Aiming for the Quiet Eye in Biathlon

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ABSTRACT

The duration of the so-called "Quiet Eye" (QE) – the final fixation before the initiation of a critical movement – seems to be linked to better perceptual-motor performances in various domains. For instance, experts show longer QE durations when compared to their less skilled counterparts. The aim of this paper was to replicate and extend previous work on the QE [Vickers and Williams 2007] in elite biathletes in an ecologically valid environment. Specifically, we tested whether longer QE durations result in higher shooting accuracy. To this end, we developed a gun-mounted eye tracker as a means to obtain reliable gaze data without interfering with the athletes' performance routines. During regular training protocols, we collected gaze and performance data of 9 members (age 19.8 ± 0.45) of the German national junior team. The results did not show a significant effect of QE duration on shooting performance. Based on our findings, we critically discuss various conceptual as well as methodological issues with the QE literature that need to be aligned in future research to resolve current inconsistencies.

CCS CONCEPTS

• Human-centered computing → Empirical studies in HCI; • Computing methodologies → Activity recognition and understanding;

KEYWORDS

Eye tracking, pupil, eye movements, Quiet Eye, Biathlon

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1 INTRODUCTION

The aim of this paper is to investigate the Quiet Eye (QE) hypothesis in elite biathletes and to replicate and extend on the previous work on QE in biathlon [Vickers and Williams 2007]. The question of why some people are more skilled in complex domains than other people has long been debated. It is specifically pronounced in high-performance sports where marginal advantages can make the difference between winning or loosing (e.g., getting a medal or breaking a record).

Optimal performance may require that the athlete is capable of picking up the right information at the right time and then take action as swiftly and accurately as possible. Various interacting systems are involved in the visual control of action: the motor system and the visual system [Land and Tatler 2009]. Temporal and spatial relationships between gaze fixations and motor action are seen as a key factor for performance [Mann et al. 2007]. In many sports, the duration of the final fixation before initiating the critical movement, the so called Quiet Eye [Vickers 1996b] is seen as a measure for perceptual-cognitive expertise, even though the cognitive mechanisms underlying the QE hypothesis are not fully understood.

Gaze information can potentially yield important insights into human performance, and in turn, enhance elite athletes' performance. To this end, eye tracking has become important in identifying elite athletes’ eye movement patterns [A.M. Williams and Frehlich 2002; Klostermann et al. 2013; Vickers 1996b; Vickers and Williams 2007]. Eye tracking is the process of monitoring eye movements for the purpose of analyzing the eye movement patterns relative to the head or determining the point of gaze. Eye tracking is an active multidisciplinary research field, which has shown great progress in the last decades in a range of domains including Medicine, Marketing, Psychology and Human factors [Duchowski 2007]. Several experiments have investigated performance of athletes by e.g., identifying differences between novices and experts or training novices based on knowledge of eye movements from experts [Afonso et al. 2012; Hayhoe et al. 2012; Huttermann et al. 2013; Mann et al. 2013; Paeglis et al. 2011; Pires et al. 2013; Pluijm et al. 2015].

Biathlon. Biathlon is a winter sport which combines cross-country skiing with rifle shooting. The athletes have to complete a given distance on skis while carrying their rifle (the minimum weight of the rifle is 3.5 kg). The total skiing distance is divided into either two or four shooting rounds on targets at a distance of 50 meters. Half of the shootings are performed in prone position, the other half in standing position. The size of the shooting targets are 4.5 cm in the prone position and 11.5 cm in the standing position, reflecting that postural control and hence keeping the rifle stable is harder in the standing condition. Each shooting round consist of five shots at five circular targets. Misses are penalized. The overall performance is determined by skiing time, shooting accuracy and time at the range. The biathletes are looking through the diopter while trying to bring the rifle in a position where the ring of the global sight and the focused target overlap as much as possible.
where the foveated object is typically much smaller than the visual angle for a minimum of 3°. Vickers and Williams [2007]. An overview of the QE hypothesis is provided in Vickers [1992]. The Quiet Eye is a popular hypothesis that relates fixation duration to performance [Vickers 1992]. An overview of the QE hypothesis is provided in Vickers [2016]. The definition of Quiet Eye varies between studies, but in this paper we will refer to the definition used by Vickers [1992] "the final fixation that is located on a specific location or object in the visuo-motor workspace within 3° of visual angle for a minimum of 100 ms". Vickers and Williams [2007] suggest that task-relevant environmental cues are processed, and motor programs are retrieved and coordinated for the successful completion of the task during the QE period [Vickers 1996a,b]. In several types of aiming tasks, such as rifle shooting, basketball and golf, studies have found that experts had longer QE periods and more pronounced hemispheric asymmetry than non-experts [Janelle et al. 2000; Vickers 1992; Vickers and Lewinski 2012]. While the validity of the QE hypothesis is confirmed by several studies the underlying processes are not fully understood. Studies in which the task demands have been manipulated reveal that more complex tasks required longer QE durations and only under a high information-processing load was QE beneficial [A.M. Williams and Frehlich 2002; Klostermann et al. 2013]. Studies on for example dart and bowling did not confirm QE beneficial [A.M. Williams and Frehlich 2002; Klostermann et al. 2013]. Studies on for example dart and bowling did not confirm QE beneficial. QE was shown in biathlon [Vickers and Williams 2007], but (1) QE is not explicitly related to fatigue, the obvious time pressure for the athletes nor the fact that keeping the eyes open for longer dries the eyes. (2) The criterion of 3° of visual angle within a foveated object is a rather large quantity especially in aiming tasks where the foveated object is typically much smaller than 3°. It is also a bit unclear why 3° is the critical value; (3) The critical action in biathlon may be interpreted as when the trigger is pushed but within biathlon the entire trigger action constitutes several critical steps. In other words, what is the critical action in a sequence of unfolding actions in this case?

3 EXPERIMENTAL SETUP

The purpose of the experiment is to scrutinize the QE hypothesis and to evaluate whether it is a reliable measure that can be used for training expert biathletes.

Participants. 5 men and 4 female athletes age 19.8 ± 0.45 from the German junior biathlon national team participated in the experiments. The athletes are expert shooters and are all competing at national and international levels.

Location. The experiments were conducted in an indoor shooting range at a biathlon training center in Germany. The training center is used both for training and conducting performance tests. On the 50 meters range the athletes can use live munition on biathlon competition targets. Directly connected to the shooting range is an indoor sports laboratory containing a treadmill for roller skiing (about 20 meters apart).

Equipment. The gaze behavior was assessed with an eye tracker tailored for this purpose (shown in Figure 1). The reasons and design criteria for the eye tracker are further discussed in section 4. For power supply and data transfer, the eye tracker was connected via USB to a MacBook Pro. The frame rate of eye tracker is 60 fps. A Piezo electric force sensor (> 200 samples/s) synchronized with the eye tracker and connected to a micro controller has been made and used to measure the force put on the trigger. The sensor data is transferred to the computer via a serial connection. A Scott [Scott 2019] shooting system (weight 30 g) was mounted at the rifle’s barrel and connected to a PC. The system provides, after initial calibration, detailed information about shooting performance such as radial error within the target (e.g., not only hit and miss) and the movement of the rifle relative to the target before the shot. It can be used under live firing conditions on actual biathlon targets. The Scott system does not allow for frame-based synchronization with the eye tracker and is used in these experiments for determining where the gun is pointing and gaze is directed.

Performance tests. The eye tracking experiment was conducted as part of a standardized performance test. The performance test involve roller skiing on a treadmill at four increasing intensity levels and shooting series of five shots after every intensity level. The intensity level is specified by treadmill slant angles (set at 1,3,6 and 0 degrees). Each level lasts 6 minutes. Immediately after each level, the athlete had to continue with rollerskis to the shooting range where the athlete’s rifle was located. The athlete made a standard 5 shot sequence in either prone or standing position and returned to the treadmill where the next level started.

4 THE NEED FOR A TAILORED EYE TRACKER

Commercial eye trackers are either remote, tower mounted or mobile / head mounted. Eye trackers need calibration to give accurate
gaze estimates. Typical eye trackers yield accuracies from 0.5-1.5 degrees measured on the screen in remote eye trackers or in the scene image when using mobile eye trackers. However, user calibration is a bit time consuming and the accuracy of eye trackers are typically influenced by changes in head position and especially with depth changes e.g., when leaving and returning to the eye tracker [Hansen and Ji 2010].

A pre-study revealed that standard eye trackers would be unsuitable for experiments with biathlon. Some arguments are: (i) To obtain unbiased results it is important to minimize how much the eye tracking equipment, calibration and test procedures influence the existing procedures. Each athlete needs to be able to use their own rifle. Each rifle is customized to the athlete and hence the morphology of the rifles and how the athlete place the head relative to diopter impose significant variability. The eye tracker consequently needs to be as compact and adaptable as possible. (ii) Research on performance analysis of athletes is typically conducted using a mobile eye tracker, but in biathlon it would be inconvenient for the athletes to wear a mobile eye tracker while skiing and shooting. It would be unacceptable to stop the tests between skiing and shooting to change equipment. (iii) Existing remote eye trackers are typically too wide and would interfere with other equipment if mounted on the rifle. (iv) When using eye tracking glasses the athletes would typically look upwards or even over the frames. This means that there could be significant data-loss due to missed eye detections. Beside, the frames of the mobile eye trackers would typically interfere with the athletes’ line of sight hence interrupting the normal procedures. (v) The procedure for how calibration should be done when the eye tracker is placed on the rifle is unclear. (vi) Calibration seems to be needless for these experiments since even with a good calibration there are, to our knowledge, no gaze estimation methods which yield sufficiently accurate estimates of gaze to determine where (through the diopter) the athlete is looking. (vii) Gaze estimation errors occur in head mounted eye trackers as a consequence of parallax; that is when the distances of the athlete-to-calibration-targets and athlete-to-gazed-objects during experiments are different [Mardanbegi and Hansen 2012; Narcizo and Hansen 2015]. Even with a good initial calibration the athletes’ head position change between standing and prone shootings. Parallax errors will therefore occur thus influencing the calibration accuracy even more. (viii) It is sufficient to have a reference point to indicate whether or not the athletes are looking though the diopter as (1) the QE only describes the duration on the final target (here only through the diopter) (2) it is fair to assume the target is not observable by an eye tracker. In other words, calibration would be needless in this case.

**Diopter-mounted eye tracker.** The eye tracker developed for these experiments is designed to be mounted directly on the diopter and can easily be switched between rifles. The athlete is therefore not significantly disturbed by the equipment. The IR sensitive USB camera (60 fps) can be reoriented as to account for different head positions and anthropomorphic difference of the athletes as well as the physical constraints of the individual rifle. A set of LEDs is placed concentrically around the diopter to illuminate the eye and make corneal reflections. The weight of the eye tracker is about 40 grams and hence when mounted on the diopter of the rifle it will not generally not influence the athletes.

![Figure 1: The diopter-mounted eye tracker used in the experiments. (Top) details of LED and camera (Bottom) Mounting of the eye tracker on the rifle.](image)

**Eye Tracking.** A statistically learned model was applied to indentify the pupil and visible glints in each image [Hansen et al. 2014b, 2002a,b]. Despite the camera was placed relatively close to the eye, the variable light conditions, shadows from the diopter and variable viewing angles complicated the analysis. The number of glints visible in the images also varied as a function of head pose relative to the diopter and camera pose. The virtual glint (VG) is defined as the mean of the stable glint centers. Stable means those glints that can be consistently detected during a shooting [Hansen et al. 2014a]. The difference between VG and the pupil center, $p_c$, indicates how close the athlete is looking towards the diopter. There will typically be an offset between the pupil and VG due to (1) the angle kappa (difference between optical and visual axes), (2) viewing angle; (3) distance between light source and eye; (4) the spatial offset between the corneal reflection and the pupil [Hansen and Ji 2010].

It makes sense to use the VG as the relative measure of gaze on the “object” since (1) even with a good calibration the eye trackers would be insufficiently accurate compared to the size of the hole in the diopterhole; (2) the definition of QE is only concerned with the final fixation on the object, which in turn is measured through the diopter; (3) the angle kappa is fixed for an individual hence only imposing a (relatively) stable offset between VG and the center of the pupil. Under these fair assumptions it is easy to integrate...
the trigger data with the eye movement data it is evident that there is so little eye movements that the recoil from the shot can be seen in the eye data. In these experiments the effect of recoil is quite low since it is expert shooters participating in the experiment. As shown in figure 4, the Kernel Density Estimate of the relative positions of the pupil and VG measured in consecutive frames (> 40 000) in all video frames indicate that, eye movements are rare and small during a shooting session but larger eye movements occur with low probability.

The paper investigates whether QE is related to performance e.g., whether fixation duration influences hit and miss rates. Figure 5 shows the distributions of the fixation duration conditioned on hit, miss and their combined distribution. The investigations of fixation duration on hit/miss rates naturally induces a binomial distribution.

The generalized linear model (GLM) is a generalization of ordinary linear regression (e.g., ANOVA) that allows for response variables from the exponential family e.g., binomial distributions [McCullagh and Nelder 1989]. The figure shows, the somewhat expected result for elite shooters, that there are significantly more hits than misses. As there are no observations of misses with a long duration it may at first appear as if the athletes always hit the target with a long duration (e.g., QE). This misleading observation is caused by the highly unbalanced distributions of hits and misses. In fact, the analysis of these distributions under a binomial GLM did not confirm that the two distributions are the same. In other words the results indicate that fixation duration did not influence
hit/miss rates (p=0.687) and thus no apparent influence of QE for elite biathletes.

Figure 6 shows a boxplot of the fixation duration for hit/misses conditioned on the work intensity levels and in prone/standing positions. The results of a binomial GLM analysis yields p-values $P = [0.033, 0.256, 0.058, 0.341]$ where $p_i$ is the p-value for work intensity $i$. The p-values in prone positions are generally lower than in standing positions. The experiments did generally not confirm QE but when athletes are in low work intensity and in prone conditions QE seems to have an effect.

Figure 7 shows the fixation duration conditioned intensity level. Overall the athletes had a shooting hit rate of $\mu = 0.81, \sigma = 0.15$ and fixation times (sec) $\mu = 2.86, \sigma = 1.61$. The figure shows that the median fixation duration remain similar despite intensity however the variance increases as a function of the intensity.

7 DISCUSSION
This paper investigated QE on elite biathletes in a ecologically valid setting. An eye tracker was developed to accommodate limitations of existing eye trackers.

While the athletes are typically keeping their gaze through the diopter and the eyes very still, these experiments do generally not support previous findings for aiming in biathlon tasks e.g., [Vickers and Williams 2007] but we found support of QE in low workload cases and where athletes were in prone position. This result is somewhat different from the previous findings of Klostermann et al. [2013]. The evidence for training QE is generally equivocal for biathlon and it requires more sophisticated longitudinal designs to demonstrate retention.

Figure 7 indicates that the athletes may have a rather stable shooting rhythm but that this is slightly but insignificantly influenced by the intensity level. These are expected signs of elite performers; they perform consistently and robustly to trained conditions.

We believe that there are several reasons for the discrepancy to previous work:

(1) The experiments were conducted as part of a standardized performance test that is known by the athletes. The equipment did not need calibration or required the athletes to wear the eye tracker and hence this study was based on an ecologically valid setup that did not influence the standardized test or the athletes in any significant way.

(2) The eye tracker used in this experiment was made to work on the rifle and without calibration. Without calibration disturbing the experiment, we also avoided parallax errors and erroneous gaze estimates.
Figure 6: Boxplot of fixation duration as a function of (top) hits (bottom) misses and conditioned on intensity level (increasing left to right).

Figure 7: Boxplot of fixation duration as a function of intensity levels.

(3) Vickers and Williams [2007] recorded the movement of the trigger movement with an external camera and defined “QE as the final fixation that was maintained on any part of the target for more than 100 ms. before and after the trigger pull”. This definition is uncertain to when the ‘final’ action is measured: before building the trigger force, during the plateau or at the final pull? In this paper we differentiated the stages of the trigger force and defined the final fixation as the final fixation before the last trigger pull that initiates the shot.

While the fixation duration has an influence on human performance (e.g., for perception), the current definition may be insufficient in fully describing the observations.

(1) Drying eyes and blinking interrupt the fixation. When shooting with real ammunition it is common (also for elite athletes) to blink during or even before the shot. Our data even shows cases where athletes blink before or during the shot and still hit the target. Hence more intricate models may be needed to fully describe the observations.

(2) The criterion of a final fixation within 3 degrees in the definition of QE seems to be an unwarranted condition biathlon.

The large variance of fixation durations indicates (Figure 5) that there could be many factors influencing the outcome of the shooting beyond fixation duration. The results may have practical importance for daily training: Fixation duration is clearly important for the athletes to perceive the target but the results show that further studies are needed to better understand QE and the other factors...
that influence performance in biathlon. We speculate that dynamic properties of hand-eye coordination, blinks, and shoot rebounds could have some significance to QE.

REFERENCES


