Adaptive working memory training reduces the negative impact of anxiety on competitive motor performance.

Submitted on 26/07/2017

Re-submitted on 06/11/2017

ABSTRACT

Optimum levels of attentional control are essential to prevent athletes from experiencing performance breakdowns under pressure. The current study explored whether training attentional control using the adaptive dual n-back paradigm, designed to directly target processing efficiency of the main executive functions of working memory (WM), would result in transferrable effects on sports performance outcomes. Thirty tennis players were allocated to an adaptive WM training or active control group and underwent 10 days of training. Measures of WM capacity, as well as performance and objective gaze indices of attentional control in a tennis volley task were assessed in low and high pressure post-training conditions. Results revealed significant benefits of training on WM capacity, quiet eye offset, and tennis performance in the high-pressure condition. Our results confirm and extend previous findings supporting the transfer of cognitive training benefits to objective measures of sports performance under pressure.

Keywords: attentional control, anxiety, working memory training, Quiet Eye, neuro-training

Adaptive working memory training reduces the negative impact of anxiety on competitive motor performance

Successful performance in sports is commonly evaluated in terms of technical or physical abilities. However, the cognitive aspects of sports performance also need to be taken into consideration. This is especially relevant when athletes are required to perform complex and fine motor skills under elevated levels of pressure (Nicholls, Holt, Polman, & James, 2005). Indeed, it is not uncommon to witness both amateur and professional athletes' performance breaking down under the perceived pressure of competition (Geukes, Harvey, Trezise, & Mesagno, 2017; Moore, Wilson, Vine, Coussens, & Freeman, 2013). It has been suggested that such performance breakdowns can be explained in terms of impairment in the attentional control required to ensure the efficient preparation and execution of complex movements (Vine, Lee, Moore, & Wilson, 2013; Eysenck & Wilson 2016).

According to recent models of working memory (WM; Unsworth, Redick, Spillers, & Brewer, 2012; Shipstead, Lindsey, Marshall, & Engle, 2014) attentional control, or working memory capacity reflects individual differences in the efficacy by which executive functions of inhibition (e.g., resistance to distraction), shifting (e.g., within-task control), and updating operate in attaining a task goal. As such, WM capacity and attentional control can be considered as somewhat analogous. Anxious apprehension as well as worrying about performance disrupts execution by reducing WM capacity and increasing bottom up processing (for a review see Berggren & Derakshan, 2013), supporting one of the main predictions of Attentional Control Theory of Anxiety (ACT; Eysenck, Derakshan, Santos, & Calvo, 2007; Derakshan & Eysenck, 2009). There is now substantial evidence that anxiety-induced distractibility reduces processing efficiency, impairing goal directed behaviour in both cognitive and sporting tasks (see Moran, 2016; Eysenck & Wilson, 2016, for reviews).

The Quiet Eye (QE; Vickers, 1996) is a widely used index of attentional control in sports and is defined as the final fixation or tracking gaze towards a relevant target prior to the critical phase of a goal-directed movement. The QE is postulated to support task performance by promoting efficient top down motor preparation and online control functions, and has been shown to be a valid index of task proficiency and expertise across a range of targeting and interceptive tasks (see Lebeau, Liui, Saenz-Moncaleano, Sanduvete-Chaves, Chacon-Moscoso, Becker, et al., 2016, for a recent meta-analysis). In line with the predictions of ACT (Eysenck et al., 2007), the QE is also sensitive to the impact of competitive pressure in both self-paced (e.g., golf putting, Vine, Lee, Moore, & Wilson, 2013; basketball free-throw shooting, Wilson, Vine, & Wood, 2009), and interceptive (e.g., shotgun shooting, Causer, Holmes, Smith, & Williams, 2011) sporting tasks. In these studies, a reduction in QE is also generally associated with a reduction in performance under pressure.

Interventions have been designed to maintain or increase QE to protect against performance breakdowns under pressure in skilled performers (e.g., in golf putting, Vine, Moore, & Wilson, 2011; shotgun shooting, Causer, Holmes, & Williams, 2011; and football penalty taking, Wood & Wilson, 2011). However, such interventions are task specific and based on the observation of an expert model, with the specific mechanisms by which they exert their effects being unknown (Vine, Moore, & Wilson, 2014). As such, it is not possible to target the specific cognitive mechanisms by which training may protect athletes against the negative impact of anxiety, making it difficult to draw firm conclusions on the role of executive functions and efficiency in sports.

Ducrocq, Wilson, Vine, and Derakshan (2016) employed a training paradigm specifically designed to target the inhibition function of WM with the aim of protecting tennis players from the negative impact of competitive anxiety via improved inhibition. Compared to a control group, adaptive training improved inhibitory control, which led to enhanced tennis specific attentional control in a return of serve task, as well as improved tennis performance and visual attention control on a tennis volleying task performed under pressure. Specifically, relative to controls, trained tennis players showed a reduction in the percentage of volleys that missed a target in a pressure condition. They also revealed greater task-specific inhibitory control; maintaining longer gaze fixations around the area of contact with the ball and resisting the tendency to direct gaze towards the target to check the outcome of their shots.

A key feature of Ducrocq et al. (2016) was that the training task was designed specifically for improving the efficiency of a specific executive function of WM, namely inhibitory control. However, it is possible that greater transfer to more generalizable functions and performance outcomes may be possible employing combined WM training, which also includes shifting and updating functions (Koster, Hoorelbeke, Onraedt, Owens, & Derakshan, 2017). In relation to sport, it is likely that the mechanisms involved in the QE rely on the combined processes of these fundamental executive functions, whose interplay determines performance efficiency in sports (Wood, Vine, & Wilson, 2016; Wood & Furley, 2015). Specifically, the ability to maintain a steady gaze for long periods of time under high levels of pressure should not only necessitate good resistance to distraction (i.e., inhibition), but also efficient within-task attentional control (i.e., shifting) and the maintenance of accurate representations of non-fixated targets (i.e., updating). This is consistent with the ACT (Eysenck et al., 2007, Derakshan & Eysenck 2009), which denotes that under pressure, fundamental executive functions of WM are affected by anxiety, thereby reducing processing efficiency. Indeed, there is compelling evidence for an anxiety-related impairment on major executive functions of WM involved in sports (e.g., Castiello & Umilta, 1992; Han et al., 2011; Wood et al., 2016).

Capitalising on Ducrocq et al. (2016) and promising recent findings that adaptive WM training targeting fundamental executive functions can enhance attentional control and performance outcomes in clinical populations (Course-Choi, Saville, & Derakshan, 2017; Owens, Koster, & Derakshan, 2013; Sari, Koster, Pourtois & Derakshan, 2016), the current investigation assessed the effects of adaptive WM training on tennis volley performance under pressure. We employed an online version of the adaptive dual n-back training task that has been shown to increase WM capacity and processing efficiency, and reduce emotional vulnerability-related impairments on performance (see Sari et al., 2016). We predicted that participants allocated to an adaptive WM training group, relative to their control counterparts, would (1) perform better in a near transfer test of WM capacity; and (2) reveal more efficient attentional control (extended QE durations) and superior performance under pressure in a far transfer tennis volleying task.

Method

Participants

Participants were recruited from an opportunity sample of recreational club tennis players who engaged in competitive tennis activities between one and three times per week at a London based Tennis Club. The sample included 30 participants (25 males, 5 females; *M* age = 33 years, range: 17 to 50). An a priori power analysis (G*Power; Faul, Erdfelder, Lang, & Buchner, 2007) indicated that based on the effect size of $\eta p^2 = .30$ observed in Ducrocq et al.'s (2016) training study, 24 participants were considered sufficient to achieve a power of 0.8 in an *F* test, given $\alpha = .05$. We recruited 30 participants to account for potential dropout during the training period and potential loss of gaze data, which can occur following calibrations issues when employing portable eye tracking equipment. Participants were initially matched on pre-test measures of: trait anxiety (STAI; Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983; Control *M* = 41.15, *SD* = 7.48; Training *M* = 43.00, *SD* = 7.60); tennis volley performance (see Transfer Tasks section; Control *M* = 2.58, *SD* = .77; Training *M* = 2.62, *SD* = 1.09); and age (Control *M* = 32.46, *SD* =13.60; Training *M* = 34.76, *SD* = 13.29), and were pseudo-randomly allocated to an active control or a training group. Ethical permission was obtained prior to the study. All participants provided written informed consent and were debriefed at the end of the experiment.

Online Training Tasks

Training group: Adaptive dual n- back task. The training task was derived from the task employed in Owens et al. (2013), which was based on the original work of Jaeggi, Buschkuehl, Jonides, and Perrig (2008). Training was delivered online using PHP and JavaScript (jQuerry; see Procedure). Accuracy rate for each training block and for each participant was recorded online, and the experimenter routinely monitored task performance remotely. All trials started with a green fixation cross which appeared in the centre of the screen. Participants were then presented with a 3x3 grid within which a green square appeared at one of 8 possible locations. Concurrently with the presentation of the green square, one of 8 possible consonants (c, h, k, l, q, r, s, t and t) was also verbally presented. Participants were required to memorize the position of the square as well as the letter spoken and asked to respond whenever either of the audio or visual stimuli previously presented matched the letter spoken or the position of the green square ‘n’ trials back.

Both sets of stimuli were presented at a rate of 500ms and each trial was separated by a 2500ms interval. Participants made their response by pressing “L” for auditory matches and “A” for visual matches. Participants were also informed not to respond to non-matches and to simultaneously press “L” and “A” if both auditory and visual stimuli matched. They were also asked to make their response as quickly and as accurately as possible. Each training session comprised of 20 blocks with 20 + n trial in each (for example, in a 2-back block there were 20+2=22 trials; in a 3 back block there were 20+3=23 trials). Each block contained an equal numbers of matches (4 for the position, 4 for the letter, and 2 for both). The location of the square and the letter spoken were randomly distributed within each block. A fifteen seconds fixed break was programed between each block and the task could not be terminated once it was started. Each training session lasted around 30 minutes.

Adjustments in the level of task difficulty (n) were contingent on participants' performance on the task, reflecting the adaptive nature of the training. If accuracy on both the position and letter elements reached 95% or above, the level of n increased by 1 in the following block. If accuracy rates were between 75% to 95%, participants remained on the same level. If performance declined (less than 75% accuracy), task difficulty decreased by one level of n. Participants were given written information about level difficulty upon starting each block.

Control group: Non-adaptive dual 1-back control task. The non-adaptive control task was also delivered online. The control group undertook 20 blocks of dual 1-back trials across the ten days of training irrespective of their performance achievement. This task followed the same basic procedure as the adaptive training task with participants being required to respond if they either noticed a position or a letter (or both) match with the preceding trial (1-back). No level increments were in place for the control task and as such it required limited engagement of WM.

Transfer Tasks

Near transfer: Change detection Task (CDT). A shortened version of the Change Detection Task (CDT; Owens et al., 2013, based on Vogel et al., 2005; see Figure 1) was employed to evaluate participants' working memory capacity (WMC). The CDT was programmed using E-prime software and delivered on an HP Pavilion 15inches laptop set at a resolution of 1024 × 768 (refresh rate 65 Hz). The task began with a fixation cross appearing in the center of the screen followed by an arrow serving as a cue and pointing either to the right or left of the fixation cross for 700ms. A memory array subsequently appeared for 100ms, followed by a retention interval lasting 900ms. A test (comparison) array then appeared for 2000ms. Participants were instructed to memorize the orientation of the red rectangles on the cued side in the memory array and indicate whether the orientation of any of the red rectangles had changed or not in the test array.

The memory and test array consisted of two sets of either two or four rectangles presented on the right and left side of the screen, randomly positioned within a 4° x 7.2° rectangular region and spaced around 2° apart. The two regions were positioned approximately 3° from a white central fixation cross on a black background. All rectangles were randomly orientated along one of four positions (vertical, horizontal, left 45°, right 45°). The task comprised of a two item, a four item, and a distractor condition. In the two item and four item conditions, all rectangles were red in colour while the distractor condition included two blue rectangles as distractors in addition to two red rectangles. For all conditions, on 50% of the trials, no change in the orientation of any of the red rectangles occurred from the memory array to the test array. For the other half of the trials the orientation of one of the red rectangles did change between the memory array and test array. The task comprised a total of 192 trials, which were divided into 4 blocks of 48 trials. The number of items comprised in the arrays as well as the direction of the initial cueing arrow and the type of trials (change vs. no change) were randomized across blocks and appeared at the same frequency across the whole experiment.

****Insert Figure 1 about here****

Far transfer: Tennis volley task. A modified version of the volleying task employed in Ducrocq et al. (2016, experiment 3) was designed for this study. The tennis volley is one of the most technically and attentionally demanding shots in tennis and can be prone to break down under pressure (Roetert & Groppel, 2001). In contrast to Ducrocq et al. (2016) where the tennis balls were fed by hand, a ball machine was employed to provide a more consistent delivery. Participants were required to execute a series of volleys as accurately as possible onto a 120cm x 120cm Federation International de Tir a l'Arc (FITA) approved archery target placed on a blank wall at a distance of five meters from the player and one meter from the floor (as Ducrocq et al., 2016).

The volley task comprised 20 trials, divided into blocks of 10 forehands and 10 backhands. A set of 10 Dunlop Fort All Courts balls and a Babolat Pure Drive tennis racket were employed for the duration of the study. The ball was delivered from a ball machine (Tennis Tutor Tennis Cube), placed centrally below the target and against the wall. The time interval between ball deliveries was kept constant at a frequency of one ball every six seconds. For both backhand and forehand blocks, the ball machine was positioned at a horizontal angle of 16˚from the participant's location. This was determined through pilot testing so players were able to reach the ball with a straight arm to execute their shot. Additionally, the height of ball delivery was also determined in pilot testing with the ball machine set at a delivery angle of 25˚and speed of level 3 on a scale of 1 to 5 (a constant speed of 22 mph). These settings enabled a participant standing 4.6 meters away from the machine to consistently make contact with the ball between waist and shoulder height.

'Pupil Lab' Eye Tracking head mounted glasses (https://pupil-labs.com) were used to measure and record momentary gaze during the performance of the tennis volley task. The scene camera captured video data at 30 fps (resolution, 1024x720p) while the eye cameras captured eye movements at a rate of 60 fps. The eye tracker was set to capture pupil positions with the gaze position 2D fixation detector. A circular cursor (representing 1° of visual angle) indicating the location of gaze in a video image of the scene (spatial accuracy of ± 0.5° visual angle; 0.1° precision) was recorded for offline analysis. A Go Pro Hero 4 camera was also employed to film tennis performance from an external point of view. The recordings were captured at 30 fps and at a resolution of 720 dpi and employing medium angle of view. Depending on the shot to be executed (forehand of backhand) the camera was set on a tripod which was placed on either side (100cm) and behind (20cm) of where the player stood.

Measures

Training task performance. As in Owens et al., (2013) and Sari et al., (2016), performance on the adaptive training task was calculated as the average level of difficulty attained (value of 'n') across 20 blocks of the task for each day of training. Since the level of difficulty did not change for the control task (n = 1), accuracy scores were computed to confirm that the control group's performance was sustained over the training period[1].

State anxiety. Cognitive state anxiety was measured using the Mental Readiness Form (MRF-3; Krane 1994), a shorter and more expedient alternative to the Competitive State Anxiety Inventory-2 (CSAI-2; Martens, Burton, Vealey, Bump, & Smith, 1990), which enables data to be collected quickly during performance. Krane (1994) revealed correlations between the MRF-3 and the CSAI-2 cognitive anxiety subscale of .76. As in previous studies examining the impact of cognitive state anxiety on sports performance (e.g., Ducrocq et al., 2016; Vine et al., 2011; Wilson et al., 2009), participants completed the cognitive anxiety subscale of the MRF-3 (an 11-point Likert scale anchored between 'not worried' and 'worried') at 3 time points in each condition; before the first block of 10 volleys, after the first block of ten volleys (midway), and after the second block of ten volleys (the end). A mean of these three values for each condition was used in subsequent analyses to reflect average anxiety experienced in that particular condition.

CDT performance. Performance in the near transfer, working memory capacity (CDT) task was calculated employing the formula [K = S x (H - F) / (1-F)] (Pashler, 1988); with K (WMC) calculated as a function of S (the set size of the array), H (the observed hit) rate, and F (proportion of false alarms). In line with previous research employing the CDT task (Lee, Cowan, Vogel, Valle-Inclan and Hackley, 2010; Owens et al., 2013), K was calculated for the 4-item condition, eliminating potential ceiling or floor effects that may occur from two-item or distractor conditions.

Tennis volley performance. Tennis performance was assessed in terms of shot accuracy, obtained by determining where the ball bounced within the scoring rings on the archery target, from post-test analysis of video footage. Accuracy scores for each shot ranged from 0 to 10, with 0 being registered when the ball missed the target. An average accuracy score of all shots executed in each condition was calculated for each participant.

Quiet eye (QE) period. Video data from the mobile eye tracking glasses and external camera were analyzed using Quiet Eye Solutions software (www.QuietEyeSolutions.com). This software permits the synchronization of the eye-tracking and the external camera video files allowing frame-by-frame coding of the movement phases from the external video in relation to the gaze location and duration from the mobile eye-tracking glasses. Based on previous research investigating the QE in ball interception tasks (Rodrigues et al., 2002; Wilson et al., 2013) the QE period for the tennis volleying task was operationally defined as the final tracking gaze on the ball prior to the initiation of the forward swing of the racquet. A tracking gaze was defined as a gaze sustained on the ball within 1° of visual angle for a minimum of 100 ms (Wilson et al., 2013).

QE onset occurred relative to the time of ball release from the machine and prior to the forward swing of the racquet, and QE offset occurred when the gaze deviated off the ball by 1° or more, for 100ms or more. If the cursor disappeared for one or two frames (e.g., a blink) and then returned to the same location, the QE duration resumed. As in Vine et al. (2011) and Ducrocq et al. (2016) a second independent rater, who was blind to both the aim of the experiment and participants' group allocation, independently analyzed ten percent of the video data. Results revealed high levels of agreement between the two raters for the QE duration, $r = .93$, $p < .001$, confirming the reliability of the coding process.

Procedure

The design of the experiment followed a pre-intervention, intervention, post-intervention (including low and high pressure conditions) format. Participants were tested individually and arrived at the testing venue (a squash court at the Tennis Centre), to first perform the CDT task; hitting the 1 key when they detected a change in the orientation of one of the red rectangles presented and the 0 key if no change was observed. The CDT task started with a training block of 12 trials. Once the practice block was completed with at least 50% accuracy, participants were instructed to undertake the full CDT task, which lasted around 10 minutes.

Next, participants had a short practice on the tennis task in order to warm up and get familiar with the speed of the ball delivery. The eye-tracking equipment was then fitted and calibrated using a 6-point calibration procedure. Participants were then asked to complete the MRF-3 before starting the tennis volley task. Participants were instructed to stand with both feet on a designated line whilst keeping a steady ready position, holding their racquet with both hands at around waist height. Upon finishing the first block of 10 volleys, participants completed the MRF-3, which was completed again at the end of the whole task.

Following the pre testing session, participants were given instructions on how to proceed with the online home training task and were later sent a designated web link directing them to the experiment website. They were told that they should complete 10 days of training within a two-week period and to undertake the task at approximately the same time each day. Participants were given automatic feedback of their daily performance and progress at the end of each session and told that their performance and completions rates would be monitored on a daily basis. After the two weeks period, participants were invited back to the lab again for the post intervention testing session.

In the post-training session, participants first completed the same procedures as in the pre-training session, before completing a pressure test. As in Ducrocq et al. (2016) participants were told that their data may be used in a proposed sports science TV program with performance being evaluated by tennis experts against the performance of other participants taking part in the study (a mock consent form which included TV branding was completed). Participants were also told that the tennis experts would analyze their facial expression during the task, to heighten awareness of the self. Lastly they were told that a ranking system based on their tennis accuracy scores was in place. Non-contingent feedback was provided, with participants being informed that their scores from their previous tennis performance would put them in the bottom 30% of the pool of participants already tested. They were in turn told that should their performance stay at this level their data could not be used for the experimenter's PhD study. Upon completion of the pressure condition participants were debriefed about the study's aims and thanked for their participation. Participants were compensated with £45 pounds for around six experimental hours of participation.

Data Analysis

One participant in the control group and two participants in the training group dropped out during the testing phase of the study. Another participant was excluded following the pre-testing session due to an inability to perform the tennis task, and the data of one participant could not be used in the analysis due to poor calibration of the eye tracking equipment. The analysis was therefore conducted on a final sample of 25 participants (13 Control and 12 Training). As the CDT was not performed under pressure conditions, these data were analyzed using 2 Group (Control vs. Training) x 2 Condition (Pre vs. Post training) mixed analyses of variance. For the tennis data, as there were no group differences between any of our dependent variables at pre-test[2] we focused our analysis on the post-training conditions (Low pressure vs. High pressure). Dependent variables were therefore subjected to 2 Group (Control vs. Training) x 2 Condition (Low vs. High pressure) mixed analyses of variance.

Results

Training Task Manipulation Check

Participants allocated to the training group performed at higher levels of difficulty on the adaptive dual n-back as training progressed. The mean value of 'n' for the last two days of training *(M* = 2.88, *SD* = .76) was significantly higher (t (12) = 5.34, p < .001) than the mean for first two days of training (*M* = 1.88, *SD* = .61). The control group maintained similar high levels of accuracy on the 1-back test throughout training. The mean accuracy score in the first two days of training *(M* = 95.52 %, *SD* = 2.27) was not significantly different (t (11) = 1.03, p = .300) to the mean of last two days of training (*M*= 96.47 %, *SD*= 3.15).

CDT task

Figure 2 shows K (WMC) scores on the CDT task for both training and control groups. ANOVA revealed no significant main effect of time, or group (F<1). However, there was a

Time X Group interaction, *F* (1, 23) = 8.56, *p* = .008, *η²p* = .27. This interaction was driven by a significant increase in K scores for the training group *t* (11) = 2.62, *p* = .02, *d* = .75 (Pre *M* = 1.32, *SD* = 1.1; Post *M* = 2.09, *SD* = .88), compared to the control group who revealed no change in K scores between the two testing sessions, (Pre *M* = 1.68, *SD* = .87; Post *M* = 1.14, *SD* = 1.16), *t* (12) = 1.61 *p* = .131,

****Insert Figure 2 near here****

Cognitive Anxiety

ANOVA revealed a significant main effect of Condition, *F* (2, 44) = 16.16, *p* <.001, *η²p* = .40 with participants reporting significantly higher levels of cognitive anxiety in the high pressure (*M* = 4.25, *SD* =2.01) compared to the low-pressure session (*M* = 3.41, *SD* = 1.24) indicating that the pressure manipulation was successful. There was no main effect of Group, nor a Condition x Group interaction, *Fs* < 1, reflecting that both groups reported similar emotional responses to the pressure manipulation.

Tennis Performance

ANOVA revealed no main effects for Group (*F*<1), but a significant main effect of Condition, *F* (1, 23) = 7.58, *p* = 0.1, *η²p* = .248. There was also a Condition X Group interaction, *F* (1, 23) = 4.535, *p* = .044, *η²p* = .165. This interaction was driven by a significant increase in accuracy scores for the training group, *t* (11) = 3.208, *p* = .008, *d* = .54 (Low pressure *M* = 2.67, *SD* = 1.15; High pressure *M* = 3.44, *SD* = 1.62), compared to the control group, who revealed no significant improvement between the two testing sessions (Low pressure *M* = 2.56, *SD* = .79; High pressure *M* = 2.65, *SD* = .99), *t*< 1. Volley accuracy scores are presented in Figure 3.

****Insert Figure 3 near here****

QE Period (QE)

6.21 % of trials across testing sessions were lost due to gaze not being registered. ANOVA revealed a significant main effect of Condition, F (1, 23) = 4.61, p = .04, η^2p = .16 indicating that QE durations were generally longer in the high pressure (M = 446.58ms, SD = 45.26) compared to the low pressure session (M = 432.63ms, SD = 45.75). There was no significant Condition X Group Interaction, F (1, 23) = 1.90, p = .18, η^2p = .07, nor a main effect of Group (F< 1; see Table 1).

QE Onset (QE-ON)

ANOVA revealed neither a significant main effect of condition F (1, 23) = 2.08, p = .16, η^2p = .083, nor a main effect of group, nor a significant Condition X Group interaction (Fs < 1; see Table 1).

****Table 1 near here****

QE Offset (QE-OFF)

ANOVA revealed a significant main effect of Condition, F (1, 23) = 4.96, p = .03, η^2p = 17 indicating that QE Offset generally occurred later in the high pressure (M = 554.13ms, SD = 27.98) than in the low pressure session (M= 547.88ms, SD = 27.98). There was also a Condition X Group interaction, F (1, 23) = 9.05, p = .006, η^2p = .28. This interaction was driven by a later occurrence of the QE offset for the training group in the High pressure (M = 561.13ms, SD = 24.26) compared to the Low pressure testing session (M = 545.59ms, SD = 21.57), t (11) = 3.74, p = .003, d = .67. In contrast, the control group revealed no significant improvement between the two testing sessions, (Low pressure M = 550.00ms, SD = 29.84; High pressure M = 547.66ms, SD = 30.43), t< 1. The main effect of Group was not significant F<1. QE offset data are presented in Figure 4.

****Insert Figure 4 about here****

Discussion

We examined whether a computer-based adaptive cognitive training method targeting the efficiency of executive control functions of WM could improve performance in tennis players when confronted with elevated levels of competitive pressure. It was predicted that improving WM capacity as a result of the adaptive dual n-back training task would result in transferrable benefits on processing efficiency, which in turn would protect tennis players against the negative impact of competitive anxiety on objective indices of attentional control and performance outcomes in a tennis volleying task.

Results initially revealed a near transfer effect of training. More precisely we found that WM training resulted in transferrable gains to WM capacity; an improvement that was not evident for the active control group whose task only required limited engagement of WM. The training related gains observed in WM capacity are in line with previous research employing the dual n-back adaptive training paradigm in both healthy and vulnerable populations (Jaeggi et al., 2008; Jaeggi et al., 2011; Owens, et al., 2013; Siegle et al., 2014; Sari et al., 2015; Course-Choi et al. 2017).

Importantly, our results also indicate that it is possible to find far transfer effects of adaptive WM training on sporting performance under heightened levels of pressure - when WM demands are at their greatest. The training group's volley performance significantly improved under pressure relative to the non-pressure post training session, whereas volley performance for the control group did not change. Although pressure did not cause a decrease in performance (cf. choking) for the control group, it appears as though increased pressure attenuated potential learning effects that would be expected due to the high-pressure condition always following the low-pressure condition (e.g., Ducrocq et al., 2016).

The QE duration results mirrored the tennis performance results in terms of this significant main effect for condition (both being greater under high, compared to low pressure). While this supports a functional role for QE in underpinning accurate performance (see Lebeau et al., 2016 meta-analysis), there was no additional interaction effect for QE duration. The lack of variance in QE onset across conditions or groups may partly explain why the overall QE duration was not sensitive enough to reveal why WM training revealed the far transfer effect. Instead, the training effect observed on tennis performance appears to have been modulated by extensions in the later phase of the QE period specifically; participants in the training group did reveal significantly later QE offset under pressure than those allocated to the control group. Previous research has revealed that the QE offset may be particularly sensitive to the influence of pressure – in golf putting (Vine et al., 2013), basketball shooting (Oudejans Langenberg & Hutter, 2002) and dart throwing (Nibbeling, Oudejans & Daanen, 2012) – and our results support this contention in an interception task.

The importance of maintaining a later QE is related to the suggestion that overt gaze shifts from an object to be struck (e.g., a ball) are preceded by a covert attentional shift occurring earlier (Vickers, 2007). Maintaining a later QE offset therefore provides conditions by which both overt and covert attention are more likely to be maintained on the contact area at the moment of impact. While previous research has revealed that this attentional strategy can be explicitly taught (Vine et al., 2011; Moore et al., 2012), the current study reveals that similar benefits can be achieved by targeting general functions of WM involved in the efficient execution of such actions.

The current study therefore adds to the findings of Ducrocq et al. (2016) who showed that computer-based inhibition training could lead to enhanced inhibitory control and improved tennis volley performance. Participants who engaged in inhibition training were better able to inhibit the action of glancing at the target while (or before) making contact with the ball. We show that by training additional shifting and updating functions of WM it is also possible to extend functional attentional control on the tracked target (the ball) via a delayed QE offset. Additionally, while the inhibition training task adopted by Ducrocq et al. (2016) included task-relevant search items (i.e. tennis balls in an array of other spherical items), the training task in the current study was both multi-modal (visual and auditory) and not sport specific. These findings therefore provide stronger support for a generic effect of WM training on the functions of attentional control that are important in sport settings, and as such, have important theoretical and practical implications.

First, the results support the predictions of ACT (Eysenck et al., 2007) that worrying about performance disrupts execution by reducing WM capacity and increasing bottom up processing. Similar levels of worry were reported by both groups, but the impact this had on processing efficiency was greater for the control group; who were unable to achieve the levels of extended attentional control (later QE offset) and performance effectiveness of the trained group when under pressure. As research suggests that negative thinking related to distraction tends to be more common than any other thought category among elite performers in high-pressure sporting contexts (Oudejans, Kuijpers, Kooijman, & Bakker, 2011), future research should investigate the potential efficacy of cognitive training methods specifically designed to target sports-related negative thinking and cognitive biases. Such research would support the refinement of a new development of ACT specifically for sport (ACTS; Eysenck & Wilson, 2016), which considers the influence of the performer's interpretation of the pressurised situation on subsequent attentional control.

Second, while it is important to acknowledge that the claims for the utility of so-called brain training (neuro-doping) devices for sport outstrips the evidence for their generic far-transfer benefits (see Simons, Boots, Charness, Gathercole, Chabris et al., 2016, for a critical review and commentary), the findings of the current paper suggest that specific far-transfer – to WM intensive, pressurised environments - is achievable. The empirical evidence therefore supports ACT's theoretical predictions for a moderating role of attentional control, revealing exciting implications for training in sport and other domains where motor performance must be accurate under pressure (e.g., military, surgery, aviation, etc.). Specifically, it may be possible for generalizable cognitive training to benefit performance under pressure in a range of related skills, rather than each skill requiring targeted training based on specific expert models (cf. quiet eye training; Vine et al., 2014).

Whilst the present results are highly encouraging, the current study comprises several potential limitations which could be addressed in future studies. Cognitive and tennis performance was assessed immediately following the completion of the training period and it remains unclear whether the training effect observed is sustainable over time. While there is evidence for sustained neural plasticity for WM training (Dahlin, Stigsdotter Neely, Larsson, Bäckman & Nyberg, 2008), future studies could include a delayed retention test occurring several weeks after training (cf. Miles et al., 2015). Additionally, future research could also monitor players' tennis performance during competitive games to determine if effects transfer to the 'real world' (cf. Causer et al., 2011a; Vine et al., 2011). Furthermore, whilst the tennis players recruited for the present study were club players who engage in regular competitive activities they can still be considered as recreational players. With research showing that expert performance can be mediated by individual differences in WM capacity (Furley & Wood, 2016; Buszard & Masters, 2017) future research should therefore aim to test the efficacy of cognitive training on elite / professional tennis players.

There are also potential limitations with the design of the active control group task, despite its use in previous research (Owens et al., 2013) and its ability to control for any confounding effect of time exposure to a computerised task (Shipstead, Lindsey, Marshall, & Engle, 2014). First, as the level of difficulty did not increase during training, performance accuracy could not be meaningfully compared to the adaptive n-back group (see footnote 1). Additionally, it is possible that performing the same n-back task for 10 days was demotivating and this could explain the performance differences in post-training conditions. However, as performance on the 1-back task was maintained throughout training, and there were no group differences in far transfer performance in the post-training, low-pressure condition, this explanation is unlikely. Finally, a stronger conclusion for the benefits of WM training to performance under pressure could potentially have been made if both groups had undergone a pre-training pressure test. However, as in previous research testing the efficacy of training on performance under pressure (e.g., Ducrocq et al., 2016; Moore et al., 2012; Vine & Wilson, 2011) concerns related to repeated exposure to pressure manipulations was a more pressing concern.

To conclude, the present results lead the way for future research to further explore the potential application of cognitive training methods in improving processing efficiency of WM and attentional control. Training updating, inhibition and shifting functions of WM led to enhanced WM capacity (near transfer) and improved ability to maintain effective attentional control and subsequent tennis performance under pressure (far transfer). The strength of the findings - when compared with much of the neuro-training literature - emanate from the focused empirical test of theoretically developed predictions about the influence of worry on specific functions of WM (ACT, Eysenck et al., 2007; ACTS, Eysenck & Wilson, 2016). As such, the potential practical significance of the findings can be targeted towards far transfer to sporting or non-sporting domains where complex and fine movements are performed under elevated levels of pressure.

Footnotes:

[1] As performance is assessed in different ways, it is not possible to meaningfully compare training task performance between groups across the ten days. The important metric for the control group is accuracy, which should be high throughout training if participants remain engaged in this simple task. Accuracy is less relevant to the training group as their task becomes more difficult over time. Instead, it is the degree to which they increase this difficulty of the task ('n') that is important.

[2] In the pre testing session, the QE durations for both control (M = 428.84ms, SD = 42.87) and training groups (M = 432.30ms, SD = 63.74) were similar (t<1). The timing of the QE Offset was also similar for both training (M = 542.50ms, SD = 24.89) and control groups (M =549.01ms, SD = 33.49), as was the timing of the QE onset (training; M=115.21ms, SD = 49.85 vs control; M = 110.38ms, SD = 34.65; t's<1). Lastly in the pre testing session, tennis accuracy scores did not differ between the control group (M = 2.58, SD =.77) and the training group (M =2.68, SD =1.11), t < 1.

References

Au, J., Sheehan, E., Tsai, N., Duncan, G. J., Buschkuehl, M., & Jaeggi, S. M. (2015). Improving fluid intelligence with training on working memory: A meta-analysis. *Psychonomic Bulletin and Review, 22*(2), 366–377. doi:10.3758/s13423-014-0699-x

Behan, M., & Wilson, M. (2008). State anxiety and visual attention: The role of the quiet eye period in aiming to a far target. *Journal of Sport Sciences*, *26*, 207-215, doi: 10.1080/02640410701446919.

Berggren, N., & Derakshan, N. (2013). Attentional control deficits in anxiety: Why you see them and why you don't*. Biological Psychology, 92*, 440-446. doi: 10.1016/j.biopsycho.2012.03.007

Buszard, T., & Master, R, S, W. (2017). Adapting, correcting and sequencing movements: does working-memory capacity play a role? International review of sports and exercise psychology, 1-21. http://dx.doi.org/10.1080/1750984X.2017.1323940

Castiello, U., & Umiltà, C. (1992). Orienting of attention in volleyball players. International Journal of Sport Psychology, 23, 301-310.

Causer, J., Holmes, P. S., Smith, N. C., & Williams, A. M. (2011a). Anxiety, movement kinematics, and visual attention in elite-level performers. *Emotion*, *11*, 595-602, doi: 10.1037/a0023225.

Causer, J., Holmes, P. S., & Williams, A. M. (2011b). Quiet eye training in a visuomotor control task. *Medicine & Science in Sports & Exercise*, *43*, 1042-1049, doi: 10.1249/MSS.06013e3182035de6.

Course-Choi, J., Saville, H., & Derakshan, N. (2017). The effects of adaptive working memory training and mindfulness meditation training on processing efficiency and worry in high worriers. *Behaviour Research and Therapy 89*, 1-13. https://doi.org/10.1016/j.brat.2016.11.002

Dahlin, E., Stigsdotter Neely, A., Larsson, A., Bäckman, L., & Nyberg, L. (2008). Transfer of learning after updating training mediated by the striatum. Science, 320(5882), 1510–1512.

Derakshan, N., & Eysenck, M.W. (2009). Anxiety, processing efficiency, and cognitive performance: new developments from attentional control theory. *European Psychologist 14,* 168-176.

Ducrocq, E., Vine, S., Wilson, M., Derakshan, N, (2016). Training attentional control improves cognitive and motor task performance. *Journal of sport and exercise psychology, 5*,521-533. doi: 10.1123/jsep.2016-0052

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion*, *7*, 336-353.

Eysenck, M. W. & Wilson, M. R. (2016). Pressure and sport performance: A cognitive approach. Introducing Attentional Control Theory: Sport. In D. Groome & M. Eysenck (eds). *An introduction to applied cognitive psychology* (pp. 329-350). London: Routledge.

Faul, F., Erdfelder, E., Lang, A.G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*, 175-191.

Furley, P., & Wood, G. (2015). Working memory, attentional control, and expertise in sports: A review of current literature and direction for future research. *Journal of Applied Research in Memory and Cognition 5*,415–425.

Geukes, K., Harvey, J.T., Trezise, A., & Mesagno, C. (2017). Personality and performance in real-world competitions: Testing trait activation of fear of negative evaluation, dispositional reinvestment, and athletic identity in the field. *Psychology of Sport & Exercise, 30,* 101-109.

Han, D. H., Park, H. W., Kee, B. S., Na, C., Na, D.-H. E., & Zaichkowsky, L. (2011). Performance enhancement with low stress and anxiety modulated by cognitive flexibility. *Psychiatry Investigations, 8,* 221-226.

Horowitz-Kraus, T., and Z. Breznitz. 2009. Can the error detection mechanism benefit from training the working memory? A comparison between dyslexics and controls- an ERP study. *PLoS One* 4:e7141.683. doi: 10.1371/journal.pone.0007141

Jaeggi, S.M., Buschkuehl, M., Jonides, J., & Perrig, W.J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences, 105*, 6829–6833.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Shah, P. (2011). Short- and long-term benefits of cognitive training. *Proceedings of the National Academy of Sciences of the USA, 108*, 10081-10086.

Kassner, M., Patera, W., & Bulling, A. (2014b, April). Pupil: an open source platform for pervasive eye tracking and mobile gaze-based interaction. arXiv: 1405. 0006 [cs-cv]. Retrieved from http://arxiv.org/abs/1405.0006

Koster, E, H, W., Hoorelbeke, K., Onraedt, T, Owens, M., & Derakshan, N. (2017). Cognitive control interventions for depression: A systematic review of findings from training studies. *Clinical psychology review, 53,* 79-92. doi: 10.1016/j.cpr.2017.02.002

Lebeau, J. C., Liui, S., Saenz-Moncaleano, C., Sanduvete-Chaves, S., Chacon- Moscoso, S., Becker, B. J., et al. (2016). Quiet eye and performance in sport: A meta-analysis. *Journal of Sport & Exercise Psychology, 38,* 441-457. http:// dx.doi.org/10.1123/jsep.2015-0123

Luu, P., Tucker, D.M., Derryberry, D., Reed, M., & Poulsen, C. (2003). Electrophysiological responses to errors and feedback in the process of action regulation. Psychological Science,14, 47-53.

Miles, C. A. L., Wood, G., Vine, S. J., Vickers, J. N., & Wilson, M. R. (2015). Quiet eye training facilitates visuomotor coordination in children with developmental coordination disorder. *Research in Developmental Disabilities, 40*, 31–41. doi:10.1016/j. ridd.2015.01.005

Moore, L., Vine, S. J., Cooke, A. M., Ring, C., & Wilson, M. R. (2012). Quiet eye training expedites motor learning and aids performance under pressure: The roles of response programming and external attention. *Psychophysiology, 49,* 1005-1015. doi:10.1111/j.1469-8986.2012.01379.x

Moore, L.J., Wilson, M.R., Vine, S.J., Coussens, A., & Freeman, P. (2013b). Champ or chump? Challenge and threat states during pressurized competition. *Journal of Sport & Exercise Psychology, 35,* 551-562.

Moran, A., Quinn, A., Campbell, M., Rooney, B., Brady, N., & Burke, C. (2016). Using pupillometry to evaluate attentional effort in quiet eye: A preliminary investigation. *Sport Exercise and Performance Psychology, 5*(3). http://dx.doi.org/ 10.1037/spy0000066.

Nibbeling, N., Oudejans, R. R. D., & Daanen, H. A. M. (2012). Effects of anxiety, a cognitive secondary task, and expertise on gaze behaviour and performance in a far aiming task. *Psychology of Sport & Exercise*, *13*, 427-435. doi:10.1016/j.psychsport.2012.02.002

Oudejans, R. R. D., Kuijpers, W., Kooijman, C. C., & Bakker, F. C. (2011). Thoughts and attention of athletes under pressure: Skill-focus or performance worries? *Anxiety, Stress & Coping*, *24*, 59-73. doi: 10.1080/10615806.2010.481331

Owens, M., Koster, E. H. W., & Derakshan, N. (2013). Improving attention control in dysphoria through cognitive training: Transfer effects on working memory capacity and filtering efficiency. *Psychophysiology, 50(3),* 297-307. doi: 10.1111/psyp.12010

Rodrigues, S. T., Vickers, J. N., & Williams, A. M. (2002). Head, eye and arm coordination in table tennis. *Journal of Sports Sciences, 20,* 187 - 200.

Sari, B. A., Koster, E. H. W., Pourtois, G., & Derakshan, N. (2015). Training working memory to improve attentional control in anxiety: A proof-of-principle study using behavioural and electrophysiological measures. *Biological Psychology*, doi: 10.1016/j.biopsycho.2015.09.008.

Shipstead, Z., Lindsey, D. R. B., Marshall, R. L., & Engle, R. W. (2014). The mechanisms of working memory capacity: Primary memory, secondary memory, and attention control. *Journal of Memory and Language*, *72*, 116–141.

Spielberger, C.C., Gorsuch, R.L., Lushene, R., Vagg, P.R., & Jacobs, G.A. (1983). *Manual for the State-Trait Anxiety Inventory*. Palo Alto, CA: Consulting Psychologists Press

Siegle, G. J., Price, B. P., Jones, N. P., Ghinassi, F., Painter, T., & Thase, M. E. (2014). You gotta work at it: Pupillary indices of task focus are prognostic for response to a neurocognitive intervention for rumination in depression. *Clinical Psychological Science*, *2,* 455–471.

Simons, D. J., Boot, W. R., Charness, N., Gathercole, S. E., Chabris, C. F., Hambrick, D. Z., & Stine-Morrow, E. A. L. (2016). Do "Brain-Training" Programs Work? *Psychological Science in the Public Interest, 17(3),* 103–186. https://doi.org/10.1177/1529100616661983

Sun, G., Zhang, L., Vine, S.J., & Wilson, M.R. (2016). The quiet eye provides pre-planning and online control support for interceptive task performance. *Journal of Sport & Exercise Psychology, 38,* 458-469. DOI: http://dx.doi.org/10.1123/jsep.2016-0012.

Unsworth, N., Redick, T. S., Spillers, G. J., & Brewer, G. A. (2012). Variation in working memory capacity and cognitive control: Goal maintenance and micro adjustments of control. *The Quarterly Journal of Experimental Psychology*, 65(2), 326 - 355. doi: 10.1080/17470218.2011.597865

Vickers, J. N. (1996). Visual control when aiming at a far target. *Journal of Experimental Psychology: Human Perception & Performance, 2*, 324-354.

Vickers, J. N., & Williams, A. M. (2007). Performing under pressure: The effects of physiological arousal, cognitive anxiety, and gaze control in biathlon. *Journal of Motor Behavior*, *39*, 381-394, doi:10.3200/JMBR.39.5.381-394

Vine, S. J., Lee, D., Moore, L. J., & Wilson, M. R. (2013). Quiet eye and choking: Online control breaks down at the point of performance failure. *Medicine & Science in Sports & Exercise, 45*, 1988–1994, doi.org/10.1249/MSS.0b013e31829406c7

Vine, S. J., Moore, L. J., & Wilson, M. R. (2014). Quiet eye training: The acquisition, refinement and resilient performance of targeting skills. *European Journal of Sports Sciences, 14*, 235-242.

Vine, S. J., & Wilson, M. R. (2011). The influence of Quiet Eye training and pressure on attentional control in a visuo-motor task. *Acta Psychologica, 136,* 340-346. doi: 10.1016/j.actpsy.2010.12.008

Vogel, E. K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature, 438*, 500–503.

Walters-Symons, R., Wilson, M.R., & Vine, S.J. (2017). The Quiet Eye supports error recovery in golf putting. *Psychology of Sport & Exercise, 31,* 21-27. doi.org/10.1016/j.psychsport.2017.03.012.

Wilson, M. R. (2012). Anxiety: Attention, the brain, the body and performance. In S. Murphy (Ed), *The Oxford handbook of sport and performance psychology*. New York, NY: Oxford University Press. p. 173-90.

Wilson, M. R., Miles, C. A., Vine, S. J., & Vickers, J. N. (2013). Quiet eye distinguishes children of high and low motor coordination abilities. *Medicine & Science in Sports & Exercise, 45,* 1144-1151. doi:10.1249/MSS.0b013e31828288f1

Wilson, M. R., Vine, S. J. & Wood, G. (2009a). The influence of anxiety on visual attentional control in basketball free-throw shooting. *Journal of Sport & Exercise Psychology, 31,* 152-168.

Wilson, M. R., Wood, G. &, Vine, S. J. (2009b). Anxiety, attentional control and performance impairment in penalty kicks. *Journal of Sport & Exercise Psychology, 31,* 761-775.

Wood, G., Hartley, G., Furley, P.A., & Wilson, M (2016). Working memory capacity, Visual Attention and hazard perception in driving. *Journal of Applied Research in Memory and Cognition, 5,* 454–462

Wood, G. & Wilson, M. R. (2012). Quiet-eye training, perceived control and performing under pressure. *Psychology of Sport and Exercise, 13*, 721-728. doi:10.1016/j.psychsport.2012.05.003

Table 1: Mean (standard deviations) Quiet Eye Onset and Quiet Eye durations between training groups and across conditions.

Condition	Group	QE (ms)	QE ON (ms)
Low Pressure	Training	435.40 (47.06)	110.13 (34.28)
High Pressure	Training	459.09 (49.08)	102.06 (36.00)
Low Pressure	Control	429.89 (46.26)	120.13 (34.28)
High Pressure	Control	435.04 (39.87)	111.15 (28.54)

Figure captions

Figure 1: An example of a distractor condition in a change trial in the Change Detection Task (CDT) designed to test near transfer (working memory capacity). Participants were first cued to which side of the memory array they should attend to (right hand side in this example). They were instructed to memorize the orientation of the red (dark grey) rectangles in the cued side of the memory array and ignore any blue (light grey) rectangles. Following a 900ms retention period they responded as to whether a change in any red rectangle orientation was present or not in the cued side of the test array. In the example shown there was a change in the orientation of one of the two red rectangles between the memory and test array.

Figure 2: Mean K scores on the change detection task for both groups pre- and post- online training (Error bars = SEM).

Figure 3: Mean Tennis accuracy scores (0-10) for both training groups across post-training non-pressure and pressure testing conditions (Error bars = SEM).

Figure 4: Mean QE offset (ms) for both training groups across post-training non-pressure and pressure testing conditions (Error bars = SEM).

Figure 1

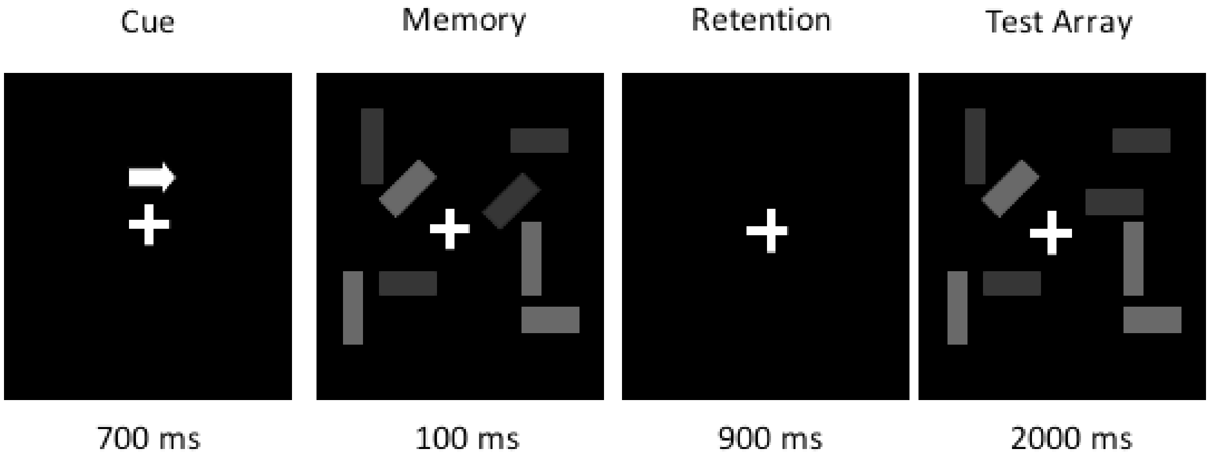


Figure 2:

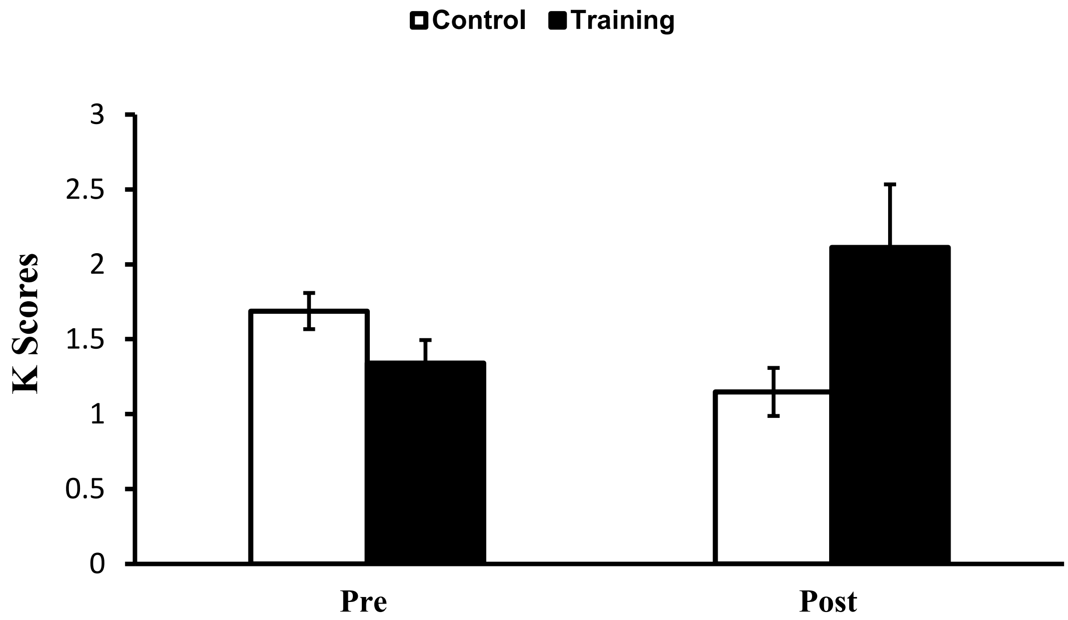


Figure 3

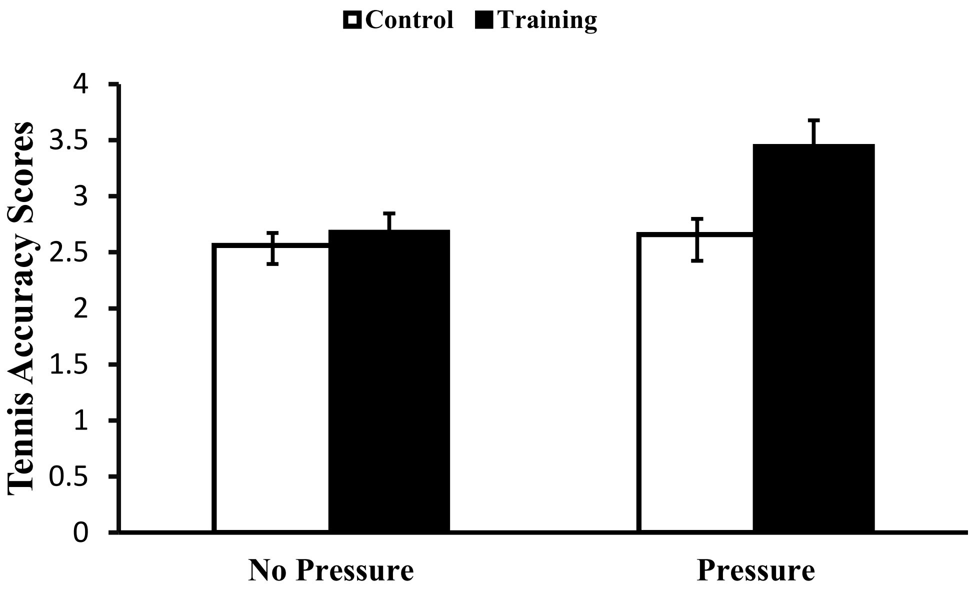
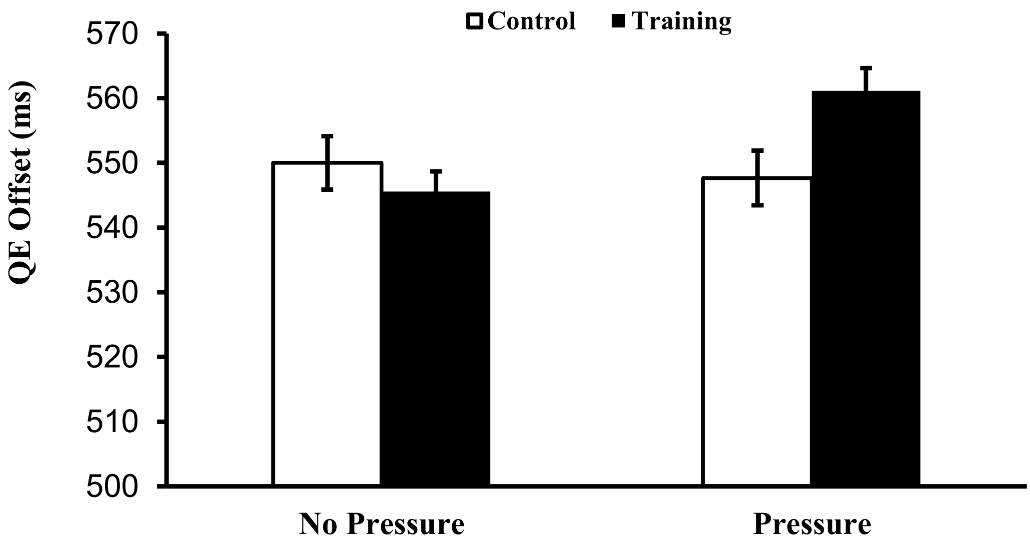

Control
Training
Tennis Accuracy Scores
4
3.5
3
2.5
2
1.5
1
0.5
0
No Pressure
Pressure

Figure 4


Control
Training
QE Offset (ms)
570
560
550
540
530
520
510
500
No Pressure
Pressure