Working memory capacity, controlled attention and aiming performance under pressure

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Abstract

This study explored the possibility that individual differences in working memory capacity (WMC) could predict those individuals who would experience attentional disruptions and performance decrements under pressure. Two WMC groups performed a Stroop handgun task under counterbalanced conditions of threat whilst wearing eye-tracking equipment that measured visual search activity and quiet-eye (QE) aiming duration. Performance was measured in terms of shooting accuracy. Low-WMC individuals experienced impaired visual search time to locate the target and reduced QE durations when shooting at incongruent target words. Furthermore, the low-WMC group experienced significant reductions in shooting accuracy when anxious. Conversely, high-WMC individuals experienced no significant differences in attentional control or performance across congruency or threat conditions. Results support the suggestion that WMC is not only a good predictor of an individual's ability to control their attention but can also predict those likely to fail under pressure.

Keywords: goal maintenance, visual attention, quiet eye, executive attention, anxiety

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The controlled attention perspective of working memory capacity (WMC) suggests that rather than WMC being indicative of an individual's capacity to store items in short-term memory, it is reflective of an individual's ability to maintain task goals, supress interference and avoid distraction (Engle, 2002). Therefore high-WMC individuals are generally better able to maintain top-down attentional control and remain focused (Engle & Kane, 2004) whereas low-WMC individuals are likely to experience periodic failures in goal maintenance due to their inability to inhibit distraction or interference (De Jong, Berendsen, & Cools, 1999). Support for this view has come from research that has explored individual differences in lab-based tasks where participants are required to maintain task goals that are in direct opposition to their prepotent response tendencies (e.g., see Barrett, Tugade, & Engle, 2004, for a review).

One such task is the Stroop task (e.g., MacLeod, 1991) which requires participants to name the colour of the ink in which a word is printed, while ignoring to the meaning of the word. For example, when the word and the meaning are congruent (the word 'RED' written in red ink) the task is relatively easy. However, when the ink colour and word are incongruent (the word 'RED' written in blue ink) the task is much more difficult. Specifically, because the prepotent response (read the word) conflicts with the task goal (name the colour of the ink) in the incongruent example, participants respond more slowly and make more errors. Importantly, Kane and Engle (2003) found that this effect was more pronounced for low-WMC individuals compared to high-WMC individuals. Similar results have also been reported in antisaccade task performance in which participants are required to inhibit the prepotent response to look in the direction of a presented target and instead, make a saccade to the opposite direction (e.g., Kane, Bleckley, Conway, & Engle, 2001). Low-WMC individuals generally make more eye-movement errors towards from the cue; initiate antisaccades more slowly; and perform poorer than high-WMC counterparts. Results of studies using both Stroop and antisaccade tasks are consistent with the view that WMC is a measure of an individual's ability to maintain task goals (Barrett, Tugade, & Engle, 2004, Engle, 2002) and their capability to inhibit interference (Kane et al, 2001). However, as yet the controlled attention perspective of WMC has not been tested in a visuomotor task performed in a high pressurised environment.

Nowhere is the ability to stay focused and inhibit distraction more critical than in highly pressurised situations where internal interference (e.g., anxiety, worry) and external distractors (e.g., salient stimuli) are prevalent. Recent theoretical attempts to explain the mechanisms behind anxiety-induced performance decrements implicate anxiety's effect on attentional control as a contributing factor behind performance failure (Eysenck, Derakshan, Santos, & Calvo, 2007). According to Attentional Control Theory (ACT; Eysenck et al 2007), anxiety creates an imbalance between two attentional systems: a goal-directed (top-down) system that is responsible for the maintenance of task goals and a stimulus-driven (bottom-up) attentional system that is sensitive and responsive to salient stimuli (Corbetta & Shulman, 2002). Anxiety is associated with an increased influence of the stimulus-driven attentional system and a subsequent reduction of goal-directed attention control (Eysenck et al., 2007). This imbalance is thought to arise as a direct consequence of anxiety impairing the inhibition function of the central executive of working memory (Ansari & Derakshan, 2010) that prevents attentional resources being allocated to task-irrelevant stimuli and responses (Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). The cumulative effect is that anxious individuals become susceptible to distraction or interference precisely when the maintenance of task goals is most important. Studies that have explored anxiety's effect on the inhibition of prepotent responses have found that anxiety impairs performance in antisaccade (Ansari & Derakshan, 2010) and Stroop (Hochman, 1967) tasks in much the same way as previously discussed with relation to WM capacity (i.e., disruptions to attentional control, slower response times and poorer overall performance).

One specific measure of goal-directed attentional control that is critical to the performance of visuomotor aiming skills is the quiet-eye (QE) period (Vickers, 2007). Defined as the final fixation on a target prior to the initiation of a planned motor response, the QE has been proposed to reflect a critical period of cognitive processing during which the parameters of a motor skill, such as force, direction, and velocity, are fine-tuned and programmed (Vickers, 2007). Consensus of the research findings on the QE phenomenon show that longer QE durations underpin expertise and superior performance and that anxiety often causes a reduction in QE duration that disrupts motor planning, control and subsequent performance (see Vine, Moore & Wilson, 2014, for a recent review). These gaze disruptions are particularly prevalent in aiming tasks where visual distractors are present; e.g., in police firearms shooting (Nieuwenhuys & Oudejans, 2010), and soccer penalty taking (Wilson, Wood & Vine, 2009, Wood & Wilson, 2010). Therefore the ability to maintain goal-directed attentional control, and inhibit distraction and interference, is critical for aiming performance in highly pressurised applied environments.

These two strands of research lead to the suggestion that the ability to maintain goal-directed attentional control – critical for accurate visuomotor performance - is influenced by both individual differences in WMC and situational variables like pressure-induced anxiety. Indeed, previous research has been supportive of such a relationship in cognitive task performance (Beilock & Carr, 2005; Laborde, Furley & Schempp, 2015), although neither took objective measurements of attentional control and neither explored the effects of this relationship on skilled movement. The aim of this study was to integrate these theoretical frameworks, using objective measures of top down attentional control in a Stroop-based handgun task, performed under conditions designed to manipulate interference (via congruence) and state anxiety (via threat). Based on the controlled attention view of WMC (Engle, 2002) and ACT (Eysenck et al., 2007), we predicted that low-WMC participants would show a greater impairment in the ability to maintain goal-directed attentional control (longer search times to find the target and reduced QE durations) in the face of interference from incongruent target words (Kane & Engle, 2003) and that this effect would be most pronounced under a high pressure condition. Due to the strong link between visual attentional control and performance in targeting tasks (e.g., Vine et al., 2014), we also predicted a similar three-way interaction effect (group x congruence x threat) for performance.

Methods

Participants

Kane et al (2007) suggested that individual differences in working memory capacity (WMC) are reflective of overall differences in general cognitive control abilities and the susceptibility to experience cognitive failures. Indeed previous research has shown that the susceptibility to experience cognitive failures correlates with WMC score ($r = -.372$, $p = .001$; Furley & Memmert, 2012). Therefore to create distinct WMC groups we firstly screened 117 undergraduate students using the Cognitive Failures Questionnaire (CFQ; Broadbent, Cooper, FitzGerald, & Parkes, 1982). In an extreme group design, the top and bottom 15 participants were then selected to complete an automated version of the operation span task (OSPAN; Unsworth, Heitz, Schrock, & Engle, 2005) in order to stratify two groups based on their WMC. Extreme group designs are very common in WMC research and help to maximise statistical power when detecting interactions between WMC and performance (Hambrick & Oswald, 2005). The low-WMC group consisted of 8 males and 4 females (mean age = 20.30, SD = 2.11) and a mean OSPAN score of 26.17 (SD = 11.46). The high-

WMC group consisted of 9 males and 3 females (mean age = 20.00, SD = 1.70) and a mean OSPAN score of 62.75 (SD = 8.99). There was a significant difference between groups in OSPAN score ($p < .001$) but no significant difference in CFQ score ($p = .139$)[1]. These group differences in OSPAN scores are very similar to WMC groups created in previous studies (e.g., Furley & Memmert, 2012). A local ethics committee granted approval of the experimental procedures and each participant gave written, informed consent prior to testing.

The Reverse-Stroop Targeting Task

Previous research has highlighted that Stroop interference is minimised when the desired response is a visually-guided action to a target; therefore, a reverse-Stroop protocol (matching the meaning of a word to a corresponding target colour) is recommended for such tasks (Durgin, 2000). The reverse-Stroop targeting task was designed using Microsoft PowerPoint software and target slides consisted of a centralized target word (Arial font size 40) with the four coloured 30cm diameter targets displayed in each corner of the projected image (see Figure 1). Each coloured target remained in the same location across trials and consisted of ten concentric circles with the 'bull's-eye' (3cm diameter) in the centre awarded 10 points and each circle emanating from the centre (1.5cm in width) awarded descending values down to 1 point for the outer most circle. At the centre of the slide a target word was displayed that was written in either congruent (e.g., the word RED written in red ink) or incongruent ink (e.g., the word RED written in blue ink). Participants had to shoot to the target that corresponded to the written word and ignore the ink that the word was written in. Each target display was presented for 2000ms and was preceded by a slide that contained a

1 Three participants from each initially screened group were omitted from the study, prior to completing the handgun task, as their OSPAN scores indicated that they were neither of high or Low WMC ($M = 47.10$, $SD = 4.43$). Also, two participants had CFQ scores that indicated high/low WMC but had contradictory OSPAN scores.

white cross in the centre that was displayed for 5000ms. Timings were programmed using the timing function of the PowerPoint software and were subject to pilot testing prior to carrying out the experiment.

Each block of target presentations consisted of 20 target slides in both practice and low and high threat counterbalanced conditions. In the low and high threat condition, incongruent target words (where the ink did not match the word meaning) were presented on five occasions. Previous research has shown that a 75% congruency rate is optimal for inducing maximum interference (Kane & Engle, 2003).

Apparatus

Participants shot using a NERF C-S6 pistol with a 20 dart capacity magazine that shoots foam, rubber-tipped darts. Prior to the commencement of the experimental conditions participants completed a gun accuracy check that required them to shoot to a target of concentric circles (identical in size to the targets in the experiment) as accurately as possible. This gun check was also repeated after the experimental conditions had been carried out. There was no difference in shot variability (*SD* of scores; $p = .529$) from pre ($M = 1.92$, $SD = 0.67$) to post experiment ($M = 1.83$, $SD = 0.71$).

The reverse Stroop presentation was projected using a multimedia mobile LCD projector (HITACHI, CP-X275) that was situated on a table 1.2 metres high and 2 meters perpendicular to a clear white wall onto which the targets were displayed (see Supplementary Video). The projector was connected to a laptop loaded with PowerPoint software. Participants stood facing the wall from a distance of 2.5 meters directly behind the projector table. An external video camera (Panasonic; SDR-S26) was situated 1 metre to the right of the participant and was used in the frame-by-frame analysis of shooting accuracy scores.

Participants wore an Applied Science Laboratories Mobile Eye XG gaze registration system (ASL, Bedford, MA), which measures momentary point of gaze at 30 Hz. The system incorporates a pair of lightweight (76 g) glasses fitted with eye and scene cameras and a portable recording device. The recording device was connected to a laptop, located on a table behind the participant, via a 3-metre Ethernet cable which allowed real-time monitoring of the calibration. Gaze data was recorded onto the laptop for offline analysis.

Measures

Anxiety levels were measured using the Mental Readiness Form-3 (Krane, 1994). The MRF-3 has three bipolar 11-point Likert scales that are anchored between worried and not worried for cognitive anxiety, tense and not tense for somatic anxiety, and confident and not confident for self-confidence.

Attentional Control

Visual search was defined as the duration of time measured in milliseconds from the onset of the target word presentation to onset of the QE. This period reflects the initial search for the correct target among the visual array. In Stroop experiments, shorter search times are associated with the maintenance of goal-directed attentional control whereas longer search times are reflective of lapses in goal-directed attentional control (Hodgson, Parris, Gregory, & Jarvis, 2009).

Quiet Eye was defined as the duration measured in milliseconds of the final fixation on the target immediately prior to trigger pull (Janelle et al., 2000; Causer, Holmes, Smith, & Williams, 2011). To control for variations in time spent preparing the shot, a relative QE was calculated (QE duration/trial duration) x 100; e.g., Causer et al., 2011). An indication of trigger pull was visible from a coloured indicator, located on the rear of the gun, which disappeared when the participant fired. This was always observable from the scene camera of the eye-tracker.

Performance

Shooting accuracy scores were taken using the concentric rings of each target. Shots where the participant missed the target completely, shot to the incorrect target or failed to take a shot in the allocated time were given a score of zero. Shots that hit directly between concentric circles were always given the higher score. Inter-observer agreement for a sample of 100 shots was 96.9%.

Procedure

Participants attended the laboratory individually, were provided with a demonstration on how to load and fire the gun, and were calibrated to the eye tracker. Once calibrated, participants completed the initial gun accuracy check. Participants then completed the Stroop targeting task, starting with the practice target condition and then counterbalanced high and low threat conditions. In the practice target condition participants were told that in the centre of the screen they would see a target word (written in white ink) and they were required to shoot to the corresponding target as quickly and as accurately as possible. In the high and low threat condition participants were told that the target words were now written in different coloured ink but that they were required to ignore the different colours and shoot to the written target word as quickly and as accurately as possible.

In the high threat condition participants were told that their speed and accuracy scores were going to be tabulated into a league table and distributed to all participants involved in the study. Furthermore, a second gun (NERF N-Strike Elite Strongarm Blaster) with a revolving chamber was loaded with one ‘bullet’ in view of the participant. They were told that in this condition if they failed to shoot to the correct target, missed the target completely or failed to make a shot in allocated time, then a researcher would fire the gun at them in a 'Russian roulette' style scenario. This researcher stood 1 metre to the participants left and remained in their peripheral vision throughout. In reality the bullet was taken out of the chamber away from the view of the participant prior to the commencement of the condition. The threat of being shot at has been shown to elevate psychophysiological indices of stress (Taverniers, Smeets, Van Ruysseveldt, Syroit, & von Gruumpkow, 2011) and also shown to be an effective method of inducing anxiety in handgun tasks (Nieuwenhuys Savelsbergh, & Oudejans, 2012). Before carrying out each condition participants completed the MRF-L (Krane, 1994). After completing all conditions and the final gun accuracy check, participants were fully debriefed regarding the aims of the study and thanked for their participation.

Data Analysis

Factorial mixed model ANOVAs were used to assess differences in visual search, QE and shooting accuracy. Threat and congruency level (2 x 2) were entered as the within-subjects factors and WMC group (low vs. high) was entered as the between-subject factor. Significant effects were followed up with Bonferroni corrected pairwise comparisons and effect sizes were reported using partial eta squared statistics (η_p^2).

Results

Anxiety

A significant main effect was found for threat, $F(1,22) = 57.80$, $p < .001$, $\eta_p^2 = .724$, showing that both groups experienced significant increases in their levels of cognitive and somatic anxiety in the high threat condition (see Table 1). All other main effects and interactions were non-significant (p's > .429).

Attention Control

Visual search (Figure 2a). Significant main effects for group ($p < .001$) and congruency ($p < .001$) were superseded by a significant group x congruency interaction, $F(1,22) = 17.43$, $p < .001$, $\eta_p^2 = .442$. This showed that while there was a near significant difference ($p = .059$) in visual search time for congruent target words between low (M = 504.88 ms, SD = 81.60) and high-WMC groups (M = 439.62 ms, SD = 78.91), the effect on visual search time between the groups was greater for incongruent words ($p < .001$). Low-WMC participants had significantly slower visual search times (M = 900.94 ms, SD = 202.20) than their high-WMC counterparts (M = 549.85 ms, SD = 101.12). All other main and interaction effects were non-significant (p's > .083).

Relative QE duration (Figure 2b). Significant main effects for group ($p = .002$) and congruency ($p < .001$) were superseded by a significant group x congruency interaction, $F(1,22) = 10.14$, $p = .004$, $\eta_p^2 = .316$. As with the search rate data, the differences in relative QE duration between low (54%) and high-WMC groups (60%) when aiming at congruent target words approached significance ($p = .055$). However, the interference caused by the incongruent words caused significant differences ($p = .001$) in relative QE durations between low (33%) and high-WMC groups (51%). All other main and interaction effects were non-significant (p's > .077).

Performance

Shooting accuracy (Figure 2c). A significant three-way interaction was found, $F(1,22) = 5.18$, $p = .033$, $\eta_p^2 = .19$, and post hoc 2 x 2 ANOVAs for each group revealed a significant interaction between threat x congruency for the low-WMC group, $F(1,11) = 6.29$, $p = .029$, $\eta_p^2 = .364$. This revealed that there was no significant difference between shooting accuracy in the low threat condition across the congruency manipulation ($p = .628$), however under high threat, low-WMC participants shot significantly poorer when shooting to the incongruent compared to the congruent words (p = .021). No significant main effects or interaction were present for the high-WMC group (p's > .277).

Discussion

This is the first study to attempt to integrate the controlled attention perspective of WMC (Engle, 2002) and ACT (Eysenck et al., 2007) in visuomotor task performance. Both accounts reflect on the importance of attentional control, although the role of dispositional working memory capacity is only indirectly considered with ACT, where trait anxiety is the main variable of interest. The aim of this study was to test whether differences in WMC could predict those individuals most likely to experience attentional and performance disruptions under conditions designed to place stress on attentional control (and in particular, inhibition), via manipulations of congruence and pressure. As such, we hoped to adopt a more interactional (i.e. dispositional and situational factors) approach than is typically used in the cognitive psychology literature. This is critical if research is to have application to human factors and other domains where individuals have to make decisions and perform accurately under considerable pressure (e.g., military, surgery, aviation, sport).

Attentional Control

In accordance with previous research, there was no significant difference in the visual search times when interpreting congruent target words between low- and high-WMC individuals (Kane & Engle, 2003). However, the interference introduced by the incongruent target words had differential effects on each WMC group. Whereas high-WMC individuals were able to maintain task goals, and therefore suffered no significant increases in visual search time, low-WMC individuals were unable to inhibit this interference and therefore suffered periodic failures in goal-directed visual search. However, contrary to our predictions the increased anxiety experienced in the high threat condition did not influence visual search behaviour. It is possible that the time pressure imposed by having a 2000 ms target presentation time across all trials, created a ceiling effect on the interference experienced.

The findings for the initial visual search measure of attentional control were also mirrored in the later QE aiming duration; the disruptions in attentional control for the low-WMC group were exacerbated in the incongruent task condition. High-WMC individuals experienced no such disruptions to aiming behaviour. This finding provides further support for the controlled attention perspective of WMC (Kane & Engle, 2003), in that low-WMC participants experience reductions in goal-directed attentional control in the face of interference compared to high WMC counterparts.

The lack of any significant effect for anxiety on QE duration is contrary to research that has shown that similar levels of anxiety caused a reduction in QE duration in other targeting tasks (Wilson, Vine & Wood 2009; Wilson et al, 2009). One explanation for this may be that as all participants completed a practice session where they became accustomed to the timing of the target presentation, they may have accrued knowledge related to the length of time available to shoot accurately. Therefore when participants experienced disruption in visual attention they may have realised that there was still enough time to utilise appropriate QE durations and aim effectively. Future research could overcome this limitation by reducing the target presentation time.

Performance

Despite the disruptions in goal-directed attentional control being not completely in the direction we expected, the findings of the performance data were exactly as we predicted. Specifically a three-way interaction was found where low-WMC individuals experienced decrements in shooting accuracy when shooting with incongruent target words and these decrements were multiplied under high threat conditions. No performance disruptions were evident for high-WMC participants. We originally expected that these performance decrements would be underpinned by fundamental changes in visual search that would negatively impact on QE durations. However as no significant differences were found in QE duration between groups and across congruency and threat conditions, the mechanisms behind this performance failure can only be alluded to.

First it is possible that this result is reflective of the Stroop interference having a much greater effect on attentional control than expected. For example, it could be that the interference did not end when low-WMC participants located the correct target and may have continued throughout the QE duration through covert disruptions in attentional control. This would mean that high-WMC participants would have profited from an optimal QE duration where target-specific parameters were effectively programmed into an accurate motor response. Conversely, although low-WMC individual exhibited similar QE durations, the continual interference could have evoked covert attentional processes (e.g., using peripheral vision to check target words) that will have compromised pre-programming and negatively impacted on performance. While this cannot be verified with the current data it does provide a coherent explanation of the findings. Interestingly Nieuwenhuys et al, (2012) also found anxiety induced changes in performance in a handgun shooting task despite no changes in visual attention. They suggested that the discrepancy between these results and other studies where anxiety had caused a reduction in QE duration was due to the additional decision-making component of the task. They argued that QE measures may only reflect accurate visuomotor control (in pure aiming tasks) and that anxiety-induced disruptions to decision-making may be more perceptual in nature and independent of QE. Our findings provide additional support for this contention which should also be tested in further studies.

The findings of other studies exploring individual differences in WMC and state anxiety may offer additional insight into our results. For example, Labourde et al (2015) found that low-WMC participants displayed a greater propensity to 'reinvest' their conscious attention over decision making processes which resulted in poor decision making performance. It is therefore possible that low-WMC participants in our study 'reinvested' in, and attempted to exert conscious control over their decisions *and* movements. Attempts to consciously control movement execution have been strongly link to performance failure in visuomotor task performance under pressure (e.g., Masters, 1992). Alternatively, Beilock and Carr (2005) showed paradoxical effects in which low-WMC individuals displayed *better* performance under pressure than high-WMC counterparts in mathematical problem solving. What both studies might suggest is that the interaction between WMC and anxiety may be dependent on the constraints of the task being performed. Future research should also explore this line of research.

Finally, possible limitations of the study may explain some of our unexpected finding. First it is possible that our measures of visual attentional control were not sensitive enough to pick up pressure-induced attentional effects in what was admittedly a low sample size. A second limitation may concern our initial formulation of WMC groups using the CFQ (Broadbent et al.). While working memory capacity is implicated in such cognitive failures (Furley & Memmert, 2012), individuals who score high on the CFQ may have other cognitive impairments that may influence their performance in pressurised and complex environments. Despite our groups not differing on this score statistically (p = .139), it is possible that formulating the groups in this way may mean that other aspects of cognitive failures, which are not just related to WMC, may have impacted upon performance.

Conclusion

Findings from this study strongly support the controlled attention view of WMC, although the effects of state anxiety on controlled attention were not as we expected. From this we conclude that individual differences in WMC do seem to offer some insight into the attentional control abilities of performers in more applied performance environments and do provide some predictive validity regarding who will experience performance decrements in pressurised and complex decision-making environments. Future research should strive to further examine the attentional or behavioural mechanisms behind these performance disruptions.

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Tables

Table 1. Mean (SD) cognitive and somatic anxiety scores for both WMC groups across low and high threat conditions.

	Low-WMC		**High-WMC**	
	Low-Threat	**High-Threat**	**Low-Threat**	**High-Threat**
Cognitive	3.70	5.50**	3.50	5.20**
	(1.64)	(1.90)	(2.59)	(3.08)
Somatic	3.70	5.60**	3.40	5.20**
	(1.57)	(1.96)	(2.67)	(3.08)

** $p < .001$

Figure Caption

Figure 1. An example slide from the reverse-Stroop targeting task. Participants had to read the written target-word located in the centre, ignoring the coloured ink it was written in, and then shoot to the corresponding coloured target (top-left = green; top-right = yellow; bottom-left = blue; bottom-right = red) as accurately as possible.

Figure 2. Mean (sems) visual search time (a), relative QE durations (b) and shooting accuracy scores (c) for both low and high-WMC groups across congruency and threat conditions.