QUIET EYE DURATION AND GUN MOTION IN ELITE SHOTGUN SHOOTING

J. Causer[1], S.J. Bennett[1], P. Holmes[2], C. Janelle[3], A.M. Williams[1]

[1]Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, UK, [2]Department of Exercise and Sport Science, Institute for Performance Research, Manchester Metropolitan University, Alsager, UK, [3]Department of Applied Physiology and Kinesiology, University of Florida, Gainesville

Corresponding author: Prof. A. Mark Williams, Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, The Henry Cotton Campus, 15-21 Webster Street, Liverpool, L3 2ET, UK. Tel - +44 151 231 4489, Fax - +44 151 231 4353, E-mail - m.williams@ljmu.ac.uk

RUNNING HEAD: EXPERTISE IN SHOOTING

Abstract

Introduction: No literature exists to document skill-related differences in shotgun shooting and whether or not these may be a function of eye movements and control of gun motion. We therefore conducted an exploratory investigation of the visual search behaviors and gun barrel kinematics employed by elite and sub-elite shooters across the three shotgun shooting sub-disciplines. **Methods**: Point of gaze and gun barrel kinematics were recorded in groups of elite (n =24) and sub-elite (n = 24) shooters participating in skeet, trap, and double trap events. Point of gaze was calculated in relation to the scene, while motion of the gun was captured by two stationary external cameras. Quiet eye (final fixation or tracking gaze that is located on a specific location/object in the visual display for a minimum of 100ms) duration and onset were analyzed as well as gun motion profiles in the horizontal and vertical planes. **Results:** In skeet, trap, and double trap disciplines, elite shooters demonstrated both an earlier onset and longer relative duration of quiet eye than their sub-elite counterparts. Also, in all three disciplines, quiet eye duration was longer and onset earlier during successful compared to unsuccessful trials for elite and sub-elite shooters. Kinematic analyses indicated that a slower movement of the gun barrel was employed by elite compared to sub-elite shooters. **Conclusion:** Overall, stable gun motion and a longer quiet eye duration appear critical to successful performance in all three shotgun disciplines.

Key Words: expertise, target shooting, visual behavior, kinematics

Introduction

Paragraph Number 1 In target sports, such as golf, archery, and billiards, the ability to accurately select the correct parameters for movement appears crucial for successful execution (24). Access to pertinent visual stimuli and the effective processing of information are essential in these sports. While performance in these sports is based on aiming at a stationary target, shotgun shooting requires competitors to hit a target that is moving away from or across them at speeds up to 100kmh^{-1}. Consequently, the event requires less of a focus on aiming and is more akin to an interceptive task, with the shooter trying to intercept the clay with the shot. To date, there have been no attempts to examine visual search or gun barrel kinematics in such targeting tasks, or how these factors interact with expertise. Our aim in this study was to explore how visual search and gun barrel movement characteristics differ between skilled and less skilled shooters across successful and unsuccessful shots. The intention was to identify the key factors that contribute to expert performance in the three shotgun sub-disciplines (i.e., skeet, trap, and double trap), providing insight into the visual and kinematic process underpinning expert performance in the sports.

Paragraph Number 2 The majority of previous researchers have focused their efforts on how objects moving towards an athlete are tracked. These include: the penalty kick in soccer (22); receiving serve in volleyball (27); attempting to strike baseball pitches (21); and batting in cricket (13). Vickers (26) identified three gaze control phases for interceptive actions: object-recognition; object-tracking; and object-control. During the object-recognition phase, fixations and pursuit tracking are used to determine the trajectory and movement parameters of the target. The object-tracking phase involves smooth pursuit-tracking to keep the target in the fovea (the center of the retina where there is close pairing of ganglion cells to photoreceptors, thereby permitting greatest visual acuity) to ensure any changes in trajectory

are detected. Finally, in the object-control phase, fixations and tracking behaviors are used to stabilize the eyes as the target is successfully intercepted.

Paragraph Number 3 In recent years, researchers investigating interceptive tasks have focused on a visual phenomenon known as the 'quiet eye period' (QE). The QE was defined by Vickers (24) as the final fixation or tracking gaze that is located on a specific location or object in the visuo-motor workspace within 3° of visual angle for a minimum of 100ms. It has been reported that the onset of the QE period occurs earlier and its duration is longer in elite compared with sub-elite athletes in sports such as golf (25), basketball (9), ice hockey (20), billiards (30), and rifle shooting (11,28). Moreover, several researchers have identified a longer QE period on successful compared to unsuccessful trials across a number of tasks (19,24,30). It has been argued that during the QE period, performers set the final parameters of the movement, process appropriate environmental cues and synchronize motor strategies (14). The key principle is that QE is associated with the amount of cognitive programming required for a successful action (30).

Paragraph Number 4 Previously, researchers that have considered shooting sports have focused on the rifle (12,29,31) and pistol (8,15,21) disciplines. These tasks involve relatively small gun movements to a stationary target. However, shotgun shooting produces a much large variability between shots and greater uncertainty with respect to the target. In shotgun shooting, there are three main sub-disciplines: skeet, trap, and double trap. In each sub-discipline, shooters attempt to accurately align their gun in preparation for the clay(s) and then anticipate the release of the target(s). Once released, shooters must track the moving target with the gun barrel before pulling the trigger at an optimal time. Abernethy and Neal (1) reported that in clay shooting an ability to rapidly and reliably detect the target on release and to track the target accurately appears critical to successful performance. However,

differences in gaze behaviors are likely to be evident across each shooting discipline because of the varying task constraints and subsequent demands of each shot.

Paragraph Number 6 In skeet shooting, two towers (high and low) are situated on the left and right of the layout and targets are released horizontally across the shooter from either one or both of the trap houses simultaneously. The shooter has one shot per target to break the clays and shoots 25 targets from eight different positions per round. In trap shooting the target is released from a 'trap' concealed in a trench 15m in front of the shooting stations. The targets can be released from one of three traps which propel the clays in different directions; the left trap throws targets to the right (up to 45° from centre), the central trap throws straight-away targets ($\pm 15^{\circ}$ from centre) and the right trap throws targets to the left (up to 45° from centre). Shooters are allowed two shots to hit the target and shoot 25 targets from 5 different stations per round. In double trap, two targets are released simultaneously from the three most central traps. The left-centre trap throws targets to the right (up to 5° from centre), the centre-centre trap throws straight-away targets and the right-centre trap throws targets to the left (up to 5° from centre). Shooters are allowed one attempt per target and shoot 25 pairs from 5 different stations per round. In both trap and double trap disciplines, the target is moving away from the shooter at speeds of up to 65mph, ensuring that the probability of hitting the target reduces as the shot cluster becomes more dispersed and the targets representation on the retina decreases.

Paragraph Number 7 There are few previous reports of shotgun shooting performance. Abernethy and Neal (1) employed a battery of standardized visual tests in a laboratory environment to determine differences in visual function between skill groups. No differences were evident for shooters in rapid tachistoscopic detection and coincidence timing selection compared to a control sample. In contrast, Czigler et al. (4) found that shooters demonstrated more efficient attentive processing, with faster and more accurate responses

than a control group in a visual discrimination task that required fast information processing. Di Russo et al. (6) reported similar findings when measuring visual scanning behavior in high level target shooters in relation to a control sample. Shooters were found to have shorter saccadic latency to targets in both a simple reaction task and a discrimination task. Morillo et al. (18) also found that trained shooters have shorter saccadic latency, as well as shorter antisaccadic latency in both gap (fixation point removed at time of target presentation) and overlap (fixation point always present) conditions. In consideration of the underlying mechanisms, Di Russo et al. (5) examined the effect of practice on the brain activity of clay target shooters using self paced flexion movements of either the right or left index finger. The data suggest that the Bereitschaftspotential and negative slope latencies were longer for shooters, indicating an extended duration of domain specific motor preparation. BP amplitudes were smaller compared to a control group, but only for the right, triggering finger. No group differences were found for motor potential and reafferant positivity. Based on these findings, the authors concluded that motor task execution is performed more economically and at a lower metabolic cost as domain specific experience increases. Overall, the results identify a number of discriminating variables in shooting performance across a variety of skill levels. While such psychophysiological evidence is indeed compelling, overt perceptual-cognitive aspects of performance as well as the movement kinematics employed by the shooters may also account for important additional variance that discriminates between skill groups and across shot outcome.

Paragraph Number 8 A biomechanical analysis of shotgun shooting was conducted by Bourne et al. (3) to identify common performance characteristics across the three shotgun sub-disciplines. The kinematic profile of the body segments and gun barrel in relation to each shooter's centre of pressure were recorded. It was concluded that a common approach is taken

to the maintenance of centre of pressure and movement across the shooting sub-disciplines, with hip rotation accounting for the majority of the horizontal displacement of the gun barrel.

Paragraph Number 9 No literature exists to document skill-related differences in shotgun shooting, and whether these may be a function of eye movements and control of gun motion. In the current paper, we explored the visual search behaviors and gun barrel kinematics employed by elite and sub-elite shooters across the three different shooting sub-disciplines. Key performance variables were analyzed in an attempt to identify the factors that discriminate shooters at elite and sub-elite levels of the sport. The QE characteristics, gun barrel kinematics, and the relationship between the final fixation on the clay (QE period), alongside the onset of the QE period and shot outcome were examined in elite and sub-elite shooters as they shot in skeet, trap, and double trap sub-disciplines. According to prior work (e.g., 24) elite shooters should exhibit both an earlier onset of QE and a longer final fixation on the clay compared to sub-elite shooters. Moreover, when a within-group analysis is employed, longer QE durations and earlier onsets of QE have been reported on successful compared to unsuccessful trials (19,24,30). We hypothesized that the same effect will be evident across all disciplines of shotgun shooting. Due to the nature of the task in the current study, we adapted the definition of QE cited in Vickers (24) to encompass the current task constraints and demands. In the present study QE is defined as the final tracking gaze that is located on the moving target for a minimum of 100ms.

Paragraph Number 10 Given the paucity of previous research on the kinematics of shotgun shooting, our approach is largely descriptive but is rooted in established conceptual notions forwarded in traditional (7) and contemporary (10) notions of skill learning. These theories advocate that elite performers exhibit more efficient and consistent action production than sub-elite or novice performers. Because the position of the barrel in relation to the clay determines whether the shot is successful or unsuccessful, movement of the gun to get to this

final position was assumed to be crucial to successful performance. The techniques that are employed for moving the gun to the final shot position were expected to differ between elite and sub-elite shooters in each of the sub-disciplines. Differences in gun motion were predicted between elite and sub-elite shooters across each of the shooting disciplines. Although differences in gun barrel kinematics between elite and sub-elite shooters (12,15,29) have been reported in other shooting disciplines (i.e., pistol, rifle), fundamental differences in the specific nature of these tasks prevent clear predictions from being articulated. We report several kinematic measures and provide a descriptive analysis of the variables in relation to the respective shooting disciplines; this is essential in order to identify fundamental differences between skill level and shot outcome and to better design training programs to enhance performance in shooters.

Materials and methods

Participants

Paragraph Number 11 Forty-eight shooters provided written informed consent prior to participating. Shooters were categorized according to their specialized sub-discipline (skeet/trap/double trap) and then each sub-discipline was sub-divided into two groups based on their skill level (elite/sub-elite). For skeet, the elite group comprised eight shooters from the Great Britain (GB) squad (age, 29.3±9.0) with an average of 11.4 years of experience in shooting. All shooters were ranked in the top ten in the country at the time of testing. The sub-elite group (age, 30.1±7.2) consisted of eight recreational shooters with an average of 7.25 years of shooting. The elite group in trap comprised eight members of the GB squad (age, 30.6±10.5) who had an average of 11.1 years of experience in shooting. All shooters were ranked in the top ten in the country at the time of testing. The sub-elite group (age, 32.0±8.5) consisted of eight recreational shooters with an average of 6.9 years of shooting. The double

trap elite group comprised eight shooters currently in the top ten GB rankings (age, 26.9±4.8) who had an average of 9.8 years of experience in shooting. The sub-elite group (age, 36.2±12.1) consisted of eight recreational shooters with an average of 5.5 years of shooting. All shooters had normal or corrected- to-normal visual acuity. Participants used their own personal shotguns and wore their normal shooting attire. Approval for the study was gained via the Ethics Committee of the lead institution and participants were free to withdraw from testing at any stage.

Measures

Visual search behaviors

Paragraph Number 12 Visual search behaviors were recorded using a mobile corneal reflection system (Applied Science Laboratories; Waltham, MA, Model ASL Mobile Eye II). This mobile system uses a method known as 'Dark Pupil Tracking' in which the relationship between two eye features, the pupil and a reflection from the cornea, is computed to locate gaze within a scene. The mobile eye has a system accuracy of 0.5° visual angle, resolution of 0.10° visual angle and visual range of 50° horizontal and 40° vertical.

Gun barrel kinematics

Paragraph Number 13 Video data were collected to calculate the coordinates of the gun barrel in order to provide a more comprehensive understanding of the shooting action. Two Cannon XM2 Digital Video cameras (Cannon, USA) sampling at 50Hz and with a shutter speed of 1/150 were employed. Each camera was positioned 4.0m in front of the shooting station at an angle of 50° relative to the centre of the range, one camera on the left side of the range and the other on the right, at a height of 0.9m. The cameras were connected to a central computer by two Firewire cables and the camera shutters were synchronized using a signal sent from the central computer. The cameras filmed simultaneously during each

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shooting trial. The shooting area was calibrated using a twelve point, three-dimensional frame.

Procedures

Paragraph Number 14 Participants only shot in their own specialized sub-discipline (skeet/trap/double trap). All trials took place from the central shooting station in the range. An International Shooting Sport Federation (ISSF) shooting range is designed to accommodate all three Olympic shooting events. In each of the disciplines the central shooting station is located at the same position in the range (station 3 for double trap and trap; station 4 for skeet). In skeet, shooters were positioned at station 4, shooting the high target first. For trap, the central trap was used with the target projected directly away from the shooter, and in double trap, targets were released from the left and central traps. Participants were required to take 20 shots from the shooting station. During all trials, the shooters were required to follow the normal rules of their discipline as stipulated by the ISSF.

Before collecting data from each participant, a 25mm diameter expanded polystyrene marker was attached to the underside of the gun barrel by a cable tie to enable digitization of the gun barrel for kinematic analysis. The marker was not visible to the shooters during their routine. Participants were fitted with the mobile eye system, which was then calibrated using reference points in the shooting range. The calibration was conducted while participants were in their 'normal' shooting stance. Before each shot the video cameras were activated to record the movement and outcome of the shot. The mobile eye system recorded data for the entire duration of the test session, although the accuracy of the calibration was checked periodically. The inter-trial interval was 60 seconds.

Statistical analysis

Paragraph Number 15 A total of four hit and four miss shots were identified for each shooter for further analysis. For skeet and double trap, a miss was defined as a successful shot on the first clay but missing the second. This was due to the low miss frequency for the first target in each of the disciplines. After each trial, participants were asked to state whether the shot was a 'good' or 'bad' trial, irrelevant of outcome. For analysis, only hits that were seen to be good shots, and misses that were seen to be bad shots were selected. This ensured only the best and worst shots were analyzed. Coaches often utilize this technique to make a qualitative judgment about the shot based on individualized quality criteria. For each trial, the saved kinematic video files were imported into the SIMI Motion 6 (SIMI Reality Motion Systems, Unterschleissheim, DE) analysis software. To increase accuracy, the marker placements were measured using three Qualysis cameras (Gothenburg, Sweden). An average calibration error of 0.76% of screen size was found, which is in the acceptable range recommended by SIMI software (between 0-3%) for accurate analysis. The gun barrel marker was manually tracked in both video recordings for five frames before the initiation of the movement and the following five frames after the completion of the shot were digitized.

Paragraph Number 16 Visual search behavior data were analyzed frame by frame using Gamebreaker (Sportstec, Camarillo, USA) software. Relative QE duration, QE onset and shot time were analyzed. Relative QE was defined as the percentage of QE duration relative to the shot time. In trap, total shot time was defined as, the moment of clay appearance to shot release, and for skeet and double trap, the time from shot one to shot two. Relative QE was used due to the variances in shot times. Onset of QE was determined as the time from shot one until QE initiation in skeet and double trap, and from clay release until QE initiation in trap. Eye movements were logged manually from the video recordings and QE characteristics were determined by frame counts. The objectivity of the eye movement data

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was established using intra-observer (97.2%) and inter-observer (95.8%) agreement methods. For the kinematic data, peak velocity, time from peak velocity to shot, total movement time, individual shot movement times (skeet/double trap) and gun barrel displacements in the horizontal and vertical axes were analyzed. Peak velocity characteristics enable elements of shooting technique to be identified (i.e., are the shooters tracking the clay until the barrel 'catches up' with the target, or accelerating ahead of the target and then waiting for the clay to reach the gun barrel). A two-way mixed design ANOVA was used to examine the effect of skill (elite/sub-elite) and shot outcome (hit/miss) on all of the individual variables with repeated measures on the last factor. The effect sizes were calculated using partial eta squared values (η_p^2) and Cohen's d as appropriate. The alpha level for significance was set at 0.05. If the sphericity assumption was violated, the Huynh-Feldt correction was used.

Results

Skeet

Relative quiet eye duration

Paragraph Number 17 There were significant main effects for skill, $F_{1, 14}= 27.269$, $p < 0.05$, $\eta_p^2 = 0.66$, and outcome, $F_{1, 14}= 77.000$, $p < 0.05$, $\eta_p^2 = 0.85$. The elite shooters displayed a longer relative duration of quiet eye on both hits ($M = 65.0\pm1.7\%$ vs. $56.4\pm4.0\%$) and misses ($M = 60.1\pm2.5\%$ vs. $52.9\pm3.8\%$) compared to the sub-elite shooters. The results are presented in Figure 1. There was no significant interaction between skill x outcome, $F_{1, 14}= 2.063$, $p > 0.05$, $\eta_p^2 = 0.13$.

Onset of quiet eye

Paragraph Number 18 There were significant main effects for skill, $F_{1, 14} = 23.750$, $p < 0.05$, $\eta_p^2 = 0.63$, and outcome, $F_{1, 14} = 33.333$, $p < 0.05$, $\eta_p^2 = 0.71$. The elite shooters

displayed significantly earlier onset of quiet eye (M = 220.8$\pm$16.7ms) compared to sub-elite shooters (M = 255.5$\pm$19.5ms). An earlier quiet eye onset was observed on hits (M = 228.8$\pm$25.7ms) compared to misses (M = 247.5$\pm$21.2ms). The results are presented in Figure 2. The interaction between skill x outcome was not significant ($F_{1, 14}$ = 2.096, $p > 0.05$, η_p^2 = 0.13).

Peak velocity for shot two

Paragraph Number 19 Significant main effects were observed for skill, $F_{1, 14}$ = 14.117, $p < 0.05$, η_p^2 = 0.50, and outcome, $F_{1, 14}$ = 4.769, $p < 0.05$, η_p^2 = 0.25. The elite shooters displayed significantly lower peak velocity (M = 0.79$\pm$0.11m/s) compared to sub-elite shooters (M = 1.01$\pm$0.15m/s). The mean peak velocity values were lower on hits (M = 0.87$\pm$0.18m/s) compared to misses (M = 0.94$\pm$0.16m/s). The interaction between skill x outcome was not significant ($F_{1, 14}$ = 0.062, $p > 0.05$, η_p^2 = 0.00).

Insert *Table 1* about here

Time from peak velocity to shot two

Paragraph Number 20 There was a significant main effect for skill, $F_{1, 14}$ = 23.282, $p < 0.05$, η_p^2 = 0.62, and outcome, $F_{1, 14}$ = 4.741, $p < 0.05$, η_p^2 = 0.25. The elite shooters displayed a significantly shorter period from peak velocity to taking the shot (M = 283.8$\pm$53.8ms) compared to sub-elite shooters (M = 455.0$\pm$69.5ms). This period of time was significantly shorter on hits (M = 350.0$\pm$ 98.7ms) compared to misses (M = 388.8$\pm$102.7ms). No interaction effects were apparent between skill and outcome, $F_{1, 14}$ = 0.400, $p > 0.05$, η_p^2 = 0.03.

Total movement time

Paragraph Number 21 There were no significant main effects for skill, $F_{1, 14} = 1.087$, $p > 0.05$, $\eta_p^2 = 0.07$, or outcome, $F_{1, 14} = 2.403$, $p > 0.05$, $\eta_p^2 = 0.15$, and no skill x outcome interaction, $F_{1, 14} = 3.380$, $p > 0.05$, $\eta_p^2 = 0.19$.

Movement time for shot one

Paragraph Number 22 There were no significant main effects for skill, $F_{1, 14} = 1.908$, $p > 0.05$, $\eta_p^2 = 0.12$. However, there was a significant main effect for outcome, $F_{1, 14} = 15.295$, $p < 0.05$, $\eta_p^2 = 0.52$, and a significant interaction between skill and outcome, $F_{1, 14} = 9.718$, $p < 0.05$, $\eta_p^2 = 0.41$. The mean movement time for shot one of sub-elite shooters did not differ between hits and misses ($d = 0.39$), whereas the elite shooters employed significantly shorter movement times on hits compared to misses ($d = 1.63$).

Movement time for shot two

Paragraph Number 23 There were no significant main effects for skill, $F_{1, 14} = 0.634$, $p > 0.05$, $\eta_p^2 = 0.04$, or outcome, $F_{1, 14} = 0.443$, $p > 0.05$, $\eta_p^2 = 0.03$, and no significant interaction, $F_{1, 14} = 0.391$, $p > 0.05$, $\eta_p^2 = 0.03$.

Displacement of gun shot two (horizontal axis)

Paragraph Number 24 There was a significant main effect for skill, $F_{1, 14} = 86.539$, $p < 0.05$, $\eta_p^2 = 0.86$ (see Table 1). The elite shooters displayed a significantly shorter gun displacement in horizontal axis ($M = 17.8\pm5.6$cm) compared to sub-elite shooters ($M = 30.7\pm2.4$cm). There was no main effect for outcome, $F_{1, 14} = 3.780$, $p > 0.05$, $\eta_p^2 = 0.21$, and no skill x outcome interaction, $F_{1, 14} = 0.889$, $p > 0.05$, $\eta_p^2 = 0.06$.

Displacement of gun shot two (vertical axis)

Paragraph Number 25 There was a significant main effect for skill, $F_{1, 14} = 9.932$, $p < 0.05$, $\eta_p^2 = 0.42$. The elite shooters displayed a significantly larger gun displacement in the vertical axis ($M = 3.3\pm0.9$cm) compared to sub-elite shooters ($M = 2.0\pm0.6$cm). There were no main effects for outcome, $F_{1, 14} = 0.094$, $p > 0.05$, $\eta_p^2 = 0.01$, and no skill x outcome interaction, $F_{1, 14} = 0.441$, $p > 0.05$, $\eta_p^2 = 0.03$.

Insert *Figure 1* about here

Trap

Relative duration of Quiet eye

Paragraph Number 26 There were significant main effects for skill, $F_{1, 14} = 55.199$, p < 0.05, $\eta_p^2 = 0.80$, and outcome, $F_{1, 14} = 227.554$, $p < 0.05$, $\eta_p^2 = 0.94$. The elite shooters displayed significantly longer relative duration of quiet eye ($M = 58.4\pm3.5\%$) compared to sub-elite shooters ($M = 50.1\pm2.8\%$). Significantly longer quiet eye durations were evident on hits ($M = 56.5\pm4.8\%$) compared to misses ($M = 52.2\pm4.8\%$). The results are presented in Figure 1. The interaction between skill and outcome interaction was not significant, $F_{1, 14} = 0.380$, $p > 0.05$, $\eta_p^2 = 0.03$.

Onset of quiet eye

Paragraph Number 27 There were significant main effects for skill, $F_{1, 14} = 5.453$, $p < 0.05$, $\eta_p^2 = 0.28$, and outcome, $F_{1, 14} = 62.618$, $p < 0.05$, $\eta_p^2 = 0.82$. As depicted in Figure 2, the elite shooters displayed significantly earlier onset of quiet eye ($M = 198.8\pm25.4$ms) compared to sub-elite shooters ($M = 228.3\pm30.0$ms). Earlier quiet eye onset was observed on hits ($M = 202.0\pm29.2$ms) compared to misses ($M = 225.0\pm29.6$ms). The interaction between skill and outcome was not significant $F_{1, 14} = 1.266$, $p > 0.05$, $\eta_p^2 = 0.08$.

Insert *Figure 2* about here

Peak velocity

Paragraph Number 28 Significant main effects were observed for skill, $F_{1,\ 14} = 17.339$, $p < 0.05$, $\eta_p^2 = 0.55$, and outcome, $F_{1,\ 14} = 6.095$, $p < 0.05$, $\eta_p^2 = 0.30$ (see Table 2). The elite shooters displayed significantly lower peak velocity ($M = 0.51\pm0.05$m/s) compared to sub-elite shooters ($M = 0.66\pm0.13$m/s). Significantly lower peak velocities were also observed on hits ($M = 0.55\pm0.12$m/s) compared to misses ($M = 0.64\pm0.15$m/s). The interaction was not significant, $F_{1,\ 14} = 3.016$, $p > 0.05$, $\eta_p^2 = 0.18$.

Insert *Table 2* about here

Time from peak velocity to shot

Paragraph Number 29 A significant main effect was observed for skill, $F_{1,\ 14} = 762.961$, $p < 0.05$, $\eta_p^2 = 0.98$. The elite shooters displayed a significantly shorter period from peak velocity to the shot ($M = 24.0\pm3.1$ms) compared to sub-elite shooters ($M = 170.0\pm20.5$ms). There was no main effect for outcome, $F_{1,\ 14} = 1.230$, $p > 0.05$, $\eta_p^2 = 0.08$, and no skill x outcome interaction, $F_{1,\ 14} = 1.060$, $p > 0.05$, $\eta_p^2 = 0.07$.

Total movement time

Paragraph Number 30 Significant main effects were apparent for skill, $F_{1,\ 14} = 17.039$, $p < 0.05$, $\eta_p^2 = 0.55$, and outcome, $F_{1,\ 14} = 7.001$, $p < 0.05$, $\eta_p^2 = 0.33$. The elite shooters displayed a significantly shorter total movement time ($M = 623.1\pm94.0$ms) compared to sub-elite shooters (M = 815.0 ± 111.2ms). Moreover, movement time was shorter on hits ($M = 685.6\pm126.4$ms) compared to misses ($M = 752.5\pm128.9$ms). There was no skill x outcome interaction, $F_{1,\ 14} = 0.006$, $p > 0.05$, $\eta_p^2 = 0.00$.

Displacement of gun (horizontal axis)

Paragraph Number 31 There were significant main effects for skill, $F_{1, 14} = 16.607$, $p < 0.05$, $\eta_p^2 = 0.54$, and outcome, $F_{1, 14} = 5.993$, $p < 0.05$, $\eta_p^2 = 0.30$. The elite shooters displayed a significantly shorter gun displacement in the horizontal axis ($M = 1.3\pm0.5$cm) compared to sub-elite shooters ($M = 2.2\pm0.6$cm). Lower displacement scores were apparent on hits ($M = 1.5\pm0.6$cm) compared to misses ($M = 2.1\pm0.7$cm). The elite shooters displayed a shorter displacement on both hits ($M = 1.1\pm0.4$cm) and misses ($M = 1.5\pm0.5$cm) compared to the sub-elite shooters hits ($M = 1.8\pm0.6$cm) and misses ($M = 2.7\pm0.4$cm). The differences in displacement increased proportionately for each skill level from hits to misses. There was no significant skill x outcome interaction, $F_{1, 14} = 0.878$, $p > 0.05$, $\eta_p^2 = 0.06$.

Displacement of gun (vertical axis)

Paragraph Number 32 A significant main effect for skill was observed, $F_{1, 14} = 23.306$, $p < 0.05$, $\eta_p^2 = 0.63$. The elite shooters displayed a significantly shorter gun displacement in vertical axis ($M = 11.9\pm0.8$cm) compared to sub-elite shooters ($M = 16.6\pm3.6$cm). There was no significant main effect for outcome, $F_{1, 14} = 6.487$, $p > 0.05$, $\eta_p^2 = 0.03$, and no skill x outcome interaction, $F_{1, 14} = 0.153$, $p > 0.05$, $\eta_p^2 = 0.01$.

Double Trap

Relative duration of Quiet eye

Paragraph Number 33 Significant main effects were evident for skill, $F_{1, 14} = 13.610$, $p < 0.05$, $\eta_p^2 = 0.49$, and outcome, $F_{1, 14} = 141.087$, $p < 0.05$, $\eta_p^2 = 0.91$. The elite shooters displayed significantly longer relative duration of quiet eye ($M = 55.0\pm3.7\%$) compared to sub-elite shooters ($M = 49.7\pm3.8\%$). A longer mean relative duration of quiet eye was apparent on hits ($M = 54.6\pm4.0\%$) compared to misses ($M = 50.1\pm3.9\%$). The results are

presented in Figure 1. There was no interaction between skill and outcome, $F_{1, 14} = 3.460$, $p > 0.05$, $\eta_p^2 = 0.20$.

Onset of quiet eye

Paragraph Number 34 There were significant main effects for skill, $F_{1, 14} = 55.041$, $p < 0.05$, $\eta_p^2 = 0.80$, and outcome, $F_{1, 14} = 58.155$, $p < 0.05$, $\eta_p^2 = 0.81$. The elite shooters displayed significantly earlier onset of quiet eye ($M = 182.8\pm19.7$ms) compared to sub-elite shooters ($M = 247.0\pm26.2$ms). An earlier mean onset of quiet eye was evident on hits ($M = 201.1\pm39.4$ms) compared to misses ($M = 228.8\pm36.2$ms). The skill x outcome interaction was not significant, $F_{1, 14} = 1.353$, $p > 0.05$, $\eta_p^2 = 0.09$. The results are presented in Figure 2.

Insert *Table 3* about here

Peak velocity for shot two

Paragraph Number 35 There were no significant main effects for skill ($F_{1, 14} = 2.001$, $p > 0.05$, $\eta_p^2 = 0.13$), or outcome ($F_{1, 14} = 0.121$, $p > 0.05$, $\eta_p^2 = 0.01$), and no interaction ($F_{1, 14} = 0.696$, $p > 0.05$, $\eta_p^2 = 0.05$).

Total movement time

Paragraph Number 36 There were significant main effects for skill, $F_{1, 14} = 361.258$, $p < 0.05$, $\eta_p^2 = 0.96$, and outcome, $F_{1, 14} = 8.391$, $p < 0.05$, $\eta_p^2 = 0.38$ (see Table 3). The elite shooters displayed a significantly shorter total movement time ($M = 943.9\pm63.1$ms) compared to sub-elite shooters (M = 1549.4 ± 77.2ms). Shorter movement times were observed on hits ($M = 1226.9\pm210.6$ms) compared to misses ($M = 1266.4\pm258.5$ms). The skill x outcome interaction was not significant ($F_{1, 14} = 1.509$, $p > 0.05$, $\eta_p^2 = 0.10$).

Movement time for shot one

Paragraph Number 37 Significant main effects were observed for skill, $F_{1, 14} = 35.741$, $p > 0.05$, $\eta_p^2 = 0.72$, and outcome, $F_{1, 14} = 6.411$, $p > 0.05$, $\eta_p^2 = 0.31$. The elite shooters displayed a significantly shorter total movement time ($M = 206.9\pm67.5$ms) compared to sub-elite shooters (M = 355.6 ± 28.5ms). There were also significant differences between hits ($M = 271.3\pm84.6$ms) and misses ($M = 291.3\pm89.6$ms). The interaction was not significant $F_{1, 14} = 2.029$, $p > 0.05$, $\eta_p^2 = 0.13$.

Movement time for shot two

Paragraph Number 38 A significant main effect for skill was observed, $F_{1, 14} = 369.106$, $p < 0.05$, $\eta_p^2 = 0.96$. The elite shooters displayed a significantly shorter movement time (M = 737.0 ± 46.6ms) compared to sub-elite shooters (M = 1193.8 ± 56.2ms). There was no significant main effect for outcome, $F_{1, 14} = 3.191$ $p > 0.05$, $\eta_p^2 = 0.19$, and no skill x outcome interaction, $F_{1, 14} = 0.254$, $p > 0.05$, $\eta_p^2 = 0.02$.

Displacement of gun shot one (horizontal axis)

Paragraph Number 39 There was a significant main effect for skill, $F_{1, 14} = 70.302$, $p < 0.05$, $\eta_p^2 = 0.83$. The elite shooters displayed a significantly smaller gun displacement ($M = 0.4\pm0.2$cm) compared to sub-elite shooters ($M = 1.1\pm0.2$cm). The main effect for outcome was not significant, $F_{1, 14} = 0.153$, $p > 0.05$, $\eta_p^2 = 0.01$, and neither was the skill x outcome interaction, $F_{1, 14} = 0.153$, $p > 0.05$, $\eta_p^2 = 0.01$.

Displacement of gun shot one (vertical axis)

Paragraph Number 40 There was a significant main effect for skill, $F_{1, 14} = 32.524$, $p < 0.05$, $\eta_p^2 = 0.70$. The means revealed that elite shooters displayed a significantly smaller

gun displacement ($M = 1.7\pm0.6$cm) compared to sub-elite shooters ($M = 3.5\pm0.6$cm). There was no main effect for outcome, $F_{1, 14} = 0.498$, $p > 0.05$, $\eta_p^2 = 0.03$, and no skill x outcome interaction, $F_{1, 14} = 2.497$ $p > 0.05$, $\eta_p^2 = 0.15$.

Displacement of gun shot two (horizontal axis)

Paragraph Number 41 Significant main effects were noted for skill, $F_{1, 14} = 7.515$, $p < 0.05$, $\eta_p^2 = 0.35$, and outcome, $F_{1, 14} = 11.624$, $p < 0.05$, $\eta_p^2 = 0.45$. The elite shooters displayed a significantly smaller gun displacement ($M = 7.3\pm1.1$cm) compared to sub-elite shooters ($M = 8.6\pm1.6$cm). A smaller gun displacement was evident on hits ($M = 7.3\pm1.0$cm) to misses ($M = 8.6\pm1.7$cm). The interaction between skill and outcome was not significant, $F_{1, 14} = 2.975$, $p > 0.05$, $\eta_p^2 = 0.18$.

Displacement of gun shot two (vertical axis)

Paragraph Number 42 There were no significant main effects for skill ($F_{1, 14} = 3.263$, $p > 0.05$, $\eta_p^2 = 0.19$), or outcome ($F_{1, 14} = 1.335$, $p > 0.05$, $\eta_p^2 = 0.09$), and no interaction, $F_{1, 14} = 0.077$, $p > 0.05$, $\eta_p^2 = 0.01$.

Discussion

Paragraph Number 43 Although research has been undertaken using static aiming and interceptive tasks with approaching objects, limited attention has been devoted to tasks where the target travels away from the participant and is intercepted by an external object, as is the case in shotgun shooting. In this paper we analyzed key performance variables in an attempt to identify the factors that discriminate shooters at elite and sub-elite levels across the three shotgun sub-disciplines. Based on previous work (9,24,28), we predicted that elite shooters would exhibit both an earlier onset of QE and a longer final fixation on the clay compared to sub-elite shooters, as well as an earlier onset of QE on successful compared to

unsuccessful shots across all sub-disciplines. It was also predicted that there would be differences in gun motion between elite and sub-elite shooters across each of the shooting sub-disciplines.

Quiet eye

Paragraph Number 44 As predicted, relative QE duration was significantly longer for elite compared to sub-elite shooters, supporting previous findings in other sport tasks (9,11,25). Longer relative QE periods were also recorded on successful compared to unsuccessful shots, regardless of skill level. The latter finding supports previous work (19,24,30) and reinforces the view that the QE duration is an important factor in successful performance across a multitude of aiming tasks. Our findings illustrate the importance of the QE period in a novel, externally paced, interceptive task, with the target moving away from the participant. This evidence advances the research on QE by identifying how it influences performance in sports that require unique orienting and visual control skills.

Paragraph Number 45 The QE period is theorized to be used for cognitive processing during which the movement parameters for the task are programmed before action is executed (14). The longer QE in the current study could, therefore, enable the shooters to more accurately process the trajectory, direction, and speed of the clay in relation to the gun barrel before selecting the correct response characteristics. However, research is required to validate this assumption either involving experimental manipulations to the task constraints or by embracing technological and theoretical advances in the neurosciences. Williams et al. (30) imposed time constraints on billiards shots to assess the impact of QE periods. The constraints led to a reduction in the preparatory phase of the movement, decreasing QE duration significantly in both skill levels. The QE period in the billiard task appears to reflect underlying cognitive processes that play a highly influential role in preparation of the

movement. A similar method could be utilized in shooting to provide a greater understanding of the underlying mechanisms associated with the QE period.

Paragraph Number 46 Those examining the QE in sport have typically focused on self-paced tasks where the last fixation can be relatively long (e.g., basketball free throws, (24); rifle shooting, (11); billiards, (30)). However, in shotgun shooting, the task is externally paced and the shooter is under severe temporal pressure. As the target is moving away from the shooter the probability of intercepting it the shot lessen as the target size decreases. Consequently, delaying the shot could substantially reduce the chances of a successful outcome. It is possible that the elite shooters have developed a strategy to pull the trigger at an 'optimal time' allowing the greatest probability of success, but enabling enough time prior to the shot to accurately program the action.

Paragraph Number 47 The earlier onset of QE that was evident for elite shooters compared with sub-elite shooters in the current study is consistent with previous research in other aiming and interceptive tasks (9,11,20). It has been suggested that this strategy enables the shooters to process information about the flight of the clay earlier than the sub-elite shooters. Moreover, this finding suggests that the elite shooters are better at anticipating the release of the clay and attending to the most critical cues to initiate the correct response. As a result of the temporal constraints inherent in clay-target shooting, shooters need to detect the clay early and then to track it in an uninterrupted manner before pulling the trigger (1). An earlier onset of QE was found in trap and double trap in relation to skeet, in both skill groups. This finding may be due to the different task constraints in each of the disciplines. The trap and double trap sub-disciplines require early clay detection and that the trigger be pulled early to increase success probability as the clay is moving away, whereas skeet shooters do not require such a quick detection and onset of QE due to the clay moving across the layout with the image size of the target being relatively stable.

Gun barrel kinematics

Paragraph Number 48 As predicted, differences were found in all sub-disciplines between skill groups and shot outcome in the gun motion. In skeet the elite shooters demonstrated a lower gun barrel displacement in the horizontal axis, but showed no differences in movement time on shot two. This finding suggests that the elite (peak velocity 0.79m/s) shooters have a slower motion from picking up the target until the shot compared to their sub-elite (peak velocity 1.01m/s) counterparts. Analysis of the velocities in both skeet and trap shows lower peak velocities are evident on hits compared to misses and the velocities are significantly lower for elite compared to sub-elite shooters. This lower peak velocity apparently results in a more stable motion of the gun with no periods of high acceleration. The ability to keep the gun barrel stable throughout the shooting movement has been seen to be critical in rifle shooting using a running target task (17) as well as in air-pistol shooting and other rifle studies with stationary targets (15,16). Although similar results are presented in the current study, the task constraints and complexities differ significantly. Both skill groups in skeet and trap demonstrated shorter movement times on hits compared to misses. A shorter movement time would enable more time to complete the second shot in skeet and decrease the distance travelled away from the shooter by the target in trap.

Paragraph Number 49 Two different strategies were determined in the skeet and trap sub-disciplines. The elite shooters shoot at, or just after, their peak velocity, implying that the gun is increasing in speed as it catches up to the clay until the trigger is pulled. In contrast, the sub-elite shooters fire significantly later after the peak velocity of the gun. Further analysis showed that sub-elite shooters tended to accelerate early in the movement to get ahead of the clay and then decrease gun barrel speed until the target catches up before then pulling the trigger. This strategy leads to higher peak velocities initially in order to get ahead of the

target. It also gives a reasonable explanation for why there are larger horizontal axis displacements in the sub-elite shooters.

Paragraph Number 50 A different strategy was used in the double trap because of the more severe temporal constraints. The elite shooters pulled the trigger significantly earlier on both shots, compared to the sub-elite shooters, and therefore had a lower total movement time. This strategy gives the elite shooters greater opportunity to hit the targets because they have not travelled as far away from the trap. The sub-elite shooters had a tendency to spend an increased time period on shot one, reducing their chances of a successful second shot. When the sub-elite shooters hit the second target they demonstrated a significantly lower movement time for shot one. The elite shooters also demonstrated lower horizontal axis displacement on the second shot. This latter finding is likely a consequence of taking the shot earlier and, in doing so, the angular displacement of the clays is smaller than when the sub-elite shooters pull the trigger. The elite shooters also demonstrated a surprisingly small gun barrel displacement from target release to shot one. The elite shooters greater task knowledge and experience in the discipline likely enables them to more accurately anticipate the clay appearance and line-up the gun barrel to allow a quick and efficient shot.

Paragraph Number 51 While a seminal investigation, our findings may have important implications for sport specific training and performance enhancement. We have highlighted a number of variables that affect performance across the different sub-disciplines of shotgun shooting. We have examined the performance strategies employed by truly elite performers *in situ,* identifying a multitude of discriminating performance measures that directly affect shot outcome and differentiate across skill levels in shotgun shooting. The results can be used to improve the perceptual-cognitive skills of shooters by using video analysis and feedback techniques in the shooting environment. For example, Adolphe, et al. (2) used video feedback of gaze behavior to train elite volleyball player's performance

accuracy in passing to the area occupied by the setter. On-court sessions to improve ball detection, tracking and forearm passing skills were utilized. Significant pre- to post-test improvements were found in tracking onset, tracking duration, and the ability to maintain a stable gaze on the contact point during step corrections. Feedback and training of gaze behaviors could similarly be developed to improve performance and the knowledge bases of both elite and sub-elite shooters.

Paragraph Number 52 In conclusion, completion of this project extended knowledge of QE and its application using a novel sporting task and world class athletes. The key performance characteristics that discriminate elite from sub-elite shotgun shooters were identified using both kinematic and point of gaze data. Longer relative QE and earlier onset of QE, coupled with a smaller gun barrel displacement and more efficient timing strategy appeared to be the most important factors mediating expert performance. Also, different spatial and temporal strategies were identified between elite and sub-elite shooters that were evident across all three sub-disciplines of shotgun shooting. The elite shooters modified their shooting strategy to increase the probability of a successful shot outcome based on the specific task constraints of the sub-disciplines allowing a more efficient and effective movement.

Acknowledgements

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Legends for Figures

Figure 1. Mean relative QE duration (%) in each sub-discipline between a) elite and sub-elite shooters; b) successful and unsuccessful trials.

Figure 2. Mean onset of QE (ms) in each sub-discipline between a) elite and sub-elite shooters; b) successful and unsuccessful trials.