Quiet eye and accuracy in the dart throw

Joan N. Vickers, The University of Calgary, Canada; Sergio T. Rodrigues, State University of Sao Paulo, Brazil, Gene, Edworthy, The University of Calgary, Canada.

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Abstract

Gaze behaviour and arm movements of skilled dart players (N = 5) were recorded as they threw an equal number of hit and misses to the centre of a regulation dart board. Quiet eye (QE) was defined as final fixation on the target, with onset prior to the extension of the arm and offset when QE deviated off the target. Accuracy was affected by the temporal offset of QE relative to the phases of the arm movement. During hits, QE onset occurred during late alignment and offset during early flexion resulting in the gaze being off the target for 550 ms. During misses, QE offset occurred during mid-alignment, resulting in the gaze being off the target for 1167 ms. The results highlight the importance of the temporal control of QE relative to the movements of arm. Quiet eye information gained too soon or too late did not lead to the same level of accuracy as that obtained optimally, just prior to the final movement being initiated.

Keywords: vision, eye movements, gaze behaviour, expertise, darts, motor control, visual imaging

Introduction

Intuitively one would think there is a direct link between the ability to maintain fixation on a far target and aiming accuracy. This view is supported by research on aiming to near targets where the hand is directed toward a target within arm’s reach (Abrams, 1994; Abrams, Meyer & Kornblum 1990). In near aiming tasks, the performer tracks the hand during the initial part of the movement and then uses efferent information derived from fixation on the target to perform the final homing-in movement. The late use of vision and it’s role in refining the action supports on-line models of motor control, ones that use vision to modify actions as the movement unfolds.

Aiming to far targets, such as that found in basketball or darts, appears to use a different form of visuo-motor control, with two theoretical models being plausible (closed, open). Closed-loop models support the on-line modulation of movements as they are performed (Schmidt & Lee, 1999). In this case, visual information arising from fixation on the target provides feedback that continually maintains and refines the movement as it is performed. A closed-loop model of control would therefore support the use of vision on a continual basis as central to achieving higher levels of accuracy.

In open-loop models of control, vision on the target is used to organize the aiming commands prior to the final movement, which is run-off without any need for feedback (Carlton, 1981a; Carlton 1981b; Schmidt & Lee, 1999). Open-loop models argue that since the aiming commands are set early during sustained fixation, there is no need to maintain vision on the target as the dart is thrown.

Author to whom all correspondence should be addressed: email:vickers@ucalgary.ca
In order to explore this issue, we recorded the gaze behaviour and arm movements of skilled dart players as they threw darts to the center bullseye of a regulation board. Gaze on the target was measured relative to the target center using a mobile eye tracker and analysed using visual imaging techniques (Rasband, 1997) that permitted the precise measurement of the gaze relative to the target centre during three phases of arm movement (alignment, flexion, extension).

Quiet eye is an objective measure of the location, onset, offset and duration of a fixation or tracking gaze recorded while the participant performs a motor or other skill (Vickers, 1996a; 1996b). During QE, fixation or tracking is maintained on a specific location or object in space, with onset in advance of movement initiation and offset a function of the gaze deviating off a specified location. QE has been found to be a characteristic of high levels of skill and accuracy in the basketball free throw (Vickers, 1996a; 1996b; 1996c); billiards, (Frehlich, 1998; Frehlich, Singer, Williams, 1999); rifle shooting (Janelle, Hillman & Hatfield, 2000a; 2000b; Vickers, Williams, Rodrigues, Hillis & Coyne, 1999); and volleyball serve reception and pass (Vickers & Adolphe, 1987; Adolphe, Vickers & LaPlante, 1997).

In the dart throw, QE was defined as the final fixation on the target prior to the extension of the arm toward the target. QE was therefore the performer’s last acquisition of target information before the final movement or MT was initiated. MT is traditionally defined as “the interval between the initiation of the movement and it’s termination” (Schmidt & Lee, 1999, p. 416). Movement time (MT) plays a critical role in the definition of QE and was defined as that portion of the final aiming movement common to all performers. In darts, as in many other skills, performers have unique preparatory actions that vary greatly from individual to individual (for example in the free throw, some participants do not have a down phase prior to shooting (Vickers, 1996a); in table tennis, some do not have a backswing (Vickers, Rodrigues & Brown, submitted). Despite considerable variability in their initial motor behaviours, however, all performers must have a final MT in order to perform a given skill. MT onset in the dart throw was therefore the final extension of the arm/hand forward to release of the dart.

If the dart throw is performed under closed-loop control, QE should remain on the target throughout the early (alignment) and late (flexion, extension) phases of the throw. A continuous stream of target information would provide on-line feedback and this should contribute to greater levels of accuracy. If the dart throw was under open-loop control, QE would be maintained on the target during the early alignment and/or flexion phases of the arm, but not during MT. The process of organizing the movement would occur during QE fixation in the alignment and/or flexion phases, removing any need for fixation to be maintained on the target as the dart was thrown. Finally, it was expected that QE would be nearer to the target center during hits than misses. Precision of the gaze relative to the target centre was expected to be characteristic of hits more than misses.

Method

Participants
Sixteen university students volunteered for the study in exchange for a free optometry examination. Five male participants were selected from this group, based on their 1) having 20/20 or better vision and no visual deficits, 2) being significantly more accurate in hitting the target than the others, F (1, 163) = 30.02, p <.0001 and, 3) having recorded at least three hits to the target out of 15 attempts while wearing the eye tracker. All participants were highly skilled but not competitive dart players; mean age, 21.7 (SD = 2.1).

Dart Task & Protocol
A regulation Danforth dart board was used. The dart board was positioned as in competitive darts, 2.36 m from the foot line at a height of 1.72 m. A high quality set of darts, weight of 24 grams was used. Upon arriving at the laboratory, the participants took
nine practice throws and then (in blocks of threes) performed 15 throws without the eye tracker. Each trial started with the command “Shut your eyes” followed by the word “Go”, when the participant opened his eyes and the gaze cursor appeared marking the onset of the trial. The eye tracker was then fitted, calibrated and an additional nine practice throws taken, followed by the final 15 throws. During data collection, the VIA data, as shown in Figure 1, was monitored continuously for accuracy. Practice, calibration and data collection took approximately 40 minutes per subject.

**Data Collection Procedures**

The Vision-in-Action (VIA, Vickers, 1996a) system recorded the gaze and arm movements of the participants as shown in Figure 1. The VIA system integrated Applied Sciences Laboratories 3001 eye tracker, an external movement camera, a time code generator and video mixers to create the perception-action coupling shown in Figure 1. The scene upper left, was recorded by the scene camera on the eye tracker and shows the dart board and target as viewed by the participant. Location of gaze is indicated by the black cursor and was recorded with an accuracy of one degree visual angle and precision 1/2 degree. The scene right was recorded by an external camera placed in the sagittal plane and provided information of the alignment, flexion and extension phases of the throw. The scene left below was recorded by the eye camera on the tracker and shows the cross hairs delineating the center of the pupil and corneal reflection. A time code generator recorded time simultaneously in all three images at 30 Hz or 33.33 ms per frame.

![Figure 1. A frame of Vision-In-Action (VIA) gaze and motor data. The three images were recorded simultaneously, thus permitting an analysis of the gaze on the target relative to the phases of arm movement.](image-url)
Data Imaging and Analysis
All hits were analysed (19; range 3-5 per participant) plus an equal number of randomly selected misses (19). The VIA data was digitized using a Silicon Graphics work station which converted the data from a frame rate of 30 Hz to a field rate of 60 Hz or 16.67 ms per field. NIH Image (Rasband, 1997) was used to determine the displacement of the center of the gaze cursor from the center of the target bullseye in pixel units during the final 90 fields or 1500 ms of each throw. NIH Image was developed at the Research Services Branch (RSB) of the National Institute of Mental Health (NIMH), part of the National Institutes of Health, and is in the public domain and available on the Internet at http://rsb.info.nih.gov/nih-image/.

Since the arm movements of the participant occluded the target on many trials, the center of the target was determined relative to the circumference of the board, which was always visible. NIH Image first determined the horizontal and vertical displacement of the center of the gaze cursor from the target center. Horizontal and vertical displacement values were then converted to a single measure of radial error (pixels units), which provided displacement of the center of the gaze from the center of the target over field units.

Three phases of the arm movement were defined, using the dart as a constant reference. During alignment, the dart was held in front and aligned in a stable manner on the target. Onset of arm flexion began with the first field indicating the movement of the dart toward the midline of the body. Onset of the extension phase began with the first field indicating the final movement of the dart away from the midline of the body. A trial ended with the field showing the dart leave the hand. QE fixation was defined as final fixation on the target (within 13.5 pixel units) for six or more consecutive fields (99.99 ms).

Results
Accuracy
No significant differences were found in accuracy due to wearing the eye tracker. Mean accuracy in centimeters, cm, without the eye tracker was 5.1 cm (SD 2.1) and 5.2 cm (SD 3.1) with the eye tracker.

Duration of alignment, flexion and extension
A one between (Phases) factorial ANOVA indicated the phases differed significantly in duration, F (2, 109 ) = 44.33, p < .0001. Mean duration of the alignment phase was M = 45.4 fields (Standard Error = 5.1), flexion was M = 34.9 (SE = 2.9) and extension (M = 9.7 fields (SE = .82). Since there were no significant differences in phase durations for hits and misses, these data were collapsed.

Gaze displacement from the target center
Mean radial error (RE, pixel units) of the gaze was plotted across 90 fields of the throw, or the final 1500 milliseconds as shown in Figure 2, for hits and misses. A RE of 0 indicated the center of the gaze cursor was located on the center of the target; a RE of 13.5 indicated the edge of the gaze cursor was located on the edge of the target. Figure 2 (inset figure) shows a graphic representation of this 13.5 RE relationship. Mean onsets of the flexion and extension (MT) phases (with SE) for hits and misses (collapsed) are indicated by the vertical dotted lines.

Five results are evident in Figure 2. First, the gaze deviated progressively off the target from field 1 to field 90, during both hits and misses. Two, during misses the gaze was closest to the target center during early alignment and deviated off the target at field 32. Three, during hits the gaze was closer to the target center during late alignment and early flexion and deviated off the target at field 57. Four, the gaze was furthest from the target center during the arm extension phase on both hits and misses. Five, QE offset occurred earlier during misses than hits, resulting in the gaze being off the target for 1167 ms during misses, as compared to 550 ms during hits.
In order to determine if the gaze deviated significantly off the target during hits and misses, the RE data were analysed using a one between (Accuracy) and one within (Fields) repeated measures ANOVA. A significant effect was found for Fields, $F(89, 3204) = 9.97, p < .0001$, but not for Accuracy, or the interaction of Accuracy x Fields. Figure 2 shows that the gaze deviated progressively off the target center on both hits and misses as the throw was prepared and executed.

Gaze displacement during each phase of the throw was similarly analysed. During extension, no significant differences were found, indicating the gaze was off the target by an equal measure during both hits and misses. During flexion, a significant effect was found for Fields ($F(34, 1224) = 2.24, p < .0001$, but not for Accuracy. The gaze moved progressively off the target equally on hits and misses. During alignment, a significant effect was found for Fields, $F(44, 1584) = 1.69, p < .003$, and the interaction of Fields x Accuracy, $F(44, 1584) = 2.07, p < .0001$. Figure 2 shows that during hits, the gaze remained nearer to the target centre during late alignment. During misses, the gaze remained nearer to the centre target during early alignment.

**Discussion**

The results showed that accuracy in darts was affected by the temporal control of QE fixation relative to the alignment, flexion and extension phases of the throw. Hits occurred when QE was of longer duration and occurred during late alignment and early flexion. The gaze deviated off the target following this, for a period of 550 ms. Misses occurred when QE was of shorter duration and had an offset that occurred too soon, during early alignment. This resulted in the gaze being off the target center for a mean of 1167ms.
These results provide support for an open-loop mode of control. Vision was not needed on the target as the final throw was performed. It was not enough to know where to look, or for how long, but also to know when to look at the target. Target information gained too soon or too late did not lead to the same levels of accuracy as that obtained optimally, just prior to the late alignment and flexion phases of the throw. Nearness of the gaze to the target centre did not affect accuracy, being similar on hits and misses over phases. Instead, it was the optimal onset, offset and duration of QE relative to the final extension phase of the throw that appeared to be the most important factor in accurate performance.

Theoretical Considerations
Posner & Raichle (1994) describe three networks of visual attention (posterior orienting, anterior executive and vigilance) that together provide information useful in interpreting the results in this study. Using the combination of reaction time and PET scan methods, they describe the posterior orienting network as being responsible for the control of the direction of gaze in space. This network, which is located in the parietal region, functions to direct visual attention to specific locations of interest and importance in a task. In the dart throw, this network may have been responsible for directing QE to the target during the alignment phase of each throw. The second network, the executive anterior network, is then responsible for bringing into consciousness critical aspects of what is being fixated and interpreting what is seen relative to task goals. In the dart throw this may have been responsible for the longer duration of QE, characteristic of higher levels of skill and accuracy. The anterior network imposes higher-order understandings on a task and allows the performer to control an action relative to specific goals. The vigilance network co-ordinates the functions of the posterior and anterior networks and prevents unwanted or distracting information from gaining access to either system. The vigilance network may be responsible for the sustained concentration one sees during highly competitive games of darts.

Recommendations
The results lead to a number of recommendations that can be applied in clinical, coaching and teaching settings. In darts, QE fixation should be timed so that its onset occurs on the target during late alignment and duration extends into early flexion. During this time, the target should be fixated during a period of sustained QE focus and concentration. QE offset should occur just prior to the arm extension, during mid-flexion resulting in the gaze being off the target for less than a half second. During extension of the arm and completion of the throw, it is not necessary to maintain fixation on the target. It is more important to perform the throw in a fluid quick manner, without concern for holding the gaze on the target center at this time.

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References


