maneuvers in order to acclimatise to the simulator and aircraft control properties. Pilot experiments showed task difficulty to be high if IMC flights were performed before VMC flights. Therefore, participants followed a practice schedule that progressed from flights in VMC to IMC.

The practice schedule required participants to first perform nine landings in VMC in session one. The rest of the training phase alternated between flights in VMC and IMC. Ten further flights, following this alternating pattern, were performed in session one. Session two began with 18 flights. The remaining training flights required participants to wear the eye-tracker and heart rate monitor to allow acclimatisation before pre-test measurements. A mock calibration was performed when the eye-tracker was first worn; this was also to alleviate any observer effects during the pre-test phase. Session two then consisted of 10 further flights. Session three consisted of a further 10 flights before moving straight into the pre-test phase.

Pre-test phase: The aim of this phase of the experiment was to establish a baseline level of performance for the flight task in IMC for each participant. All participants were instructed that due to a technical fault, the eye-tracker needed to be re-calibrated and further training in IMC was required. Participants then filled out the anxiety questionnaire and completed a flight in IMC. Heart rate was recorded for the duration of the flight.

Anxiety phase: During this phase, participants completed the anxiety questionnaire and then completed one further IMC flight, with heart rate again being recorded. For the control group, this flight simply appeared to be the second flight of the pre-test phase. However, participants in the experimental group were subjected to a multidimensional anxiety manipulation before completing the flight. This between-subject design was chosen over a counterbalanced within-subject design (e.g., Wilson et al., 2009) based on pilot experiments. These experiments showed that participants who firstly experienced the anxiety phase suspected further manipulations in the pre-test phase, which led to anxiety after-effects. The anxiety manipulation involved a combination of evaluative and ego-threatening instructions, monetary incentives and immediate consequences for performance failures. Similar manipulations have been shown to successfully increase anxiety in a variety of contexts, including, aviation (e.g., Stokes & Raby, 1989), surgery (e.g., Malhorta, Poolton, Wilson, Ngo & Masters, 2012) and sport (e.g., Gray & Allsop, 2013).

The evaluative instructions firstly consisted of a script that described how the flight results in the next phase would be e-mailed to everyone else taking part in the experiment. They were also informed that the person with the best overall performance would win £50 (~$75). Secondly, a video camera was placed in front of participants, but out of view while performing the task. This was set to record at the start of the flight, and participants were informed that the recordings may be used in upcoming psychology lectures dependant on whether their performance was significantly below average. Thirdly, participants were informed that they would now be flying in an online flight environment called the Virtual Air Traffic Simulation Network. The experimenter then loaded a custom-made program that allowed a mock log-in to be performed. After 'logging-in' to the program, a screen was displayed on the monitor showing a top-down view of the airport and surrounding area. The area was populated with a number of aircraft and extended trail history indicators.

Statistical Analyses

Performance, cognitive anxiety, heart rate and scanning entropy data were analysed using 2 group (experimental, control) x 2 experimental phase (pre-test phase, anxiety phase) ANOVAs with repeated measures on the second factor. To examine whether anxiety had an overall effect on attentional allocation, percentage dwell time data was submitted to a 2 group (experimental, control) x 2 experimental phase (pre-test, anxiety) x 2 AOI (external, instruments) ANOVA with repeated measures on the last two factors. Significant effects were broken down using Tukey's HSD post hoc procedures ($p < .05$). Previous research has shown that there can be large individual differences in the response to anxiety during complex visual-motor tasks (e.g., Gray, Allsop & Williams, 2013; Malhorta et al., 2012). To evaluate possible individual differences for the experimental group in the present study, we used the analysis employed in this previous research, namely calculating pre-test phase to anxiety phase change scores for different dependent measures then computing Pearson product moment correlations between these change scores.

Results

Flight Performance

Pre-test and Anxiety Phase

The mean glideslope RMSE for the experimental group was 1.01 (*SD* = 0.41) and 0.87 (*SD* = 0.29) in the pre-test and anxiety phases, respectively. The mean glideslope RMSE for the control group was 0.93 (*SD* = 0.29) and 0.80 (*SD* = 0.33) in the pre-test and anxiety phases, respectively. The ANOVA conducted on this glideslope data revealed a non-significant main effect for group, $F(1, 23) = .49$, $p = .49$, $\eta_p^2 = .02$, a non-significant effect of experimental phase, $F(1,23) = 3.02$, $p = .10$, $\eta_p^2 = .12$, and a non-significant interaction, $F(1,23) = .01$, $p = .99$, $\eta_p^2 = .00$. Overall, flight performance was maintained in anxious conditions and the experimental group had comparable levels of performance to the control group.

Manipulation Check

Cognitive Anxiety

Mean cognitive anxiety data is shown in Figure 4.2. The ANOVA performed on the cognitive anxiety data revealed a significant main effect for group $F(1, 23) = 7.32$, $p = .01$, $\eta_p^2 = .24$, and a marginally significant main effect for experimental phase $F(1, 23) = 4.07$, $p = .06$, $\eta_p^2 = .16$. More importantly however, there was a significant Group x Experimental phase interaction, $F(1, 23) = 17.32$, $p < .001$, $\eta_p^2 = .38$. Breakdown of this interaction revealed a significant increase in cognitive anxiety between the pre-test phase and the anxiety phase for the experimental group, showing that the anxiety manipulation was successful. Cognitive anxiety did not significantly differ across the same time period for the control group.

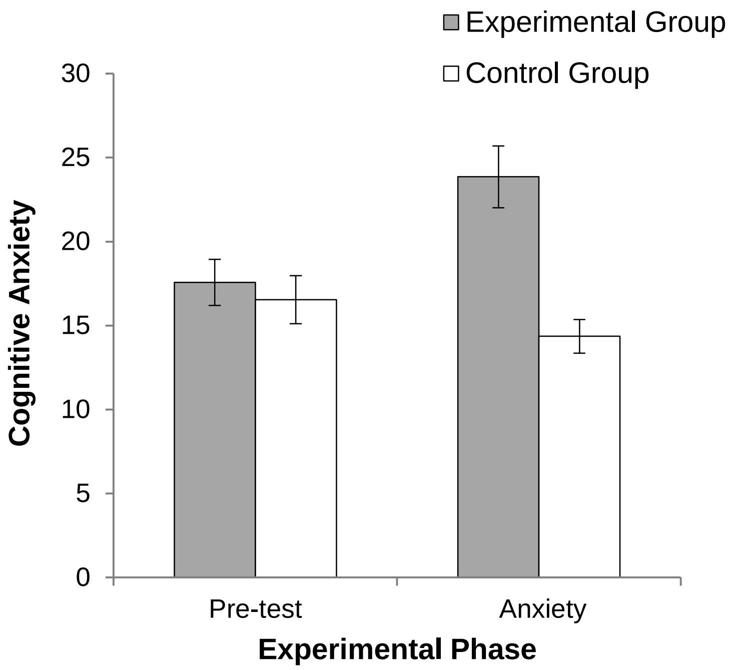

Figure 4.2. Mean cognitive anxiety scores for the experimental group and control group in the pre-test and anxiety phases. Error bars represent standard errors of the mean.

Heart Rate

Mean heart rate data is shown in Figure 4.3. For three participants (experimental group: one; control group: two), heart rate data was unavailable for the whole duration of both flights due to an equipment malfunction; data analysis was therefore performed on the remaining participants. Regardless, the ANOVA revealed a significant main effect for group $F(1, 20) = 6.73$, $p = .02$, $\eta_p^2 = .25$, and a significant main effect for experimental phase $F(1, 20) = 6.99$, $p = .02$, $\eta_p^2 = .26$. More importantly however, there was a significant Group x Experimental phase interaction, $F(1, 20) = 15.43$, $p = .001$, $\eta_p^2 = .44$. Breakdown of this interaction revealed a significant increase in heart rate from the pre-test phase to the anxiety phase for the experimental group.

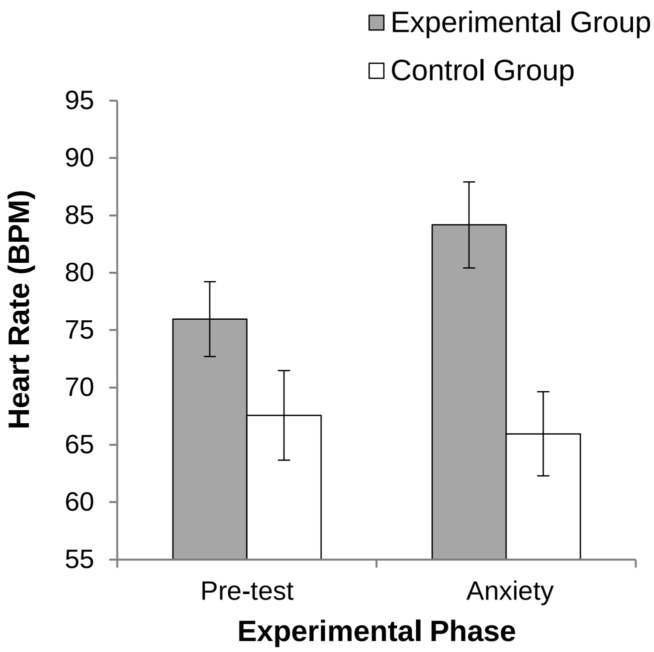

Figure 4.3. Mean heart rate for the experimental and control groups in the pre-test and anxiety phases. Error bars represent standard errors of the mean.

Gaze Data

Percentage Dwell Time

Figure 4.4 shows the mean percentage dwell time data. The analysis revealed a significant Group x Experimental Phase x AOI interaction, $F(1,23) = 4.57$, $p = .03$, $\eta_p^2 = .17$. To interpret this interaction, we performed separate, 2 experimental phase (pre-test, anxiety) x 2 AOI (external, instruments) repeated measures ANOVAs, for the experimental and anxiety groups. For the experimental group, the analysis revealed a significant interaction between experimental phase and AOI, $F(1,13) = 8.00$, $p = .01$, $\eta_p^2 = .38$. Breakdown of this interaction (see Figure 4.4A) showed that percentage dwell time on the external world was significantly higher, and percentage dwell time on the instruments was significantly lower, in the anxiety phase when compared to the pre-test phase. For the control group (see Figure 4.4B), no significant effects were found (all *p*'s >.05).

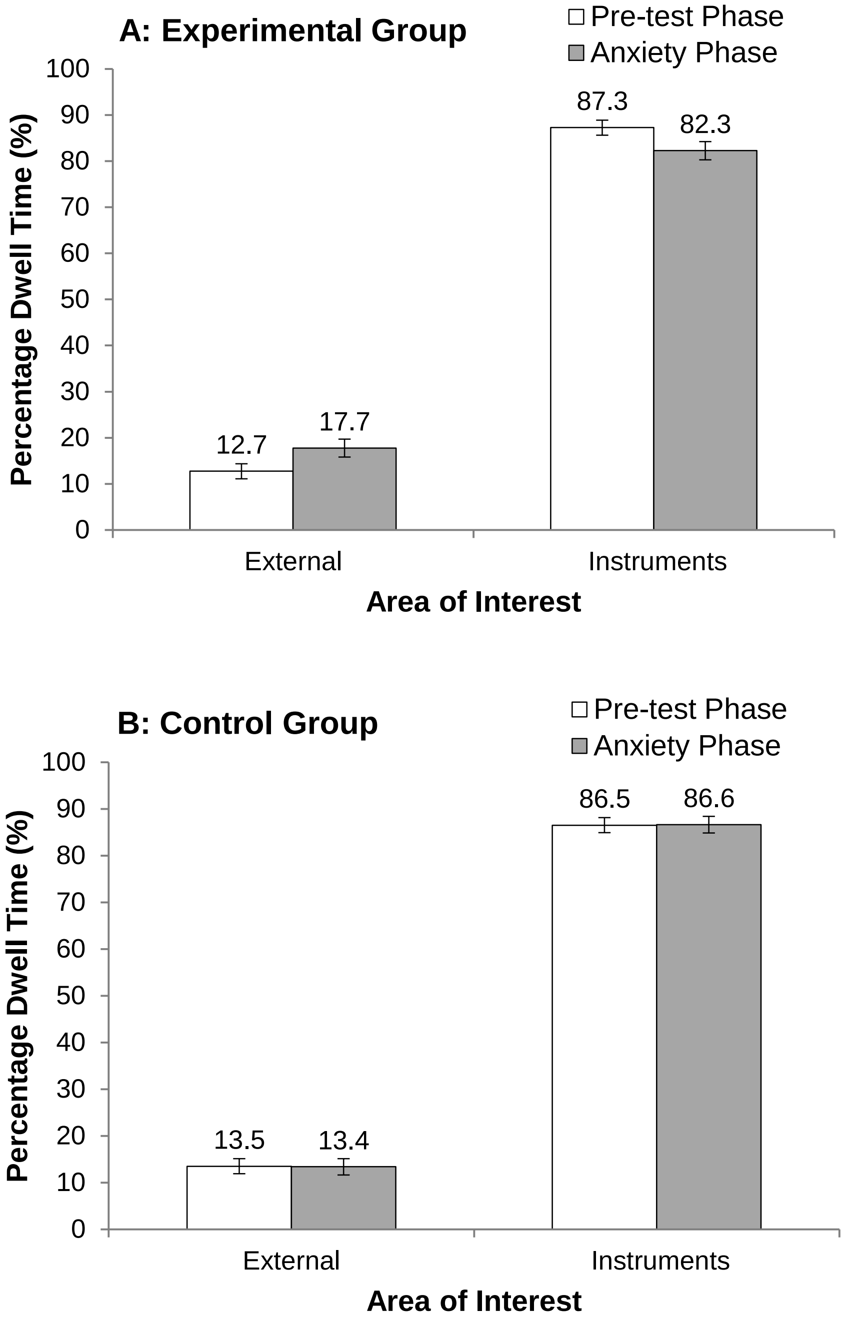

Figure 4.4. Mean percentage dwell time on the external world and the generalised instrument panel AOIs, for the experimental group (Panel A) and the control group (Panel B) in the pre-test and anxiety phases. Error bars represent standard errors of the mean.

Scanning Entropy

Figure 4.5 shows the mean scanning entropy data. The ANOVA revealed a non-significant main effect for group *F*(1, 23) = 2.43, *p* = .13, η_p^2= .10, and a non-significant main effect for experimental phase *F*(1, 23) = 1.24, *p* = .28, η_p^2= .05. As expected, there was a significant Group x Experimental phase interaction, *F*(1, 23) = 6.31, *p* = .02, η_p^2= .22. Breakdown of this interaction revealed a significant increase in scanning entropy from the pre-test phase to the anxiety phase for the experimental group. No significant differences were found for the control group across the same period.

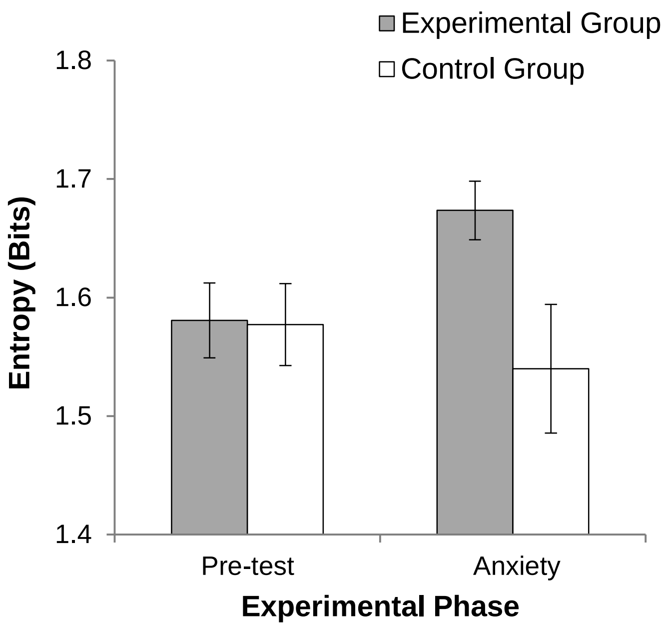

Figure 4.5. Mean scanning entropy for the experimental and control groups in the pre-test and anxiety phases. Error bars represent standard errors of the mean.

The three most frequently observed transitions remained consistent for the anxiety group across the pre-test and anxiety phases. These were, in descending order: vertical speed indicator to instrument landing system course deviation indicator (pre-test phase mean: 17.2; anxiety phase mean: 14.5), attitude indictor to heading indicator (pre-test phase mean: 16.4;

anxiety phase mean: 14.1) and instrument landing system course deviation indicator to vertical speed indicator (pre-test phase mean: 14.1; anxiety phase mean: 13.4).

Change Scores

In line with hypothesis 3 described above, we examined the relationship between change in scanning entropy and change in cognitive anxiety for the experimental group. A strong positive correlation was found between these two variables, $r(12) = .70$, $p = .01$. This suggests that participants who experienced a larger increase in cognitive anxiety after the experimental manipulation also had larger increases in scanning entropy. Interestingly, a strong positive correlation was also found between change in glideslope error and change in scanning entropy, $r(12) = .59$, $p = .03$. This suggests that participants who experienced larger increases in scanning entropy also performed worse in the anxiety phase. For the control group, the correlation between change in cognitive anxiety and change in scanning entropy was non-significant, $r(9) = .39$, $p = .22$. Similarly, the correlation between change in glideslope error and change in scanning entropy was also non-significant, $r(9) = .02$, $p = .95$. These analyses further suggest that the significant change correlations found for the experimental group resulted from the experimental manipulation.

Discussion

This study examined the influence of anxiety on the gaze behavior and performance of operators as they control a dynamic system. Participants were asked to perform a simulated aviation landing task in low visibility, instrument meteorological conditions (IMC). Participants in the experimental group were then transferred to an anxiety phase where they were asked to perform an IMC landing in anxiety-inducing conditions. The predictions were based around attentional control theory (ACT; Eysenck et al., 2007). A number of novel contributions emerged from this study. Firstly, anxiety caused an increase in the percentage of dwell time directed towards the external world. Secondly, anxiety caused visual scanning to become more random (i.e., less statistically dependant). Finally, the change in visual scanning randomness from the pre-test to anxiety phase was positively correlated with both the change in cognitive anxiety and performance error. These findings are explored in greater detail below.

Both self-report questionnaires and physiological measures indicated that anxiety was successfully invoked by the manipulation that was employed in the current study. Heart rate and cognitive anxiety significantly increased for flights performed after the anxiety-manipulation. This adds weight to the abundance of evidence suggesting that a combination of ego-threatening instructions and financial consequences can effectively manipulate anxiety (e.g., Stokes & Raby, 1989; Malhorta et al., 2012). It is acknowledged that the magnitude of anxiety is likely to be greater in real-life situations. However, the observed increase allows the examination of predictions made by ACT. According to ACT, anxiety causes the stimulus-driven attentional subsystem to take precedence over the goal-directed subsystem. This prediction is supported by an anxiety-induced increase in both the percentage of dwell time and number of dwells towards the external world.

An increased number of dwells to the external world in visual meteorological conditions (VMC) provides the operator with relevant visual information that can be used to execute a successful landing. For example, it has been previously shown that optical splay angle is a critical perceptual variable that can be used to accurately align an aircraft with the runway centerline (Beall & Loomis, 1997) whereas the runway length-width ratio can be used to regulate altitude (e.g., Mertens, 1981). Therefore in such conditions, the outside world provides task-relevant visual information that can aid performance. However, this is not the case for flights in IMC. In the IMC conditions used in the current experiment, the external world contained very little task-relevant information. The analysis of percentage dwell time showed an increase in dwells to the outside world in the anxious phase of the experiment. This suggests that anxiety caused lapses of attentional control as a result of a reduced influence of the goal-directed system. Reduced inhibitory functioning offers a specific, parsimonious explanation for the observed changes in attentional allocation towards the cockpit window.

ACT predicts that anxiety causes inhibitory functioning to decline, such that attention is less likely to be inhibited from being directed towards "incorrect prepotent or dominant responses ... or on to task irrelevant stimuli" (Eysenck et al., 2007, p. 344). Since direct perception of the environment is the dominant form of guidance when navigating, a reduction in inhibitory functioning may have caused participants to allocate attention to the external world in an attempt to pick-up perceptual variables. Therefore it is suggested that anxiety caused a decreased influence of the goal-directed system and poorer inhibitory functioning. This resulted in more attention being directed towards the prepotent source of navigational information. The analysis of visual scanning randomness provided further evidence for a reduction in the goal-directed attentional system.

The analysis of scanning entropy data revealed that visual scanning became more random during the anxiety phase. Expressed alternatively, this essentially means that the location of the present dwell location, based upon the previous dwell location, became more uncertain. In IMC, visual scanning must be effectively controlled by the top-down attentional system in order to direct attention to the appropriate gauge at the appropriate time (Bellenkes et al., 1997). The entropy results therefore suggest that anxiety interfered with this top-down control. Results from the change score analyses further support this line of reasoning. Specifically, it was found that the change in scanning entropy was positively correlated with changes in cognitive anxiety. This suggests that participants who experienced a greater increase in cognitive anxiety also had larger increases in visual scanning entropy. A positive relationship was also found between scanning entropy and performance error, which emphasises the importance of ordered scanning behavior in supporting performance for flights in IMC. The observed increase in scanning entropy dovetails well with predictions made by ACT, by giving strong evidence that anxiety can negatively influence the top-down control of attention. There are a number of possible explanations as to how top-down control may have been specifically influenced.

It has previously been proposed that the sequencing of dwells between the cockpit instruments may be based around either open-loop or closed-loop control mechanisms (Bellenkes et al., 1997; Brown et al., 2002; Ellis & Stark, 1986; Hameluck, 1990). Closed-loop control suggests that the information gathered from the current dwell location drives the next dwell location. By comparison, open-loop control suggests that the next dwell location is independent of the information gathered, and is instead driven by the operator's mental model. These two control mechanisms give rise to different explanation for how top-down control may have been influenced. From the open-loop standpoint, it is possible that anxiety interfered with the operator's mental model. ACT predicts that anxiety can cause a decrease in the ability to efficiently shift between multiple tasks, or operations within a task. This seems particularly relevant, as the aviation landing task requires the ability to shift attention between spatially separate instruments in order to control multiple axes of control. It is possible that decreased shifting ability caused interference in the mental model's ability to manage multiple sub-tasks and direct attention accordingly. Alternatively, based on the closed-loop viewpoint, it is possible that anxiety interfered with the processing or combining of information that was gathered at the current dwell location. This explanation relates with Endsley's (1995) three-level model of situational awareness.

Situational awareness is defined by Endsley (1995) as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their future status" (p. 36). Briefly, Endsley (1995) describes three levels of situational awareness. The first level merely involves perceiving the current state of relevant elements in the environment. The second level involves an overall understanding and combining of significant individual elements based on current goals. The third level involves predicting the future state of the elements based on current and desired control inputs. Developing and maintaining situational awareness is resource intensive, with a considerable portion of working memory being required (Wickens, 2002). Anxiety has also been suggested to occupy working memory resources (Eysenck & Calvo, 1992). Therefore, it is possible that the working memory space required to maintain and develop level two situational awareness was compromised in the anxiety phase of the experiment. This change would then have resulted in more random allocation of attention in order to find level one elements, as individual elements could not be combined into an overall picture. For example, Dijk, Merwe & Zon (2011) found similar increases in scanning entropy after an instrument failure was introduced while performing a simulated flight task. This increase occurred alongside decreases in subjective situational awareness ratings. Future experiments should seek to determine whether it is the open-loop or closed-loop standpoint that offers a satisfactory explanation for the increase in scanning entropy and compromised top-down control.

The scanning entropy results also lend credence to Ellis & Starks' (1986) suggestion of using measures of scanning entropy as a passive and objective indicator of an operator's stress or anxiety levels. These findings are particularly novel as previous research has only examined changes in scanning entropy as a result of increased workload, such as secondary tasks (e.g., Tole et al., 1982; Schieber & Gilland, 2008). These studies have found that secondary workload tasks cause decreases in scanning entropy. For example, Schieber & Gilland (2008) asked young and older adults to drive on a real-world rural highway while performing various secondary tasks. They found that visual-spatial secondary tasks caused a greater decrease in visual entropy for older drivers than younger drivers. The present results suggest that anxiety will cause an opposite change in visual scanning entropy. Manipulations of both workload and anxiety could be employed in future in order to examine the specificity of visual scanning entropy.

Practical Applications

There are a number of possible practical applications that could stem from the current findings. Scanning entropy could be computed 'online', during the performance of various dynamic or supervisory control tasks. The present scanning entropy results suggest that this measurement could be used to detect an operator's emotional state, or as a general marker of a divergence from an operator's optimal state. Future studies should aim to examine the specificity of the entropy measure as a diagnostic tool. As stated previously, this could be achieved by manipulating both workload and anxiety. This online monitoring could be designed to be relatively passive, by employing gaze detection methodologies that can be placed in-cockpit, in-car, or on a system operator's control panel. By incorporating the monitoring of the aforementioned variables within operator warning systems, it is possible that negative performance outcomes may be prevented before they occur. Changes in the sequencing of fixation patterns could be potentially more useful than other measures of stress, such as cardiac measures, as fixation patterns are more closely related to actual task performance. For example, in the automotive domain, passive measures of steering entropy (see Nakayama, Futami, Nakamura & Boer, 1999) have been implicated and developed as a detection method for driver inattention, distraction or micro-sleeps (Paul, Boyle, Boer, Tippin & Rizzo, 2006).

Limitations

This study revealed a number of interesting findings on how anxiety may influence gaze behavior and performance. However, there are some limitations that should be addressed in future research. First, the participants were not experts. It is felt that the extensive training on the task partially compensates for this limitation, with performance being comparable to other instrument flight studies (c.f. Hasbrook & Rasmussen, 1971). It is therefore suggested that the results may at least generalise to individuals early in their training (e.g., student pilots). However, future studies should seek to validate whether these results generalise across different levels of expertise. Second, the training schedule progressed from VMC flights to IMC flights. It is possible that anxiety may have caused participants to revert back to a strategy developed during VMC flights, which could explain the increase in dwell time towards the outside world. Future studies could attempt to test this hypothesis by asking a group to train only in IMC.

Summary

The present study investigated the effects of anxiety on gaze behavior and performance in an aviation task. Anxiety was associated with a reduction in top-down attentional control which led to an increase in dwells towards the outside world and more random instrument scanning. The change in scanning randomness was related to both cognitive anxiety and performance change. These findings have immediate potential applications, as they suggest that it is possible to passively identify anxiety-induced changes to an operator’s mental state during operational activity, via changes in visual scanning behavior. This could then be used in warning systems to potentially prevent unwanted performance outcomes before they occur.

The proceeding experimental chapter aims to replicate and expand upon the findings of the current study. While interesting changes to gaze behaviour were found in the present study, as well as correlations between changes in entropy and performance, no overall performance effects were found. It is possible that task difficulty was low after the relatively extensive training. Use of a concurrent, cognitively demanding, task should increase task difficulty and therefore potentially elicit significant performance effects. Increasing cognitive demands is also interesting from a theoretical point of view, as ACT suggest that the effects of anxiety on attention should be exacerbated when spare cognitive resources are low. If this is the case, then entropy should be expected to be highest in high-anxiety, high-cognitive load conditions. Also, it has been acknowledged that a potential limitation of the interpretation of the current study's findings centres around the training regime. Specifically, the use of an alternating visual, to instrument, trial schedule during training may have meant that participants reverted back to a visual strategy in the pressure conditions. The proceeding experiment aims to remedy potential limitation by always training participants in instrument conditions.

Endnote 1 - Attentional control theory was originally developed to explain the effect of trait anxiety on performance and attention. It has however been readily applied to explain changes that occur as a result of state anxiety.

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CHAPTER FIVE

Effects of Anxiety and Cognitive Load on Gaze Behavior in an Aviation Landing Task

Cognitive anxiety and cognitive load have separately been shown to negatively impact the performance of complex visual-motor skills. Previous research has rarely examined the combined influence of both these factors on gaze behavior and performance. In the present study, participants performed an aviation instrument landing task in neutral and anxiety conditions, while performing a low or high cognitive load auditory *n*-back task. Both self-reported cognitive anxiety and heart rate increased from neutral conditions indicating that anxiety was successfully manipulated. Response accuracy and reaction time for the auditory task indicated that cognitive load was also successfully manipulated. Cognitive load negatively impacted performance and the frequency of gaze transitions between areas of interest. Performance was maintained in anxious conditions, with a concomitant decrease in *n*-back reaction time suggesting that this was due to an increase in mental effort. Analyses of individual responses to the anxiety manipulation revealed that changes in cognitive anxiety from neutral to anxiety conditions were positively correlated with changes in the randomness of gaze behavior, but only when cognitive load was high. These results offer some support for an interactive effect of cognitive anxiety and cognitive load on attentional control.

Introduction

Being able to successfully perform complex visual-motor tasks in high-pressure, high-workload situations is essential for success in many different domains, ranging from surgical medicine to aviation. Critical performance breakdowns in these situations can often have serious consequences for both the human operator and others. Cognitive anxiety has been identified as a negative and unpleasant psychological state that can occur during performance under high-pressure (Staal, 2004). It occurs when a current goal is perceived to be under threat (Cheng, Hardy, & Markland, 2009; Eysenck, Derakshan, Santos, & Calvo, 2007), or when physical harm is perceived to be imminent (Stokes & Kite, 1997). Crucially, cognitive anxiety has been implicated as a key factor that can influence the performance of visual-motor skills (Janelle, 2002; Stokes & Kite, 1997). The cognitive demands when performing visual-motor tasks are also often high. For example, strategic choices often have to be made, or task related information must be manipulated. The present study aimed to investigate the effects of both cognitive anxiety and cognitive load on gaze behavior and performance while performing a complex, continuous, visual-motor task – specifically, landing a simulated aircraft in low visibility conditions. Attentional control theory (ACT; Eysenck et al., 2007) offers a comprehensive framework that accounts for how cognitive anxiety can influence performance through attentional changes.

ACT postulates that anxiety leads to a disturbance in the balance between two attentional sub-systems: a goal-directed system and a stimulus-driven system (see Corbetta & Shulman, 2002). The goal-directed system directs attention based on current goals, task knowledge and predictions. In contrast, the stimulus driven system directs attention based on salient sensory events. The onset of cognitive anxiety is said to result in an increased prioritization of the stimulus-driven system over the goal-directed system, causing attention to be directed away from goal-relevant information. ACT suggests that this overall imbalance is caused by anxiety-induced changes to the functioning of specific key working memory functions, namely: *inhibition, shifting* and *updating.* It is predicted that anxiety can compromise *inhibitory control*, causing attention to be more readily directed towards prepotent or task-irrelevant stimuli. Anxiety can also reduce the ability to *shift attention* efficiently between tasks, or within elements of an individual task. Finally, it is predicted that anxiety can impair the *updating* function, which will lead to a decreased ability to monitor, manipulate and store information in working memory.

Importantly however, ACT suggests that anxiety can serve a motivational function, leading to an increase in on-task effort and liberation of processing resources which can actually maintain or increase performance. Therefore ACT makes an important distinction between performance effectiveness and processing efficiency, with anxiety being predicted to more readily affect the latter. Performance effectiveness is simply the observed performance, whereas processing efficiency is the ratio between the amount of effort or resources invested and the performance outcome. In sum, ACT predicts that anxiety can influence attentional control and potentially performance, through impairment of specific working memory functions, either individually or in combination.

A number of studies have found supporting evidence for the predictions of ACT in complex visual-motor tasks by observing changes to gaze behavior (e.g., Behan & Wilson, 2008; Causer, Holmes, Smith, & Williams, 2011; Nibbeling, Oudejans, & Daanen, 2012; Wilson, Vine, & Wood, 2009; Wilson, Wood, & Vine, 2009). Anxiety has been shown to increase the frequency of fixations on goal-irrelevant stimuli (Wilson, Wood, et al., 2009) and reduce the duration of ordinarily long target-focused fixations (Causer et al., 2011; Moore, Vine, Cooke, Ring, & Wilson, 2012; Wilson, Vine, et al., 2009). Allsop & Gray

(2014) investigated the effects of anxiety on attentional control in an aviation landing task. Participants first learnt how to perform an aviation landing task on a desktop flight simulator in simulated instrument meteorological conditions, which is where visibility is low and cockpit instruments provide guidance information. Participants acquired this skill by following a training protocol that progressed from high- to low-visibility meteorological conditions. Two landings were then performed in instrument meteorological conditions while wearing a head-mounted eye-tracker. An experimental group were subjected to a multidimensional anxiety manipulation before completing the second landing, whereas a control group continued unimpeded.

Results showed that anxiety led to a higher proportion of eye-movement dwells towards the outside world and a lower proportion to cockpit instruments. Entropy, which is a measure of the randomness of scanning, also increased in anxiety conditions. Furthermore, change in anxiety from baseline to anxiety conditions positively correlated with both change in entropy and change in performance error. In line with ACT, these findings suggest that anxiety led to an increased influence of the stimulus-driven system, as attention was directed towards the task-irrelevant outside world and more randomly directed.

One limitation of this study centers on the nature of the training protocol, specifically, the progression from low to high-visibility conditions. It is possible that the increased attention towards the outside world may have been a result of a reversion to a gaze strategy developed early in training, during high-visibility trials when the outside world was actually visible. Such a reversion is in-line with a reinvestment (c.f. Masters & Maxwell, 2008) account of the anxiety-performance relationship. Briefly, reinvestment theory suggests that anxiety can lead people to revert back to strategies and rules developed during the initial stages of learning. Therefore rather than attentional changes being explained by ACT, it is possible that reinvestment theory may offer an alternative explanation of the findings. It is important from a theoretical perspective to attempt to rule out this possibility in order to determine which account offers the most parsimonious explanation. Nevertheless, Vine, Uiga, Lavric, Moore, Tsaneva-Atanasova & Wilson (2014) obtained analogous findings when investigated the effects of stress using expert, commercial pilots' gaze behavior.

In Vine and colleagues' (2014) study, gaze behavior and performance of commercial pilots was measured while undertaking a periodic proficiency exam. Pilots were asked to perform a normal start-up and take off in a commercial-grade flight simulator. However, an engine fire was initiated the moment the aircraft gained a positive vertical velocity. They were then required to respond appropriately to the fire and land the aircraft. Participants were asked to evaluate the demands of the task and their coping capabilities before commencing the exam. The results showed that evaluating the exam as more threatening, which consists of high task demand and low coping evaluations, was associated with higher search rate and more fixations on unimportant regions of the cockpit. In accordance with Allsop & Gray (2014), it was shown that such evaluations were also associated with increased entropy, and decreased performance as evaluated by a flight instructor, although both effects were marginally significant (p = .06). The present study aims to extend the research that has investigated ACT in complex visual-motor tasks by examining the effects of both cognitive load and anxiety on gaze behavior and performance.

Like other interference theories of anxiety (e.g., Sarason, 1984), attentional control theory is built around the assumption that anxiety consumes the limited resources of working memory. The effects of anxiety on attentional control and performance can then potentially be exacerbated when currently utilised resources converge on working memory limits (Berggren & Derakshan, 2013). Studies attempting to examine the interaction between working memory resources and anxiety on attentional control can roughly be grouped into two categories: those investigating dispositional differences in working memory capacity, and those experimentally manipulating working memory load.

The former set of studies have largely supported the predictions made by ACT, showing that deficits in working memory capacity can exacerbate the effects of anxiety on performance and attentional control in simple laboratory tasks (e.g Edwards, Moore, Champion, & Edwards, 2014; Johnson & Gronlund, 2009; Owens, Stevenson, Hadwin, & Norgate, 2014). For example, Johnson & Gronlund (2009) investigated the influence of working memory capacity on the relationship between trait anxiety and cognitive performance. A dual-task paradigm was employed where participants were asked to perform a short term memory task at the same as an auditory discrimination task. The results showed an interactive effect of trait anxiety and working memory capacity on auditory discrimination accuracy. Specifically, stronger negative relationships between trait anxiety and accuracy were found for low or average working memory capacity, in comparison to high working memory capacity individuals.

Similar results were found by Edwards et al. (2015), who replicated and extended the study by examining the role of experimentally manipulated state anxiety. The results showed that working memory capacity, trait anxiety and state anxiety interacted to predict shifting efficiency (i.e., frequency of correct discrimination responses divided by the mean response time for correct trials). Summarily, trait anxiety predicted efficiency in such a manner that efficiency was lowest when state and trait anxiety was high, and where working memory capacity was low (see Wright, Dobson and Sears, 2014 for similar results in relation to the inhibition function). Taken together, these experiments suggest that anxiety more readily affects attentional control and cognitive performance for individuals with low working memory capacity. Other studies have directly manipulated demands on working memory.

Increasing cognitive load on working memory resources has been shown to affect attentional control both generally (e.g., Unsworth, Schrock, & Engle, 2004), and also compound the effects of anxiety (e.g., Berggren, Richards, Taylor, & Derakshan, 2013; Qi et al., 2014) in simple laboratory-based tasks. Berggren and colleagues (2013) investigated the combined effects of trait anxiety and experimentally manipulated cognitive load on inhibitory functioning using an antisaccade task. Cognitive load was manipulated by varying the complexity of an auditory tone recognition task. Results showed that individuals with high trait anxiety scores had slower saccade latencies during antisaccade trials, which is where gaze must be directed away from visual stimuli presented on a screen. Importantly, this effect was magnified when the tone recognition task was more cognitively demanding. Kinrade, Jackson, & Ashford (2010) examined the influence of anxiety and task complexity on various cognitive and motor tasks. They found, for example, that error-rates for modular arithmetic problems that placed greater demands on working memory (i.e., high complexity), were detrimentally affected by anxiety to a greater extent than less demanding problems.

A limited number of studies have examined the effects of working memory demands on performance and gaze behavior in more complex visual-motor tasks (e.g., Nibbeling et al., 2012; Williams, Vickers, & Rodrigues, 2002). Findings from these studies are less homogenous than simple laboratory tasks. For example, Nibbeling et al. (2012) asked expert and novice darts players to perform a dart throwing task while both anxiety and cognitive load was manipulated. Cognitive load was manipulated by asking participants to either simply perform the darts task solitarily, or whilst counting backwards in steps of three from a large random number. Anxiety only negatively affected the dart performance of novices, and this performance decrement was accompanied by a shorter goal-directed fixation on the target before movement initiation. Cognitive load led to longer dart times, however there was little evidence for any main or interactive effects on gaze behavior. Using a similar design with a table tennis task, Williams et al (2002) did find evidence of an interaction between cognitive load and anxiety. Specifically, in the high working memory condition (which involved a more complex shot pattern), anxiety produced a greater reduction in performance efficiency and led to a changes in gaze behavior that were not observed in the low working memory condition (players spent more time tracking the ball).

The primary aim of the present study was to further examine the combined effects of anxiety and cognitive load on gaze behavior and performance during a complex, continuous visual-motor task. A secondary aim was to replicate the findings of Allsop and Gray (2014) whilst also ameliorating the aforementioned concerns regarding the training protocol. Participants therefore learnt an aviation landing task in instrument meteorological conditions where visibility was always low. If results were similar across both experiments then the lack of high-visibility trials early in learning mean that reinvestment explanations can be rebutted. After training, participants then completed landings whilst performing a secondary auditory task (the *n*-back task) in both neutral and anxiety conditions. There were two difficulty levels for this task. According to ACT, the influence of anxiety on attentional control and performance should be exacerbated when the demands on working memory are high. The study was therefore designed to test the following hypotheses:

Hypothesis 1: In anxiety conditions there would be significantly greater dwell time on the outside world. The rationale here was that anxiety leads to a reduction in inhibitory functioning, leading to an increased likelihood of attention being directed towards prepotent responses. Therefore as the outside world is ordinarily the preponent source of navigational information, anxiety conditions should result in more attention being directed towards this area of the visual scene even when it actual contains no task-relevant information.

Hypothesis 2: It was expected that there be an interaction between anxiety and cognitive load for dwell time on the outside world such that there would be a larger increase (from baseline to anxiety) when cognitive load was high than low. This prediction was based on the ACT prediction that anxiety-induced impairments in inhibitory functioning will be exacerbated when working memory is taxed. *Hypothesis 3:* In anxiety conditions there would be significant increase in scanning entropy as a result of less effective goal-directed attentional control and reduced ability to efficiently shift attention.

Hypothesis 4: It was expected that would be an interaction between anxiety and cognitive load for entropy such that this increase would be larger when cognitive load was high than when cognitive load was low. This prediction was based on the ACT proposal that attentional shifting will be impaired to a greater extent when both anxiety and demands on working memory are high.

Hypothesis 5: As individuals can react differently in anxious situations it was expected that there would be a positive relationship between the change in cognitive anxiety and change in entropy from neutral conditions to anxiety conditions (as was found in Allsop & Gray, 2014). Furthermore, a stronger relationship between these variables was excepted when cognitive load was high.

Method

Apparatus

X-Plane version 10 (Laminar Research) was used to simulate all landings. The simulated aircraft was a Cirrus Vision SPF50 with both the landing gear and flaps extended. Participants controlled the roll and pitch axes of the aircraft by using a Thrustmaster HOTAS Warthog joystick (Guillemot, Montreal, Canada) with their right hand (see Figure 5.1).

Auto throttles maintained indicated airspeed at 51.4 m s^{-1} (100 knots). Flight data was recorded at a rate of 52 Hz. A back-projection system (Christie Mirage S+3K DLP; 101 Hz) rendered the external world onto a large screen (2.20 x 1.92 m; 1400 x 1050 pixels). The simulator was edited to display the external scene on the upper half of this screen (0.96 m), with the lower half showing a black, blank screen. The simulator was also edited to display an instrument panel consisting of five electromechanical style instruments on a 'heads-down' TFT monitor (45 x 25 cm; 1600 x 1900 pixels). The five instruments were: attitude indicator (AI), altimeter (Alt), instrument landing system course deviation indicator (ILS), heading indicator (Hdg) and vertical speed indicator (VSI). The viewing distance for the projection screen and heads-down monitor were 1.8 and 1.0 m, respectively. A remote video-based eyetracking (faceLAB; SeeingMachines) system was used to record eye movements (precision < 1.0°) at a rate of 60 Hz. A pair of headphones (Beyerdynamic DT770 Pro) were used to deliver the cognitive load task. To respond to the cognitive load task, participants used their left hand to push a button on a custom-made USB 'collective' joystick.

Figure 5.1. Photograph of the experimental setup showing the heads-down instrument panel, back-projection screen, control devices and eye-tracking cameras

Task

The landing task began with the aircraft positioned 11.11 km (6 nautical miles) away from the runway. The objective of the task was to land the aircraft by accurately following an ideal approach path to the runway. The ideal path is comprised of both vertical and lateral components. The vertical component, termed the glide slope, is a 3º plane extending upwards from the end of the runway. The lateral component is simply an extension of the runway centreline. At the start of each landing trial, the aircraft was positioned on the ideal path and orientated (heading, roll and pitch) for the ideal approach. Every trial was performed in low visibility, instrument meteorological conditions (IMC), where visibility was set to 1.2 km. Participants therefore needed to use cockpit instruments in order to follow this ideal path. Wind speed was set to 10.3 m s^{-1} (20 knots) for all trials, however, the direction was varied based on the experimental phase, as further detailed below. Numerical and visual performance feedback was provided by a custom-made program upon completion of each trial. Numerical feedback consisted of the separate performance errors (see measures section) from the ideal vertical and lateral paths. Visual feedback consisted of a graphical representation of the ideal vertical and lateral paths compared against the participants' actual paths.

Participants

Sixteen participants (11 Male, 5 Female; mean age = 26.6, *SD* = 3.8) completed the study. All participants were right handed, reported normal or corrected vision and had no previous experience of real or simulated fixed-wing flight. Participants were remunerated in return for their participation at a rate of 8 euros per hour. Ethical approval was granted by The University of Birmingham Ethics committee and informed consent was gained from all.

Measures

Performance

Flight performance was operationalised using a vertical deviation metric used in previous studies (Allsop & Gray, 2014; Gibb, Schvaneveldt, & Gray, 2008; Gray, Geri, Akhtar, & Covas, 2008). Specifically, the root mean square error (RMSE) of the vertical deviations from the ideal 3° glideslope was calculated. This RMSE was derived directly from data displayed on the ILS instrument, with the unit of measurement therefore being in dots. In X-Plane, one glideslope dot represents a 0.28° error. The custom feedback program automatically calculated and displayed lateral error in an identical manner, with one lateral dot equalling a 1.5° error; this was displayed along with the vertical error data at the end of each flight.

Cognitive Anxiety

Cognitive state anxiety was measured using the Competitive State Anxiety Inventory 2-revised (Cox, Martens, & Russell, 2003), which has two subscales that provide typical thoughts and feelings associated with cognitive (5 items) and somatic anxiety (7 items). Only the cognitive anxiety subscale was used in the present research. An example item from this subscale is “I’m concerned about performing poorly”. Participants are then asked to rate, on a four point scale ranging from 1 (not at all) to 4 (very much so), whether the item is indicative of their thoughts and feeling. In accordance with Cox et al. (2013) the overall cognitive anxiety score was obtained by multiplying the averaged item response by ten. Cognitive anxiety was measured after each flight in the experimental phase.

Heart Rate

Heart rate was measured using a chest-strap heart rate monitor (Garmin Model HRM1G) to provide confirmatory physiological evidence of the effectiveness of the anxiety manipulation. The chest strap was positioned on the lower-mid thorax and it wirelessly transmitted heart rate data to a laptop. Data was recorded during each experimental trial at a rate of 1 Hz, with an average then being calculated for the trial.

Gaze Behavior

Raw horizontal and vertical screen coordinates on both the external world and instrument panel were stored in data files provided by the eye-tracker recording software (Facelab, Version 5; Seeing Machines). A custom-made Python script converted these coordinates into fixations using a dispersion threshold identification algorithm (c.f. Salvucci

& Goldberg, 2000). The minimum fixation threshold was set to 150 ms in accordance with previous similar research (Huemer et al., 2005). Fixations were assigned to six areas of interest (AOIs) based on the AOI screen coordinates and were confirmed manually. These AOIs were: external view, attitude indicator, altimeter, instrument landing course deviation indicator, heading indicator and vertical speed indicator. Fixation data was converted into dwells to provide dwell frequencies and durations. In order to examine general changes in attentional allocation, the various instrument panel AOIs were combined into one single instrument panel AOI. Percentage dwell times on this AOI and the external world AOI were used as dependent measures.

Scanning entropy, which indicates the randomness of scanning behavior, was calculated using Stark and Ellis' (1986) methodology in an identical manner to Allsop & Gray (2014). Higher values on this metric indicate more random scanning behavior, whereas lower values indicate more predictable scanning behavior.

Procedure

Each participant visited the lab on two occasions separated by a maximum of one week, with each session lasting approximately two hours. The experiment was split into an acquisition phase which was then followed by an experimental phase. The acquisition phase developed the participants' ability to perform the landing task. In the experimental phase, both cognitive anxiety and cognitive load were manipulated.

Acquisition phase

Participants completed a total of 22 acquisition trials, with 13 trials being completed in the first session and 9 in the second. In order to ensure that participants used the cockpit instruments, rather than adopting a similar movement strategy for each trial, the simulated wind was randomly set for the first 19 acquisition trials. Specifically, the wind direction was randomly chosen from one of 4 angles: 20º, 160º, 200º and 340º; where 0º represents a direct headwind. For the final three acquisition trials, wind was set to 160º.

At the start of the first session, after providing informed consent, the participants were seated in the simulator and an eye-tracker calibration was performed. This was merely to check for any participant-based gaze tracking issues. After confirming that there were no tracking issues, participants were given an information sheet that provided details and pictorial representations of the flight task and the cockpit instruments. The experimenter then verbally explained the task and the cockpit instruments, as well as providing a recommended order for fixating on the instruments. This order was based on recommendations by a certified flight instructor to aid motivation and acquisition of the task. The recommended order was as follows: ILS to AI, AI to HDG, HDG to VSI and VSI to ILS. Participants then watched a demonstration of the flight task by the experimenter. Following this, participants completed a 5 minute free-flight to acclimatise to the simulator, controls and cockpit instruments. Next, the participant began the actual acquisition trials. Due to the initial difficulty of the task, the experimenter supplemented the output from the feedback program with verbal feedback upon completion of each of the first three trials. At the start of the second session, the eye-tracker was calibrated and the heart rate monitor was positioned and checked. Eye-tracker calibration was checked before each trial throughout the second session. The participant then completed the remaining 9 acquisition trials.

Experimental phase

In the experimental phase, both cognitive anxiety and cognitive workload was manipulated in a 2 cognitive load (Low, High) x 2 anxiety condition (Netural, Anxiety) within-subjects design (for further details, see the cognitive load and anxiety manipulation sections below). Therefore all participants performed a total of four trials in this phase. The order of these trials was counterbalanced across participants, with half of the participants completing the anxiety trials first and half completing the neutral trials first. The ordering of cognitive load conditions was also counterbalanced across participants, the ordering was the same in neutral and anxiety conditions. Wind direction was set to 160º for all trials.

At the start of this phase participants were informed that for the remaining trials they would be required to perform an auditory task at the same time as performing the landing task. It was emphasised that both tasks were of equal importance. Participants were then given four approximately one minute practice attempts on the cognitive load task (one low-load attempt and three high-load attempts) without performing the flying task to acclimatise (these were not recorded). Once completed, the participant moved onto the experimental trials. The data recording for the cognitive load task, flight performance, heart rate and gaze behavior commenced at the start of each trial. This data was saved upon trial completion and cognitive anxiety was measured. Participants were debriefed upon completion of all the experimental trials.

Cognitive load manipulation

An auditory *n*-back task (Kirchner, 1958) was used to manipulate cognitive load. This task consisted of a series of auditory stimuli that were sequentially played at an interstimulus interval of two seconds (Kane, Conway, Miura, & Colflesh, 2007). For each stimulus, the participant was instructed to respond as quickly and accurately as possible if it was a target. In the low cognitive load condition, *n* was set to 0. This means that participants simply listened for one specific, pre-disclosed, target stimulus. Participants were instructed on the target stimulus beforehand. In the high cognitive load condition, *n* was set to 2. In this condition, a stimulus is a target only when it is the same as two stimuli before. The auditory stimuli consisted of a pool of 14 consonants. Across both conditions, 25% of stimuli were targets. Reaction time and percentage accuracy were measured. Incorrect responses were excluded from reaction time analyses as were responses of less than 300ms (no responses fell below this duration threshold).

Anxiety manipulation

Anxiety was manipulated using a combination of monetary incentives and ego-threatening instructions. A nearly identical manipulation was employed by Allsop and Gray (2014) and similar manipulations have previously been shown to successfully increase anxiety in a variety of other experiments (e.g., Cooke, Kavussanu, Mcintyre, Boardley, & Ring, 2011; Williams et al., 2002). For neutral, low-anxiety trials the instruction to participants was simply to "perform the best they can". For high-anxiety trials, the manipulation consisted of three main steps. Firstly, immediately before commencing the high anxiety trials, participants were informed that they were now entering a phase of the experiment where they could win 50 euros based on the combined performance over the next two trials. Specifically, participants were told that they would be ranked against everyone else taking part, and that the person with the best performance, which is the lowest RMSE, would be rewarded. A leaderboard sign was then revealed and participants were told that the complete leaderboard would be e-mailed to participants at the end of the study. Secondly, a video camera (Sony DCR-TRV890E) was overtly set-up and mounted on a tripod behind the participant. Participants were informed that both trials would be recorded and potentially used in upcoming conference presentations and lectures based on whether their performance was significantly below average.

Participants were also told that they would be flying in an online virtual environment called the Virtual Air Traffic Simulation Network, the experimenter loaded a custom-made program that allowed a mock log-in and connection to be made. Care was taken to ensure this deception was not suspected. Specifically, upon entering the log-in details, the program displaying a command-line interface diagnosing and establishing the connection. Then the program opened a world-mapping program (Marble, Version 1.6) which was edited to show a top-down view of the airport and surrounding area. The area was populated with a number of aircraft and extended trail history indicators. Participants were debriefed on the true nature of the experiment upon completion of all trials.

Statistical Analyses

Glideslope RMSE, cognitive anxiety, heart rate, *n*-back percentage correct, *n*-back reaction time, transition frequency and scanning entropy were analysed using separate 2 anxiety condition (neutral conditions, anxiety conditions) x 2 cognitive load (low cognitive load, high cognitive load) repeated measures ANOVAs. To examine whether anxiety and cognitive load affected attentional allocation, percentage dwell time data was submitted to a 2 anxiety condition (neutral, anxiety) x 2 cognitive load (low, high) x 2 AOI (external, instruments) repeated measures ANOVA. Significant effects were analysed using Tukey's HSD post hoc procedures ($p < .05$).

In accordance with hypothesis five and previous research (Gray, Allsop, & Williams, 2013; Vytal, Cornwell, Arkin, & Grillon, 2012), analyses were performed in order to examine whether an individual's response to the anxiety manipulation may be related to scanning entropy, and also whether cognitive load may moderate this relationship. Similar to the within-subject mediation and moderation procedure outlined by Judd, Kenny, & McClelland (2001) difference scores between neutral conditions and anxiety conditions for both low- and high cognitive load conditions, were created for the cognitive anxiety, entropy and performance variables. Three linear regressions were then performed.

Firstly, the simple overall relationship between change in entropy and anxiety, independent of any potential moderation effects, was investigated by collapsing the high and low cognitive load data. Change in entropy was then regressed onto change in cognitive anxiety. To investigate whether cognitive load may moderate any relationship between change in cognitive anxiety and change in entropy, two separate linear regressions were performed for data from the low and high cognitive load conditions. Raghunathan, Rosenthal, & Rubin's (1996) modification of the (Pearson & Filon, 1898) statistic was then used to formally compare whether there was a difference in the relationship between change in cognitive anxiety and change in entropy based on cognitive load. A final individual response analysis was performed to investigate the relationship between entropy and performance in an identical manner to Allsop & Gray (2014). Specifically, the correlation between change in entropy and change in performance was examined.

Results

Performance

The analysis of glideslope RMSE data (See table 5.1) revealed a non-significant main effect for anxiety condition, $F(1,15) = 0.16$, $p = .90$, $\eta_p^2 = .001$, a significant main effect for cognitive load, $F(1,15) = 4.62$, $p = .048$, $\eta_p^2 = .24$, and a non-significant Anxiety condition x Cognitive load interaction, $F(1,15) = .15$, $p = .70$, $\eta_p^2 = .01$. Examination of the main effect for cognitive load showed that performance deteriorated in high cognitive load conditions. In sum, performance was maintained in anxious conditions, but deteriorated when cognitive load was high.

Anxiety

Cognitive Anxiety

Mean cognitive anxiety data is displayed in figure 5.2. The analysis revealed a significant main effect for anxiety condition, F(1,15) = 10.19, p = .006, η_p^2= .41, a significant main effect for cognitive load, F(1,15) = 6.62, p = .02, η_p^2= .31, and a non-significant interaction between Anxiety condition and Cognitive load, F(1,15) = 1.62, p = .22, η_p^2= .10. Examination of the main effects revealed that anxiety was higher in the anxiety condition relative to the neutral condition and higher in the high cognitive load condition relative to the low load condition.

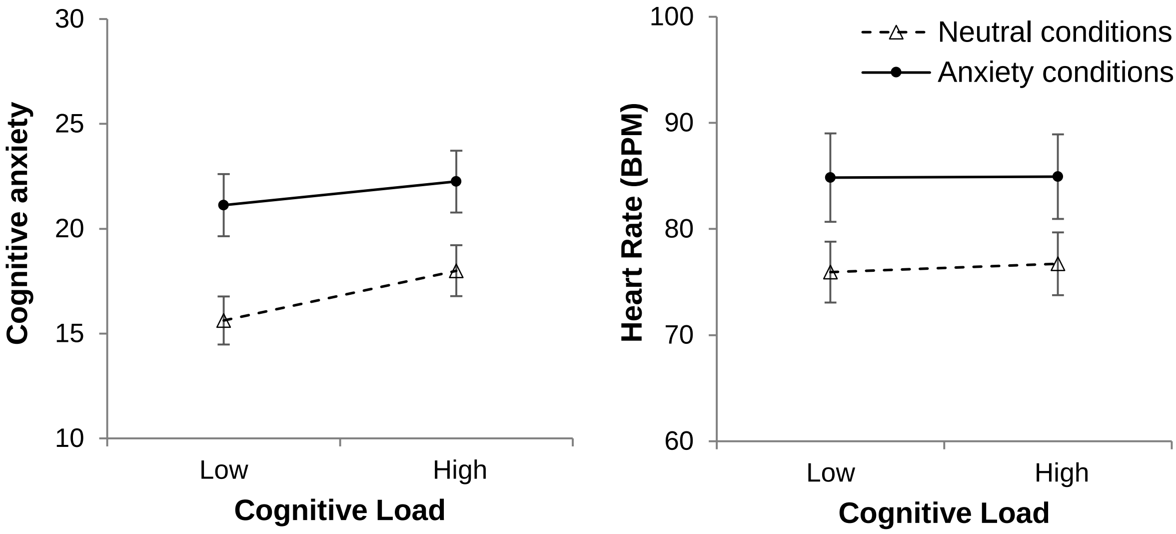

Figure 5.2. Mean cognitive anxiety (left panel) and heart rate (right panel) plotted as a function of cognitive load in neutral (dashed line) and anxiety (solid line) conditions. Error bars represent standard errors of the mean.

Heart Rate

Heart rate data is displayed in figure 5.2. The analysis on this data revealed a significant main effect for anxiety condition, F(1,15) = 18.07, p = .001, η_p^2= .55, a non-significant main effect for cognitive load, F(1,15) = .36, p = .56, η_p^2= .02, and a non-significant interaction between Anxiety condition and cognitive load, $F(1,15) = .26$, $p = .62$, $\eta_p^2 = .02$. Heart rate was higher in the anxiety conditions.

N-back task

Data from two low workload trials were lost due to a computer error at the end of the trial (1 neutral, 1 anxiety trial). Listwise deletion removed these participants from the analyses, the pattern of results remains unchanged when using mean substitution.

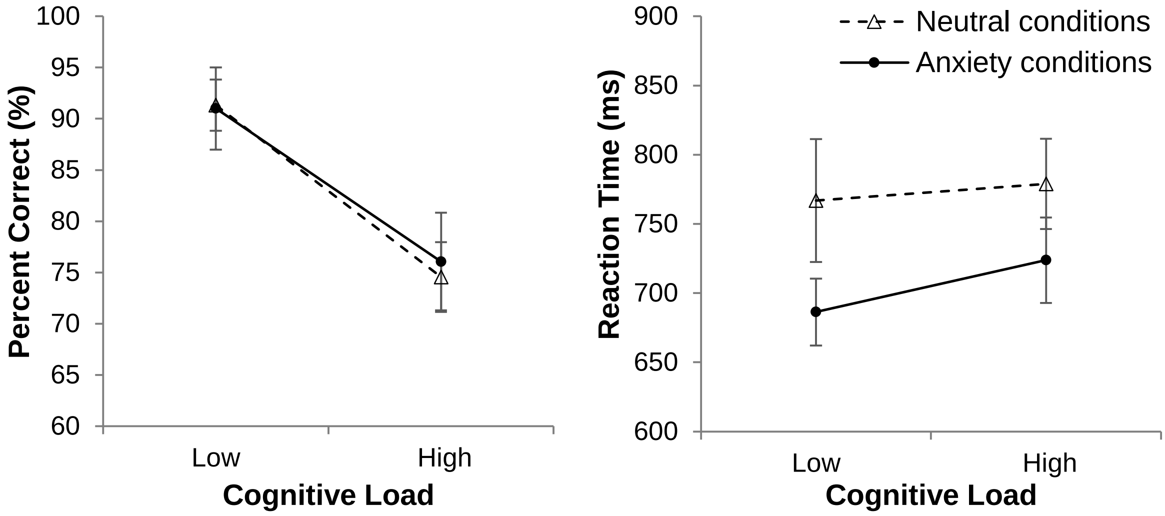

Figure 5.3. Mean *n*-back percent correct (left panel) and reaction time (right panel) plotted as a function of cognitive load in neutral (dashed line) and anxiety (solid line) conditions. Error bars represent standard errors of the mean.

Percentage Correct

Percentage correct data is displayed in figure 5.3. The analysis revealed a non-significant main effect for anxiety condition, $F(1,13) = .13$, $p = .73$, $\eta_p^2 = .01$, a significant main effect for cognitive load, $F(1,13) = 49.59$, $p < .001$, $\eta_p^2 = .79$, and a non-significant interaction between Anxiety condition and Cognitive load, $F(1,13) = .001$, $p = .98$, $\eta_p^2 = .00$. More incorrect *n*-back responses were made in 2-back conditions.

Reaction Time

Reaction time data is displayed in figure 5.3. The ANOVA conducted on this data revealed a significant main effect for anxiety condition, $F(1,13) = 7.64$, $p = .016$, $\eta_p^2 = .37$, a non-significant main effect for cognitive load, $F(1,13) = 1.52$, $p = .24$, $\eta_p^2 = .1$, and a non-significant interaction between anxiety condition and cognitive load, $F(1,13) = .35$, $p = .56$, $\eta_p^2 = .03$. Examination of the main effect for anxiety showed that reaction time was shorter in anxiety conditions.

Table 5.1. *Mean (SD) Glideslope RMSE, Transition Frequency and Scanning Entropy in neutral and anxiety conditions and low and high cognitive load conditions*

	Neutral Conditions		Anxiety Conditions	
Measure	Low cognitive load	High cognitive load	Low cognitive load	High cognitive load
Glideslope RMSE (dots)	0.46 (0.27)	0.53 (0.35)	0.44 (0.23)	0.53 (0.26)
Transition frequency	187.81 (27.45)	169.63 (36.53)	188.88 (33.68)	166.50 (34.59)
Scanning entropy	1.38 (0.18)	1.41 (0.18)	1.44 (0.20)	1.40 (0.19)

Gaze Behavior

Percentage Dwell Time

Figure 5.4 shows the mean percentage dwell time data. The analysis revealed a marginally significant interaction between anxiety condition and AOI, $F(1,15) = 4.15$, $p = .06$, $\eta_p^2 = .22$,and a non-significant interaction between cognitive load and AOI, $F(1,15) = 1.35$, $p = .26$, $\eta_p^2 = .08$. The marginally significant interaction between anxiety conditions and AOI was explored by examination of the mean data. This data shows a tendency for percentage dwell time on the outside world to be higher, and percentage dwell time on the instruments to be lower, in the anxiety conditions when compared to the neutral conditions.

The Anxiety condition x Cognitive load x AOI interaction was non-significant, $F(1,15) = .236$, $p = .63$, $\eta_p^2 = .02$, suggesting that the tendency to look towards the outside world in anxiety conditions was not exacerbated by high cognitive load.

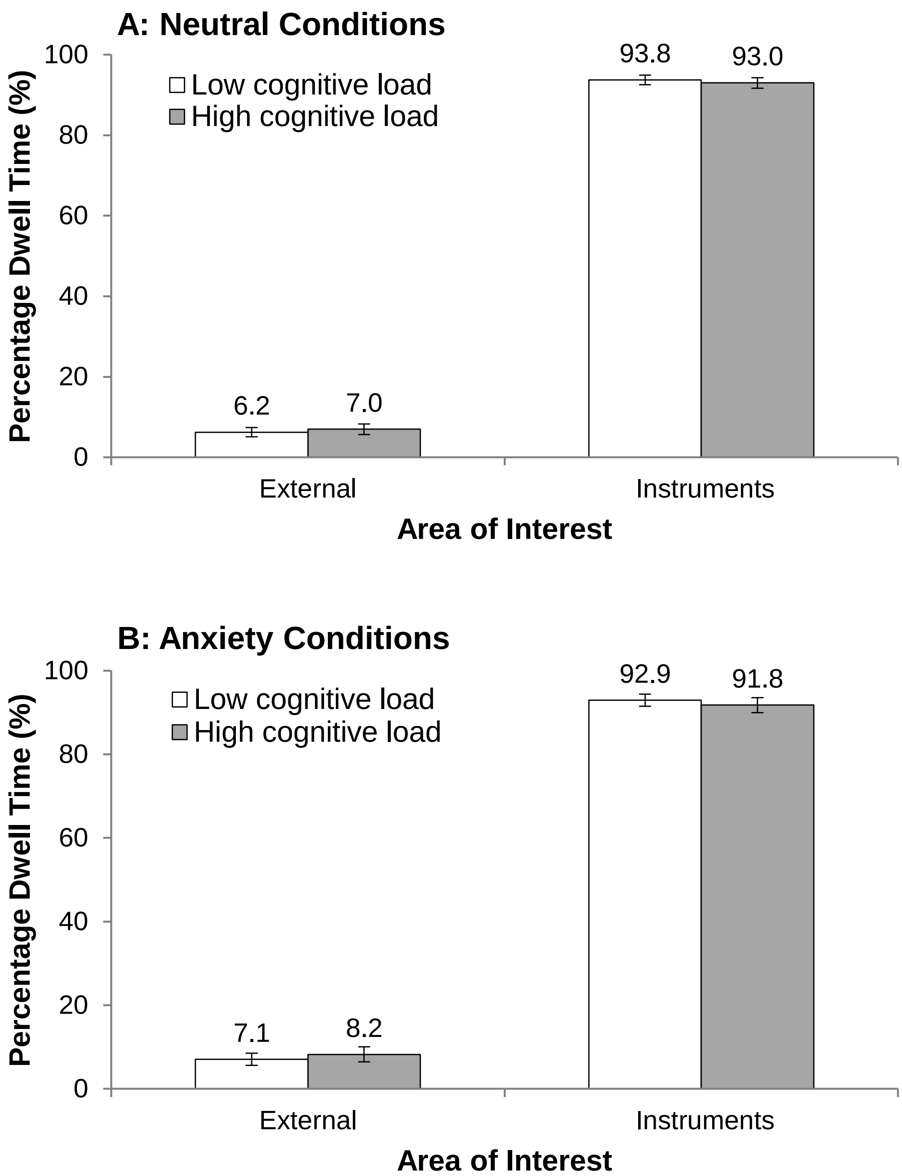

Figure 5.4. Mean percentage dwell time on the external world and the generalised instrument panel AOIs, in the neutral conditions (Panel A) and anxiety conditions (Panel B) in low cognitive load and high cognitive load conditions. Error bars represent standard errors of the mean.

Transition frequency

Table 5.1 shows the transition frequency data. The ANOVA conducted on this data revealed a non-significant main effect for anxiety condition, $F(1,15) = .05$, $p = .82$, $\eta_p^2 = .003$, a significant main effect for cognitive load, $F(1,15) = 22.78$, $p < .001$, $\eta_p^2 = .60$, and a non-significant interaction between anxiety condition and cognitive load, $F(1,15) = .41$, $p = .53$, $\eta_p^2 = .03$. Less transitions between areas of interest were made in high cognitive load conditions in comparison to low cognitive load conditions.

Scanning Entropy

Mean scanning entropy data is displayed in table 5.1. The ANOVA conducted on this data revealed a non-significant main effect for anxiety condition, $F(1,15) = .30$, $p = .59$, $\eta_p^2 = .02$, a non-significant main effect for cognitive load, $F(1,15) = .23$, $p = .88$, $\eta_p^2 = .002$, and a non-significant Anxiety condition x Cognitive load interaction, $F(1,15) = 2.27$, $p = .15$, $\eta_p^2 = .13$. Somewhat surprisingly, the experimental manipulations had no significant effects on scanning entropy.

Individual Responses to Anxiety Manipulation

For the sake of brevity, change in cognitive anxiety, change in entropy and change in performance will be referred to as Δcognitive anxiety, Δentropy and Δperformance respectively, for the remainder of this section. When data was collapsed across cognitive load, Δcognitive anxiety was a marginally significant predictor of Δentropy, $b = .009$, 95% CI [-.001, .19], $t = 1.867$, $p = .07$, explaining 10% of the variance in entropy scores. The role of cognitive load was then examined (see figure 5.5). For low cognitive load conditions, Δcognitive anxiety did not significantly predict Δentropy, $b = .002$, 95% CI [-.013, .17], $t = 0.23$, $p = .82$ and did not explain a significant proportion of the variance in Δentropy scores,

R^2 = .004. However, when cognitive load was high, Δcognitive anxiety was a significant predictor of Δentropy, *b* = .015, 95% CI [.001, .03], *t* = 2.32, *p* = .036, explaining 28% of the variance. There was also a significant difference between the correlation coefficients, *z* = 1.72, *p* = .028. This suggests that cognitive load appears to have moderated the relationship between Δcognitive anxiety and Δentropy, with the positive relationship being stronger when cognitive load was high, than when cognitive load was low. The final analysis revealed that there was no relationship between Δentropy and Δperformance, either when collapsed across cognitive load or when analysed separately (all *p*' > .1).

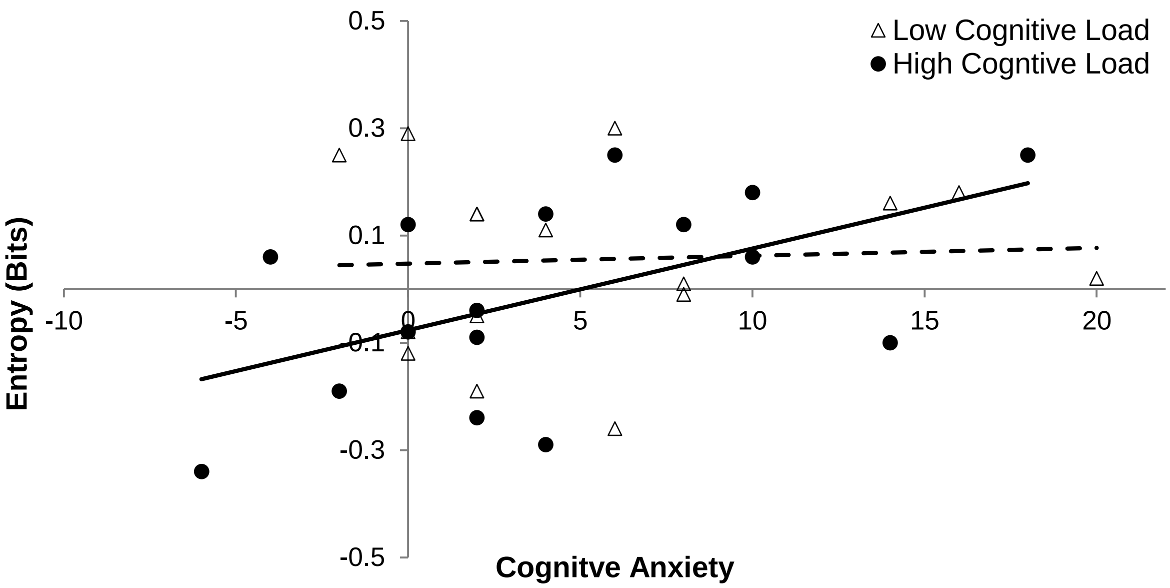

Figure 5.5. Regression lines of the relationship between cognitive anxiety and entropy in high (solid line) and low cognitive load (dashed line) conditions. Entropy refers to the difference between neutral and anxiety conditions (higher scores indicate an increase in entropy). Similarly, cognitive anxiety refers to the difference between neutral and anxiety condition scores.

Discussion

The present studied aimed to investigate the combined effects of anxiety and cognitive load on gaze behavior and performance in a complex, continuous visual-motor task. Anxiety was manipulated using a combination of ego-threatening instructions and monetary incentives. Self-reported cognitive anxiety scores supported the effectiveness of the manipulation, with average cognitive anxiety increasing across anxiety conditions. This offers supportive evidence for the use of such manipulations when aiming to investigate the effects of anxiety. Participants also had more concerns and became more doubtful of their ability to perform in high cognitive load conditions, as evidenced by an increase in cognitive anxiety. Previous research has commonly either measured anxiety on one occasion, rather than for every combination of conditions (e.g., Williams et al., 2002), or calculated an average for just each anxiety condition (e.g., Berggren, Hutton, & Derakshan, 2011). Nibbeling et al., (2012) did however measure anxiety in all anxiety and cognitive load conditions and found similar results. In conjunction with the present study, this suggests an additive effect of cognitive load and anxiety manipulations on cognitive anxiety.

The anxiety manipulation was also validated by a significant increase in heart rate, abating concerns associated with self-report measures. An 8.5 bpm average increase in heart rate was found, which is a comparable (e.g., Cooke et al., 2011) or slightly larger increase than other studies employing similar anxiety manipulations (e.g., Moore et al., 2012). These overall average anxiety responses do however mask individual differences in response to the anxiety manipulation. The present study accounted for this by performing additional analyses at an individual level. Future studies could seek to adjust the manipulations in order to produce more uniform increases in anxiety. Taking into account dispositional, trait anxiety, may also be beneficial.

Cognitive load was successfully manipulated by the auditory *n*-back task with high cognitive load trials having lower percentage accuracy scores than low cognitive load trials. Importantly, reaction time remained consistent across cognitive load conditions, suggesting that the decrease in percentage accuracy resulted from the increased demands of the 2-back condition rather than a speed-accuracy tradeoff. Interestingly however, anxiety conditions were accompanied by a decrease in reaction time, while accuracy was maintained. There are a number of likely explanations for this finding. The most parsimonious explanation is that anxiety may have served a motivational function, leading to a liberation of processing resources and more on-task effort. This increase in effort may therefore have meant that participants were better able to expediently respond to the *n*-back task. A number of previous studies support this line of reasoning, with self-reported effort consistently accompanying anxiety (Cooke et al., 2011; Wilson, Smith, & Holmes, 2007). The present study offers behavioral evidence for an increase in effort. Alternatively, it is possible that participants may have employed a strategy which aimed to expedite responses in an attempt to prioritise the flight task, at the expense of the *n*-back task. This seems less likely as accuracy would be expected to suffer as result, which wasn't the case.

According to ACT, anxiety leads to a disruption in the balance between a stimulus-driven attentional system and a goal-directed system, with the former taking precedence over the latter. The results of the present study lend some support to this prediction. Specifically, anxiety was accompanied by an increase in the percentage dwell time directed towards the outside world and a corresponding decrease on the cockpit instruments. Although this result was only marginally significant ($p = .06$), the finding is broadly in-line with the results of Allsop & Gray (2014). It is probable that statistical significance may have not been reached due to the relatively small sample size of the current study. Importantly, in the present study this result cannot be explained by reinvestment theory as participants learnt how to perform the flight task in instrument meteorological conditions from the very start of training. Therefore they could not be reverting to gaze strategies developed early in learning, as simulated visibility conditions were consistent throughout the experiment. Across both studies, anxiety seems to have led people to look towards the outside world, even though this view provides no task relevant information.

No evidence was found for a larger increase in dwell time towards the outside world when both anxiety and cognitive load was high (i.e., an interaction between anxiety and cognitive load). It is somewhat difficult to interpret this finding. In previous research it has been shown that increased cognitive load can result in longer dwell times on the instruments and decreased dwell time on the external environment in novice pilots (Tole et al, 1992). In the present study, the same pattern of results was obtained (see Figure 3), however, the effect of cognitive load on attentional allocation was not significant. Given the findings of previous research, it is possible that the effects of anxiety and cognitive load worked to cancel other out. In other words, increased cognitive load acted to maintain or restrict gaze behavior to current cues (e.g., Tole et al., 1992), whereas anxiety seems to increase allocation towards task irrelevant stimuli. Future studies should aim to test the original hypothesis with larger samples to ensure sufficient power if an underlying effect is present.

The hypothesized increase in scanning entropy during anxiety trials was surprisingly not supported. Instead, scanning entropy remained consistent across all conditions. However, a different picture emerged when the hypothesised individual differences in response to the anxiety manipulation were taken into account. Specifically, when collapsing across cognitive load, a marginally significant positive relationship was found between change in entropy and change in cognitive anxiety scores, from neutral to anxiety conditions.

A supplementary median-split analysis approach is presented in Appendix A. This alternative approach shows with greater clarity that an individual's response to the anxiety manipulation was most likely responsible for the null effect. While unexpected, this result dovetails with Vine and colleagues' (2014) study which showed that an individual's reaction to a stressful event significantly predicted entropy. Taken together, these results suggest that increased entropy reflects an anxiety-induced decrease in attentional control as predicted by ACT. The hypothesized influence of cognitive load on this relationship was partially supported.

The predicted interaction between cognitive load and anxiety conditions on entropy was not supported. However, this was most likely again due to the individual differences in response to the anxiety manipulation. In support of this assertion, cognitive load was found to moderate the relationship between an individuals' response to the anxiety manipulation and their change in entropy. Specifically, a positive relationship between change in cognitive anxiety and change in entropy was only found for high cognitive load conditions. Whereas no relationship was found when cognitive load was low. This finding offers some support for the predictions of ACT and previous studies showing interactive effects of cognitive anxiety and cognitive load on attentional control in simple tasks (e.g., Berggren et al., 2013; Qi et al., 2014). It also tentatively suggests that performing tasks in both cognitively demanding and anxiety-laden situations has the potential to lead to more random gaze behavior.

Alternative theoretical accounts should be considered when interpreting the results of the present study. Lavie's (Lavie & Tsal, 1994; Lavie, 1995, Lavie, 2010) perceptual load theory aims to isolate the circumstances in which irrelevant stimuli will capture attention. Summarily, the theory suggests that perceptual processes have a limited capacity, these processes are said to proceed until spare capacity is exhausted (Murphy, Groeger & Greene, 2016). For instance, a task that is high in perceptual load may mean that that capacity limits are reached and distractors cannot be processed. On the other hand, when perceptual load is low, spare capacity is available to process both the primary task and irrelevant distractors. Research originally focused on perceptual, rather than post-perceptual load (e.g. Lavie, 1995). Example manipulations of perceptual load included: changes to the number of items displayed on a computer screen or changes to the complexity of auditory tone recognition task (e.g., Sabri, Humphries, Verber, Mangalathu, Desai, Binder & Liebenthal, 2013). On the whole, results showed that when perceptual load was high, interference from distracting, irrelevant, stimuli was minimised (e.g., Lavie, 1995; Lavie & Cox, 1997).

Recent revisions to the theory (Lavie, 2005) have included the dissociable effects of both perceptual, and cognitive load on distractor interference. Perceptual load theory suggests that cognitive load has the opposite effect to perceptual load, acting to increase distractibility (paralleling predictions of ACT). Therefore, it could be stated that a possible combination of these sets of predictions led to, in the present experiment: anxiety acting to increase cognitive load, leading to an increase in distractibility (indexed by entropy and time spent looking to the external world), whereas the auditory *n*-back task acted, at least partially, to increase perceptual load, leading to a decrease in distractibility. However, if this was the case, differences in distractibility should have been evidenced in neutral conditions. Specifically, if perceptual load was increased by the *n*-back task, a decrease in distractibility should have been evident in the neutral, high-cognitive load, condition. Furthermore, the *n*-back task has previously been shown to correlate with higher level working memory functions (Gray, Chabris & Braver, 2003) and is quite different in nature to tasks used in auditory, or cross-modal, perceptual loading experiments (e.g., long versus short auditory tones). Nonetheless, it will be important for future research to incorporate perceptual load theory when trying to disentangle the interactive effects of anxiety and cognitive load on performance and attention.

It appears however that the combined effects of cognitive anxiety and cognitive load on attentional control are less discernible in complex visual motor skills. Across several studies, the combined effects of anxiety and either cognitive load (e.g., Nibbeling et al., 2012; Williams et al., 2003) or working memory capacity (Wood, Vine, & Wilson, 2015) on gaze behavior are far from clear. It is possible that certain gaze behavior metrics may not be a sensitive enough proxy measure of attentional control. In the current study, gaze data was modelled as a Markov process which allowed changes to the sequencing of dwells to be investigated. This methodology offered preliminary evidence of an interaction between anxiety and cognitive load on attentional control. This could however be taken a step further by employing hidden Markov models to infer underlying psychological states from gaze data. Of particular interest, such methods have successfully been employed in similar instrument landing tasks to accurately predict task switching (c.f. Hayashi, 1997). It may therefore be possible to use this technique to more directly detect changes to attentional control as a result of anxiety. This would be particularly novel, as it could elucidate the specific underlying changes that occur, such as less efficient task switching, as a result of anxiety. This level of specificity is usually only possible in more 'process pure' laboratory tasks.

Task performance in the present study mirrored the findings of Allsop & Gray (2014) and other complex continuous visual motor studies (Wilson, Chattington, Marple-Horvat, & Smith, 2007) with no significant change in performance error across anxiety conditions. Unlike Allsop & Gray (2014), performance changes from pre-test to anxiety conditions did not correlate with change in entropy either. It should be noted however that the flight task in the current study did not require any interception manoeuvres to obtain the perfect approach path. Instead, participants were required to track and follow the perfect path after being correctly positioned at the start of the trial. The present task may therefore not have been demanding enough for this relationship to emerge.

Collating the results across studies, it may suggest that continuous tasks are less susceptible to anxiety induced performance failures. Continuous tasks inherently offer greater opportunity for compensatory strategies to be developed or employed than discrete tasks. For instance, performance decrements for certain portions of each trial may be recovered during other portions. However, other research does not support the argument that continuous tasks are less prone to the effects of anxiety (Wilson, Smith, Chattington, Ford, & Marple-Horvat, 2006). The most likely explanation for the null effect in the current study is an increase in effort or cognitive resources. The reduction in *n*-back reaction time across anxiety conditions offers behavioral evidence to support this. Numerous studies have found that anxiety more readily affects performance efficiency than performance effectiveness. Indeed, compensatory effort has not only been connected with performance maintenance, but also performance increases in pressure situations (Mullen, Faull, Jones, & Kingston, 2012).

Cognitive load detrimentally impacted task performance in the present study which supports findings from numerous driving studies (e.g., Lei & Roetting, 2011; Reimer, Mehler, Wang, & Coughlin, 2012; Ross et al., 2014). Cognitive load has been shown to increase average dwell time on instruments (Tole, Stephens, Harris, & Ephrath, 1982) and decrease variability of gaze location (Riemer et al., 2012), both of which can consequently lead to fewer transitions between areas of interest over a given period. In line with these findings, increased cognitive load led to fewer dwell transitions in the current study. A likely consequence of this reduction was that each instrument was not ‘sampled’ frequently enough. This would mean that individual pieces of information were not being satisfactorily updated in order to sustain performance.

This study has revealed a number of interesting findings on the interaction between cognitive anxiety and cognitive load on gaze behavior and performance. However, the study is not without limitations and these should be considered when interpreting the results. Firstly, the participants in the current study were novices, future research should aim to examine these findings in other populations, such as expert pilots. Second and relatedly, the sample size was relatively low due to the inherent costs of training naïve participants. This may have meant that certain smaller effects could not be detected due to low power. Better powered studies should be pursued in future. Finally, participants were recommended a specific gaze pattern due to the initial difficulty of the task. It is possible that participants may have reverted to this gaze pattern in anxiety conditions, as per reinvestment theory, therefore potentially dampening any increases in entropy. Analyses presented in appendix B however offer evidence to quell this argument, but future studies could aim to test participants without any training instructions at all.

In conclusion, the present study investigated the combined effects of cognitive anxiety and cognitive load on the gaze behavior and performance of a complex visual motor task. Cognitive load negatively impacted performance and was accompanied by a reduction in transitions between areas of interest. Results also offered evidence in support the predictions of ACT. Anxiety led to a reduction in response time to auditory *n*-back task implying an increase in effort. Of particular interest, cognitive load moderated the relationship between individual changes in cognitive anxiety and entropy. It is hoped that this study will stimulate future research in this area.

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CHAPTER SIX

General Discussion

Summary of Findings

The aim of this thesis was to investigate the mechanisms that underpin visual-motor performance changes in pressurised situations. Experimental studies were designed in order to examine kinematic (chapter two) and attentional mechanisms (chapters three, four and five). The study presented in chapter two examined the effects of pressure on club head kinematics in a golf-putting task. Specifically, the study aimed to investigate whether the relationship between putt distance and downswing amplitude is affected by pressure. Predictions were based around self-focus theories of choking under pressure. Significant increases in self-reported cognitive and somatic anxiety intensity scores indicated that pressure was successfully manipulated. At a group-level, performance was not affected by pressure, however, analyses at an individual-level showed that responses to pressure varied across participants. Furthermore, correlations between individuals' changes in performance from pre-test to pressure conditions correlated with changes in the slopes of the relationship between putt length and downswing amplitude. This demonstrated that golfers who performed worse under pressure employed a smaller range of downswing amplitudes for different putt distances. These findings were explained in-line with self-focus theories by suggesting that pressure caused increased monitoring of movements. Alternative explanations were also outlined.

Chapter three investigated whether pressure leads to attentional narrowing by utilising a novel useful field of view (UFOV) test. The experiment also aimed to investigate whether the individual-level analysis technique utilised in chapter two would again show that performance variables related to mechanistic variables. Novice golfers performed the same putting task employed in chapter two, whilst also being asked to pause at regular intervals in order to perform the useful field of view task. Results indicated that participants who were subjected to a pressure manipulation reported higher cognitive and somatic anxiety intensity scores, and also perceived somatic anxiety symptoms as more debilitative. Pressure was shown to negatively affect UFOV performance, but only for targets presented at large visual angles. Consistent with chapter two, pressure had no group-level influence on performance. However, individual-level analyses again showed that changes in UFOV performance from neutral to pressure conditions correlated with performance changes. These results were interpreted as providing support for attentional narrowing effects, as pressure negatively impacted the processing of peripheral stimuli. Findings were also tentatively linked with golf-putting movement kinematics, such as those described in chapter two, by suggesting that changes to peripheral vision may interfere with the regulation of the downswing movement.

Following on from chapter three, the effect of pressure on attention was again investigated in chapters four and five. Specifically, both studies investigated the effects of pressure on attentional control in a different type of task, namely, a continuous instrument flight task. Predictions were based on attentional control theory. In chapter four, novice participants learnt how to perform the instrument flight task by attending a number of training sessions where the instruments were accompanied by a clear, or clouded, view of the external world in a trial-by-trial alternating manner. In a test session, gaze behavior was recorded using a head-mounted eye tracker, and a novel entropy metric was used to quantify the randomness of visual scanning. In order to extend upon previous chapters, heart rate was also measured (in both chapters four and five) in order to provide corroborating evidence to support the effectiveness of the pressure manipulation. Results again showed that pressure was successfully invoked for participants subjected to a pressure manipulation, this was evidenced by both an increase in cognitive anxiety and a concomitant increase in heart rate. Gaze data indicated that attentional control was impaired under pressure, with scanning becoming less predictable and a greater proportion of time spent fixating on task irrelevant information. Similar to previous chapters, pressure again had no overall effect on performance. However, individual-level analyses showed that changes in scanning randomness from neutral to pressure conditions were negatively correlated with performance changes, and also positively correlated with changes in cognitive anxiety. This suggests that attentional control may be influenced when pressure situations invoke cognitive anxiety, and also that performance may be affected when attentional control is impaired. A limitation of the training schedule meant that alternative reinvestment explanations could not be ruled out.

In order to replicate and extend upon the findings of chapter four, whilst also addressing the training limitation, chapter five investigated the effects of both pressure and cognitive load on attentional control and performance. It was predicted that attentional control and performance would be most affected when pressure and cognitive load was high due to consumption of limited cognitive resources. In this experiment, a heads-down instrument panel was accompanied by a large field-of-view external screen that showed, in all trials, a clouded view of the external world. In the test session, pressure was again manipulated, however, an auditory *n*-back task was also utilised in order to manipulate cognitive load. In accordance with the results of all previous chapters, pressure was successfully manipulated and performance was maintained under pressure. Reaction time for the *n*-back task decreased under pressure, which suggested an increase in effort or cognitive resources. This potential increase in effort may have been responsible for the maintenance of performance under pressure. Performance was however impaired by cognitive load, and this was accompanied by a decrease in the number of transitions between instruments. In contrast to chapter four, the pressure manipulation did not lead to a group-level increase in scanning randomness and changes in scanning randomness did not correlate with changes in performance. However, in line with chapter four, changes in cognitive anxiety from neutral to anxiety conditions predicted changes in scanning randomness, but interestingly, only when cognitive load was high. This result provided preliminary evidence for an interaction between cognitive anxiety and cognitive load on attentional control.

Implications

A number of interesting findings regarding the underlying mechanisms responsible for performance changes under pressure have emerged from the present body of research. The aim of this section is to discuss the findings in the context of previous research and examine the implications that these findings have from both theoretical and practical viewpoints.

Effects of Pressure on Performance

Chapter one outlined previous research showing that pressure has the potential to impact the performance of visual-motor tasks. Contrary to expectations, pressure had no overall, group-level, effect on performance in any of the four experiments reported in this thesis. This occurred despite investigating different types of visual-motor tasks (discrete: chapters one and two; continuous: chapters three and four) and different levels of participant expertise. This also occurred despite manipulation checks indicating that pressure was successfully invoked in all four experiments. Specifically, self-report anxiety measures showed significant increases in cognitive anxiety for all four experiments, while objective heart rate measures employed in latter experiments (chapters four and five) provided corroborating evidence. The results of the current thesis are therefore contrary to many studies demonstrating that pressure can impair (e.g., Beilock & Carr, 2001; Gray, 2004), or improve (e.g., Cooke, Kavussanu, McIntyre, Boardley & Ring, 2011) performance overall. It is possible that the magnitude of pressure that was created in all of the current experiments was not sufficient in order to produce group-level effects. It is however argued that changes in manipulation check measures were comparable to, or larger than, those reported in previous studies showing significant performance effects, for both heart rate (e.g., Cooke et al., 2011; Janelle, Singer & Williams, 1999) and cognitive anxiety (e.g., Gucciardi & Dimmock, 2008).

A number of components were commonly included in the manipulations used in this thesis, including: monetary rewards, competition, a viewable leaderboard, a video camera and ego-threatening instructions (e.g., results would be made known to others). These factors were incorporated in an attempt to maximise pressure and were included based on previous research validating their efficacy (e.g., Gray, 2004; Hardy, Mullen & Jones, 1996; Masters, 1992). Further justification for their inclusion comes from the fact that high-level performance in a variety of domains will include many of these factors. However, the lack of pressure effects on group-level performance may potentially be due to certain components having opposing influences. Therefore, with hindsight, it is unclear whether these factors do additively increase pressure as suggested by Baumeister & Showers (1986). For instance, Mesagno, Harvey and Janelle (2011) specifically compared different pressure manipulations and showed that monetary incentives led to improved performance. In contrast, the presence of an audience, or the presence of a camera along with evaluative instructions, led to impaired performance. Furthermore, these manipulations led to differences in cognitive anxiety and these differences mediated the performance effects. Other research has also recently shown that relatively small changes to the words and phrases used in framing pressure manipulations can cause differences in performance, anxiety and attentional control (Moore, Wilson, Vine, Coussens & Freeman, 2013). Therefore, it seems that very careful consideration must be given to the pressure manipulation employed, and interactions between individual components must be investigated more thoroughly, in order for pressure to be maximized and more uniform responses to be elicited.

The findings of this thesis further highlights the importance in considering the level of analysis when examining performance under pressure (see Beilock & Gray, 2007). Although in the present studies no effects were found when examining performance across all individuals, analysis at the individual level indicated that this was caused by differences in response to pressure, thus nullifying each other. Techniques that allow the concurrent examination of different levels of analysis may be employed in future, such as hierarchical linear modeling (e.g., Beattie, Lief, Adamoulas & Oliver, 2011). Regardless of the method employed, by continuing to investigate performance under pressure at a group level, researchers may be missing the factors that separate 'chokers' and 'clutch' individuals.

Kinematic Mechanisms

A novel kinematic mechanism was found to be responsible for expert golfers' performance changes under pressure in a golf-putting task (chapter two). Specifically, changes in the relationship between downswing amplitude and putt length correlated with changes in performance. While this analysis approach was novel in itself, kinematic mechanisms responsible for expert golfers' performance changes under pressure are scarce more generally. Previous research has mainly found kinematic mediators in novice golfers (e.g., Cooke, Kavussanu, McIntyre & Ring, 2010; Moore, Vine, Wilson & Freeman, 2012) but not expert golfers (e.g., Moore et al., 2013). Preliminary evidence for a pressure-induced reduction in downswing amplitude has been previously reported (e.g., Tanaka & Sekiya, 2010; 2011), however these studies did not manipulate putt distance and the reduction did not correlate with performance changes. Unbeknownst to myself, other similar research published at the same time as the experiment reported in chapter two also investigated the effects of pressure on golf-putting kinematics in experienced golfers, while also manipulating and analysing putt distance.

Hasegawa, Korama & Inomata (2013) asked experienced golfers (mean handicap: 5.7) to putt to a standard sized hole from 1.25, 1.5 and 1.75m. A median split approach was used in order to categorise participants into low and high pressure manipulation response groups based on increases in heart rate and cognitive anxiety (similar to the supplementary analyses presented in Appendix A for the experiment reported in chapter 5). Unfortunately the authors only reported backswing amplitude. Interestingly however, they did show that backswing amplitude reduced under pressure for the high manipulation response group and remained the same for the low response group. Also, the high response group's performance deteriorated under pressure while the low response group's improved. It is argued that these results are highly comparable to the results presented in chapter two.

No reported analyses examined the relationship between performance change and backswing amplitude. The interaction between group, pressure condition and putt distance was also not significant, suggesting that pressure reduced backswing amplitude for each putt distance for the high response group, rather than leading to a smaller range of backswing amplitudes. There are a number of possible reasons for this discrepancy. First, it is possible that utilising a median split approach to dichotomise responses to the pressure manipulation may have meant that such subtle effects could not be detected. Secondly, perhaps more similar results could have been found if downswing amplitude was analysed instead of backswing amplitude. Thirdly, in Hasegawa & colleagues study, participants putted into a hole, which means the control of putt distance was probably less important than in the study presented in this thesis (putts can be holed from multiple different speeds, a marker requires a precise speed from each putt distance). However, when taking the similarities between the studies, it is suggested that pressure can reduce putter-head movement amplitudes and that this may lead to performance changes.

From a practical point of view, it may be tempting for expert golfers to attempt to maintain their usual movement amplitudes when in pressure situations. However, the above changes were qualitatively similar to those produced by self-focus manipulations (Beilock & Gray, 2012). Therefore it is suggested that the observed kinematic changes under pressure in chapter two may have possibly occurred, at least partially, as a result of increased movement monitoring. Therefore, take the golfer who has been informed that pressure has the potential to reduce movement amplitudes. They then find themselves in a pressure situation on the last hole of a competition and they begin to control their movement in an attempt to maintain their movement amplitude. Having not done so for the rest of the round, they are likely not aware what their normal amplitude is for the given putt distance. They are in a catch-22 situation, the act of attempting to protect against reduced movement amplitudes may, in-fact, reduce them. Coaches and athletes should carefully consider how best to use this information.

Attentional Mechanisms

Chapters three to five investigated attentional mechanisms that may be responsible for performance changes under pressure. The results of chapter three supported the assertion that pressure can lead to attentional narrowing (e.g., Easterbrook, 1959) and extends upon previous studies by using a useful field of view (UFOV) test to show that the detection of peripheral stimuli decreases under pressure, but only for larger (i.e., 20 degree) visual angles. Previous research supporting this assertion in visual-motor tasks (e.g., Bahrick, Fitts and Rankin, 1952; Janelle et al., 1999) had been criticised. Briefly, this research commonly presented a continuous salient, task to central vision, while an infrequent, less salient target was presented in the periphery. These studies found that the accuracy of detection for peripheral targets decreased under pressure. However, it was suggested that the difference in saliency was responsible for this decrease, with participants attending more to the salient central task. This limitation does not apply to the current results as equally salient stimuli were presented to both central and peripheral vision. The findings of chapter two are supported by previous studies demonstrating that life stress can lead to attentional narrowing, which can in-turn lead to a greater chance of athletic injury (e.g., Rogers, Alderman and Landers, 2003; Rogers and Landers, 2005). The present findings further suggest that performance changes under pressure may be another consequence of attentional narrowing. Apart from adding to previous attentional narrowing literature, the current results also add to UFOV research by showing that UFOV is also affected by pressure, as well as previously reported factors such as cognitive load (e.g., Ikeda & Takeuchi, 1975; Murata, 2004), age (e.g., Sekuler, Bennet & Mamelak, 2000) and fatigue (e.g., Ho & Wang, 2010).

It could be argued that participants invested less effort in performing the UFOV test under pressure, therefore offering an alternative explanation for impairments in UFOV. This is possible, as the contingencies and rewards introduced during the pressure manipulation were not linked with performance on the UFOV test. Therefore participants may have chosen to invest effort on the putting task, which offers potential rewards, over and above the UFOV task. However, it is unclear why lack of effort would selectively impair performance at large eccentricities. If lack of effort was responsible, it is argued that performance would be impaired across all eccentricities.

The observed impairments in UFOV may be due to a number of mechanisms. UFOV performance has previously been suggested to involve both low-level perceptual processing abilities and higher-level cognitive abilities, such as attentional control (Owsley, 2013). For instance, psychophysiological studies have shown that UFOV performance is related to both low and high-level stimulus processing abilities. Specifically, when examining the relationship between UFOV performance and visual event related potentials (ERP), certain early (i.e., low level) and late (i.e., high-level) ERP features have been shown to correlate with UFOV performance (O'Brien, Lister & Peronto & Edwards, 2015). However, it appears that very few studies have specifically examined the effects of emotion on the underlying mechanisms that may be responsible changes in UFOV.

Schmitz, De Rosa & Anderson (2009) conducted a noteworthy functional magnetic resonance imaging (fMRI) study where participants viewed images of faces in central vision, while various buildings (i.e., houses) were simultaneously presented to peripheral vision. Immediately preceding this, participants viewed positive (e.g., photogenic animals, people on the beach) or negative images in order to manipulate emotion. Results showed that negative emotions decreased the coupling between the primary visual cortex and areas of the brain associated with processing of unattended places (i.e., houses in peripheral vision), while positive emotions had the opposite effect. Based on this finding, it was suggested that emotion directly influences early perceptual processes. Taken together, these studies are presented as an indication that the observed effects of pressure on UFOV performance may have been due to low-level abilities, higher-level abilities, or both.

Chapters four and five provided evidence to support the predictions of attentional control theory in a continuous, instrument landing visual-motor task. Pressure led to impairments in gaze behavior, supporting previous research (e.g., Wilson, Smith, Chattington, Ford & Marple-Horvat, 2006). Furthermore, the present findings extend upon previous research by suggesting that anxiety can lead to increases in the randomness of scanning behavior. There was also a tendency across both studies for participants to look towards the outside world, even though this contained very little task relevant information. Taken together these results suggest that anxiety disrupted the balance between goal-directed and stimulus-driven attentional systems.

While the findings of these experiments dovetail with the predictions of attentional control theory, the null effects found in experiment four could be suggested to be explainable by perceptual load theory (Lavie, 1995, Lavie, 2010). Summarily, this theory predicts dissociable effects of cognitive and perceptual load, on distractibility to task irrelevant stimuli. Specifically, cognitive load is predicted to increase distractibility, whereas perceptual load is predicted to have the opposite effect. It is possible that the increased difficulty of the employed *n*-back task increased perceptual load, at least partially, whereas anxiety increased cognitive load, thus leading to a null effect. However, the the *n*-back task is different in nature to auditory tasks used in previous perceptual studies (e.g., Sabri, Humphries, Verber, Mangalathu, Desai, Binder & Liebenthal, 2013). Also, if perceptual load was increased by the *n*-back task, then results (either entropy or percentage dwell time data) should have shown evidence for a decrease in distractibility in the high-load, neutral conditions.

The results also cannot be definitively used to implicate the underlying processes that were responsible for changes in gaze behavior. Convergent evidence should be sought to examine the extent to which changes in entropy are representative of changes to attentional control. Furthermore, sequencing of gaze behavior may be due to closed-, or open-loop control mechanisms, or a combination of both (Ellis & Stark, 1986; Hameluck, 1990). Closed-loop control suggests that information gathered at the current gaze location determines the next gaze location, whereas open-loop control suggests that internal mental models of the task drives future gaze locations. Mental models, or scanning patterns (open-loop control), are suggested to be stored in long-term memory (e.g., Endsley, 1999), and similar previous research has providing some evidence to indicate that information retrieval from long-term memory is less affected by pressure (Stokes & Raby, 1989). In contrast, the information gathering and processing implicated by control-loop processes requires working memory resources. For instance, maintaining situational awareness is resource intensive (Wickens, 2002). Taken together, it is therefore tentatively suggested that the results of the experiments presented in this thesis are more in-line with impairments to closed-loop control processes. Specifically, the findings of chapter five provided preliminary evidence to suggest that entropy is related to cognitive anxiety only when cognitive load is high. The combined influence of cognitive anxiety and load apparently consumed resources needed to process and integrate information gathered at each dwell location. This then lead to greater searching, and consequently, more random gaze behavior.

Limitations

While it is argued that the results of this thesis have contributed to knowledge in this area, a number of limitations should be considered when interpreting the findings. Firstly, the sample size in each of the experiments was relatively low. Although the sample sizes were similar to comparable studies examining the effects of pressure (e.g., Beilock & Carr, 2001; Gray, 2004), this may have meant that smaller effects were harder to detect. Future studies should employ larger sample sizes to alleviate this potential problem.

Secondly, anxiety was measured retrospectively in all but one of the experiments (chapter three also measured anxiety during performance), meaning that memory bias may have impacted the response accuracy. As an example, participants who performed well in pressure situations may have reported less cognitive anxiety, and vice versa. However, retrospective methods of assessing anxiety have been previously validated (Butt, Weinberg & Horn, 2003), and prospective methods are not without their limitations. For instance, individuals with a repressive coping style are likely to underreport anxiety in self-report measures (Woodman & Davis, 2008).

The third set of limitations relate to the pressure manipulations employed throughout the current thesis. As stated previously, various manipulation checks indicated that pressure was successfully invoked. However, the magnitude of pressure created by these experimental manipulations almost certainly does not match the levels found in the real-world. It is unclear why the mechanisms that underpin performance changes under pressure should be different based on the severity of the pressure situation, nevertheless, care should be taken before generalising these findings across contexts.

Fourthly, in experiment one, it is possible that learning effects may have resulted in the observed null overall effect of pressure on performance. However, two latter experiments

(experiments two and three) both used between-subject designs and also found null effects of pressure on overall group-level performance. More significantly, learning effects were not seen for the control group, instead, the control group's performance was comparable to the pressure group. This lends some support to oppose the potential learning effect limitation, however, it is conceded that experiment one's use of a non-counterbalanced, repeated measures design, means that this possibility cannot be ruled out.

Fifthly, gaze behavior (chapters four and five) only provides an indication into the direction of overt attentional allocation. Therefore, as overt and covert attention are not inseparably linked (e.g., Posner, 1980), it is possible that participants were internally attending to different features than were indicated by the gaze data.

Directions for Future Research

The studies presented in this thesis have examined, in laboratory experiments, the mechanisms that underlie performance changes under pressure. Investigating these mechanisms in such a manner has obvious experimental control advantages. However, as stated in the limitations section, the magnitude of pressure is likely to be much lower than experienced in real-life pressure situations. In order to allow researchers the opportunity to determine, with greater confidence, the changes that actually occur in the real-world, studies could be designed to take advantage of naturalistic pressurised contexts. For instance, kinematic mechanisms, such as reported in chapter two, could be relatively easily captured in real-life competition using commercially available club head mounted motion trackers. It is acknowledged that this approach presents a number of challenges. From an ethical standpoint, the methods used to collect data in real-life situations would need to be unobtrusive in order to not interfere with performance.

Unobtrusive data collection methods are available. Doppler radar (e.g., Trackman™, Interactive Sports Games, Denmark) systems are now extensively used during most PGA Tour competitions in order to track players' ball flights, for both research and viewer entertainment purposes. These systems could be used to derive club head parameters at impact, and therefore prerequisite swing changes, that are associated with pressure-induced performance changes. Remote eye-tracking camera systems (as employed in chapter five) could be used to examine changes to gaze behavior during the performance of visual-motor tasks, such as driving or flying, in real-world pressure situations. Furthermore, manipulation checks in the latter situations would not necessarily need to be sacrificed. For example, heart rate could be assessed completely unobtrusively using camera-based computer vision photoplethysmography techniques (c.f., Poh, McDuff & Picard, 2011; McDuff, Gontarek & Picard, 2014). Future studies could also build upon the gaze behavior analyses employed in the current thesis.

The studies presented in chapters four and five offer evidence, for the first time, to suggest that anxiety influences the randomness of gaze behavior. While these results are interesting, future studies should seek to better understand the cognitive processes that are responsible for these changes. If entropy is representative of attentional control, it is suggested that individuals with dispositional deficits in attentional control should exhibit larger increases in entropy in pressure situations. Deficits could be assessed, for example, using the trait attentional control scale (Derryberry & Reed, 2001). Convergent evidence from self-report or think aloud protocols could also be used to examine the underlying processes associated with increases in entropy. Related to this point, more complex statistical models may be able to elucidate the underlying processes that cause pressure-induced changes in gaze behavior. The current entropy calculation modelled the gaze data as a

Markov process, where the location of the next dwell location is dependent on the current dwell location. Hidden Markov models have, for instance, been used to correctly infer (as validated by think aloud procedures) underlying psychological states from gaze data. In particular, such methods have been employed in similar instrument landing tasks to accurately predict task switching (c.f. Hayashi, 1997). More advanced statistical methods may also be utilised in a different manner.

Various different theories outlined, and explored, in this thesis attempt to explain the underlying changes that lead to performance changes in pressure situations (e.g., theory of reinvestment, attentional control theory). Research into these theories has often been conducted independently, by focusing on one theoretical account over another. However, as stated previously by Beilock and Gray (2007), pressure may cause changes to multiple underlying processes at the same time. A more integrated approach is needed in future, both theoretically, and as a consequence, statistically. Some advancements have been made on both the former (e.g., Nieuwenhuys & Oudejans, 2011), and latter fronts (e.g., Otten, 2009). For instance, Otten (2009) utilised structural equation modelling to investigate the casual relationships between a large range of processes (e.g., reinvestment, perceived control and confidence) on performance under pressure. This approach acknowledges the complexity of predicting performance under pressure by allowing the influence of a number of antecedents, processes and outcomes to be investigated collectively.

Conclusion

The present thesis aimed to investigate the psychomotor mechanisms responsible for visual-motor performance changes in pressure situations. The results of the present thesis suggest that pressure can lead to individual differences in behavioral responses to pressure situations, both in terms of performance and mechanistic variables. Importantly, changes to both kinematic and attentional mechanistic variables under pressure were shown to correlate with performance changes. It is hoped that this thesis provides a base for future research and will lead to interventions that support the robust performance of visual-motor skills in pressure situations.

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APPENDICES

Appendix A

Supplementary Median-Split Analysis for Chapter Five

An alternative median-split approach is presented to analyse whether individual responses to the anxiety manipulation may be responsible for the non-significant effects of experimental conditions on entropy. Eight participants were categorised into a 'high manipulation response' group, while eight were catergorised into a 'low manipulation response' group using a median split approach. Specifically, two average cognitive anxiety variables were calculated for each participant: one for the neutral conditions, one for the anxiety conditions. An average change score was then calculated for each participant by subtracting the anxiety condition average from the neutral condition average. Finally, a median split grouping was performed based on these changes scores, with the means (and standard deviations) for the low- and high manipulation response groups being 0.38 (±2.33) and 9.38 (±5.32), respectively. An independent samples -test confirmed that this process was successful in creating groups that were significantly different $t(14) = -4.39$, $p = .001$.

The manipulation response groups were used as a between-subjects factor in a 2 anxiety manipulation response (low manipulation response, high manipulation response) x 2 anxiety condition (neutral, anxiety) x 2 cognitive load (low cognitive load, high cognitive load) mixed factorial ANOVA with repeated measures on the last 2 factors. Of central interest are the results from two interactions. Firstly, the ANOVA revealed a significant interaction between anxiety manipulation response and anxiety condition, $F(1,14) = 6.84$, $p = .02$, $\eta_p^2 = .33$. Breaking down this interaction revealed that entropy significantly increased between neutral and anxiety conditions for the high manipulation response group, but remained constant for the low manipulation response group (see figure A1). This finding closely supports the results from chapter four. Secondly, there was a non-significant interaction between manipulation response, anxiety condition and cognitive load, $F(1, 14) = 1.51$, $p = .24$, $\eta_p^2 = .10$. This suggests that cognitive load did not have a significant effect on the interaction between manipulation response and anxiety conditions. The considerable loss of power associated with median split approach may be responsible for this null effect. This loss of power, along with other concerns with the median split approach stated by numerous authors (e.g., Irwin & McClelland, 2003; MacCallum, Zhang, Preacher & Rucker, 2002), mean that the non-dichotomised analysis is the preferred approach.

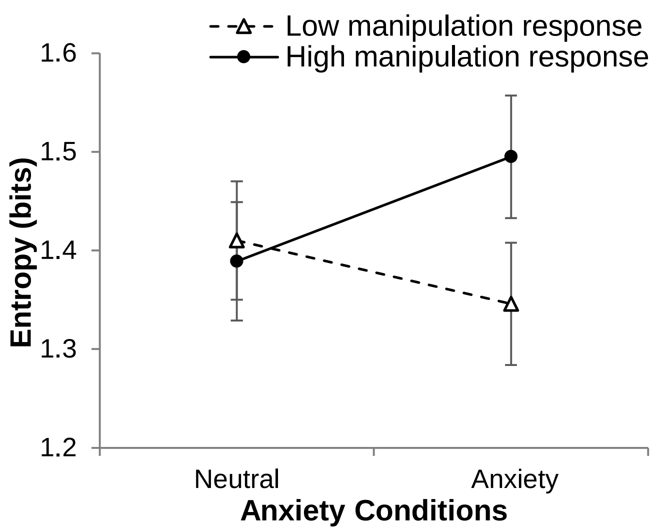

Figure. A1. Mean scanning entropy in neutral and anxiety conditions for the low anxiety manipulation response (dashed lines) and high anxiety manipulation response (solid lines) groups. Error bars represent standard errors of the mean.

Appendix B

Supplementary Gaze Behavior Analysis for Chapter Five

Supplementary gaze behavior analyses were performed to mitigate concerns that participants may have reverted to the explicitly recommended gaze pattern (see acquisition phase description) in anxiety conditions. Specifically, participants' AOI sequences were compared against a perfect AOI sequence which strictly adhered to the recommended AOI transition order. Comparisons for all experimental trials were then made using the ScanMatch (Cristino, Mathôt, Theeuwes & Gilchrist, 2010) Matlab toolbox which uses a Needleman-Wunsch algorithm (Needleman & Wunsch, 1970) to produce an alignment score. Higher alignment scores indicate a closer match between the ideal sequence and the actual sequence. Identical statistical analyses were performed on this data as the entropy data.

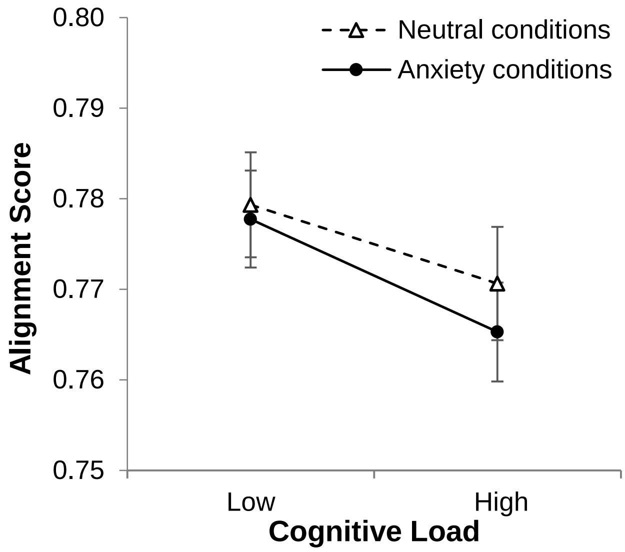

Figure. B1. Mean alignment score plotted as a function of cognitive load in neutral (dashed line) and anxiety (solid line) conditions. Error bars represent standard errors of the mean.

This analysis revealed a non-significant effect for anxiety $F(1,15) = 1.86$, $p = .19$, $\eta_p^2 = .11$, a significant effect for cognitive load $F(1,15) = 14.66$, $p = .002$, $\eta_p^2 = .49$, and a non-significant interaction *F*(1,15) = .50, *p* = .49, η_p^2= .03. Cognitive load led to greater dissimilarity between the actual gaze sequences and the ideal prototypical sequence (see Figure B1). There was no significant effect of anxiety on alignment scores, which shows that participants did not revert to the pre-described gaze pattern in anxiety conditions.

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