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; Pluijms 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

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[Baca and Kornfeind 2012]. It is held that athletes either follow a precision strategy (i.e., the rifle is kept as stable as possible in the center of the target before shooting) or a reaction strategy (i.e., they shoot as soon as the target travels through the center of the diopter). Both strategies seem to be applied independent of the postural condition. Examining the relationship between gaze control (including QE) and shooting performance is therefore of utmost importance to provide athletes and coaches with evidence-based recommendations regarding performance and training.

Section 2 presents related work and in particular introduces the QE hypothesis and its relevance to the present experiments. Section 3 presents the experimental setup and arguments of designing QE experiments in an ecologically valid setting. In Section 4 we propose a rifle-mounted eye tracker that is intended for measuring eye movements on biathletes. The main findings are presented in Section 6 and further discussed in Section 7.

2 MOTIVATION

Gaze behavior in sports has predominantly been studied in terms of location, duration, and fixation frequency. Initial scientific effort on gaze behavior reveals that experts use fewer fixations, of longer durations than non-experts across a wide range of sports [Mann et al. 2007; Nieuwenhuys et al. 2008]. Several studies indicate that the gaze behavior prior to an action is an important performance factor e.g., that the fixation duration of elite performers is significantly longer than that of less skilled performers, suggesting that those who consistently achieve high levels of performance have learned to fixate or track critical objects or locations for earlier and longer durations [Vickers 2016]. 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 hypothesis [J.S.Chia et al. 2017; Rienhoff et al. 2012].

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 Scatt [Scatt 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 Scatt 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.

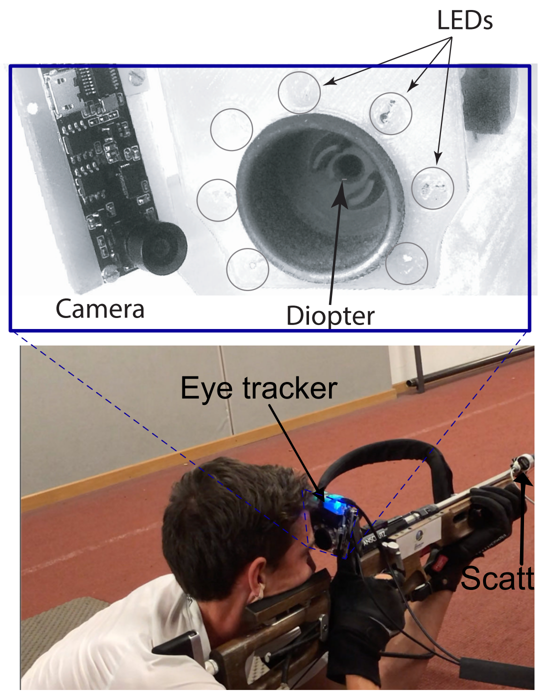

Figure 1: The diopter-mounted eye tracker used in the experiments. (Top) details of LED and camera (Bottom) Mounting of the eye tracker on the rifle.

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 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 calibration free QE investigations into the normal training and test procedures used by the athletes and coaches.

Without calibration it is clearly not possible to know exactly where the person is looking [Hansen and Ji 2010]. However, provided the distance between pupil and VG is small (due to angle kappa and viewing angle) and stable, it is likely (in this setup), that the person is looking through the diopter. This assumption is more strict than the 3 degrees used in the definition of QE.

Notice that the Scatt system indirectly provides a measure of the gaze on the target as (1) the athlete is looking at the target through the diopter; (2) the relative orientation of the rifle, diopter and the Scatt system was calibrated prior to use.

5 DATA ANALYSIS

The video and trigger data was manually annotated using an annotation tool developed for these experiments. The tool synchronizes video, eye tracker and trigger data and allows the annotator to make single frame annotations.

The start of the sequence is defined at the point in time where the chin touches the rifle for the first time while the end is defined when the cheek leaves the rifle after the last shoot. Similarly the onset and the offset of the final fixation as well as for the onset and offset of blinks and shoot rebounds were manually annotated. The synchronization of the trigger data and the video allowed the detection of the final movement that initiated the shot. For the athletes there is much involved in delivering an ideal shot. As shown in row 4 of Figure 3, the athletes strive towards an ideal trigger force curve. First they try to achieve a plateau at $70-80$ percent of the total force leading to a shot and then make the final pressure on the trigger. In line with Vickers and Williams [2007] the QE duration is defined as the final fixation before the initiation of the final action. This means that the QE is to be measured from an initial fixation until the rifle is fired.

The athlete may momentarily loose focus of the target e.g., due to eye blinks and gun motion and hence a re-fixation of the target is needed. Here we define the *final action* as the peak of trigger force that leads to the shot. *Fixation duration* is defined as the interval where the eye remains stable and uninterrupted by eye blinks, head movements or eye movements. Blinks, shoot rebounds and eye movements were manually identified and annotated. The onset of the final fixation is identified by backtracking from the shoot. The duration of the final fixation was calculated (in seconds) for every shot based on the number of frames between the start and stop of a fixation multiplied by the sampling rate (60 Hz).

6 OBSERVATIONS

Eye movements. This section presents the main findings of these experiments. Figure 3 shows the eye tracking data of a single shooting sequence. The pupil centers and the reference points have been normalized to zero mean for display purposes. The fairly constant and relative short distance of the pupil centers and the virtual glints (*VG*), displayed in the first three rows of the figure, shows that the athlete is looking through the diopter quite consistently from the start. There is a bit of head movements e.g., after a shot has been fired. In this example the athlete makes Vistibulo Ocular Reflexes (VoR) to maintain focus through the diopter. In fact, by comparing 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.

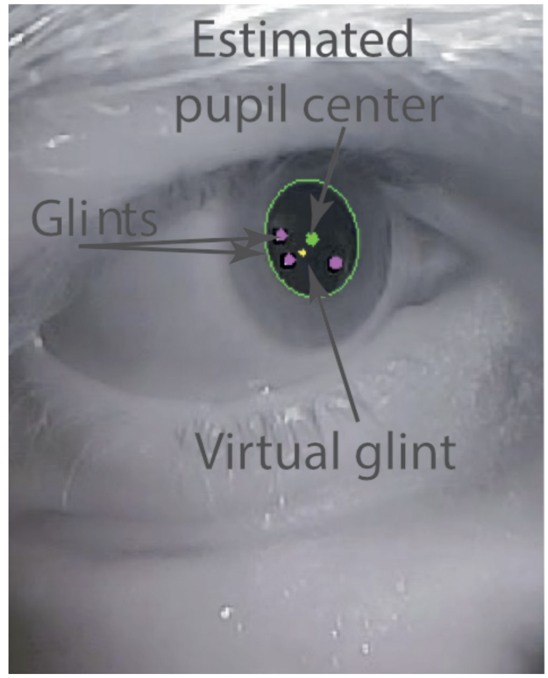

Figure 2: (left) A single frame from a shooting with the pupil estimate (green), reflections (red) and the virtual glint (VG) (yellow).

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

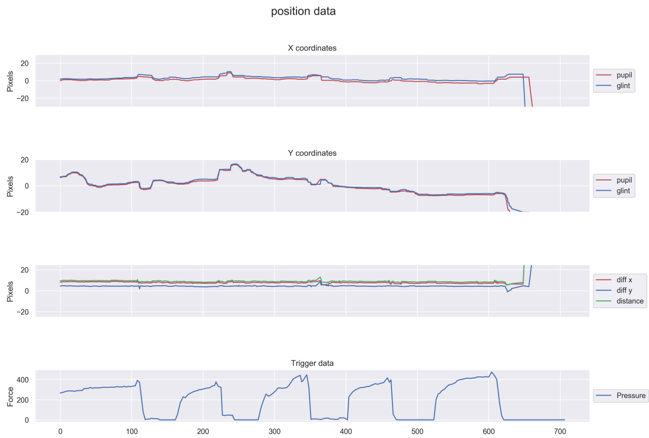

Figure 3: A sequence of 5 shootings of a single athlete. The two top rows show the center of pupil (red) and virtual glint, VG (blue) for the x and y coordinates, respectively. Row 3 shows the difference between VG and pupil center in x and y coordinates. Row 4 shows the trigger force over time. Notice the trigger force cycle: initial pressure, plateau, final force (to fire) and release.

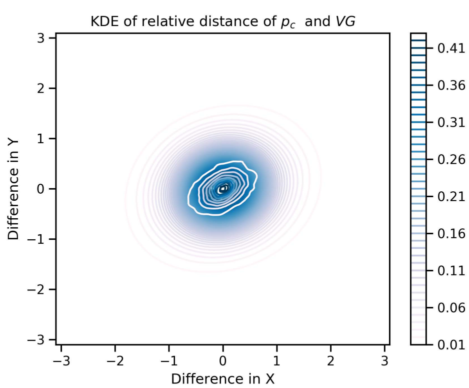

Figure 4: Kernel density estimate of the difference of the pupil and VG in consecutive frames. The distribution is centered around the origin and with only very few large changes.

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

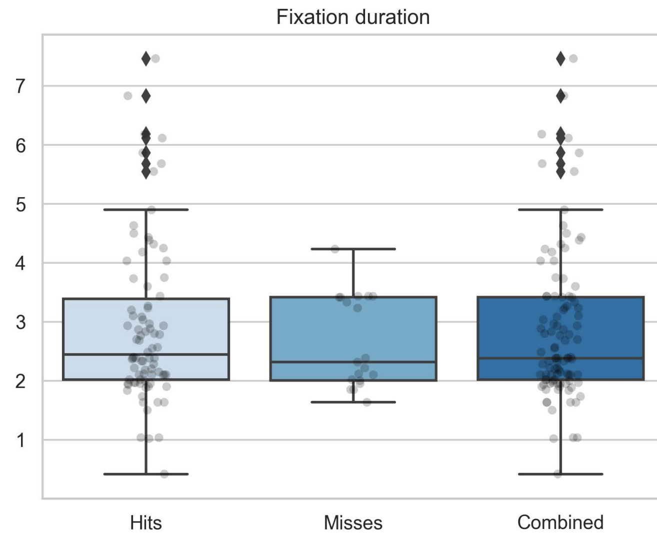

Figure 5: Boxplot of fixation durations as a function intensity level.

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.

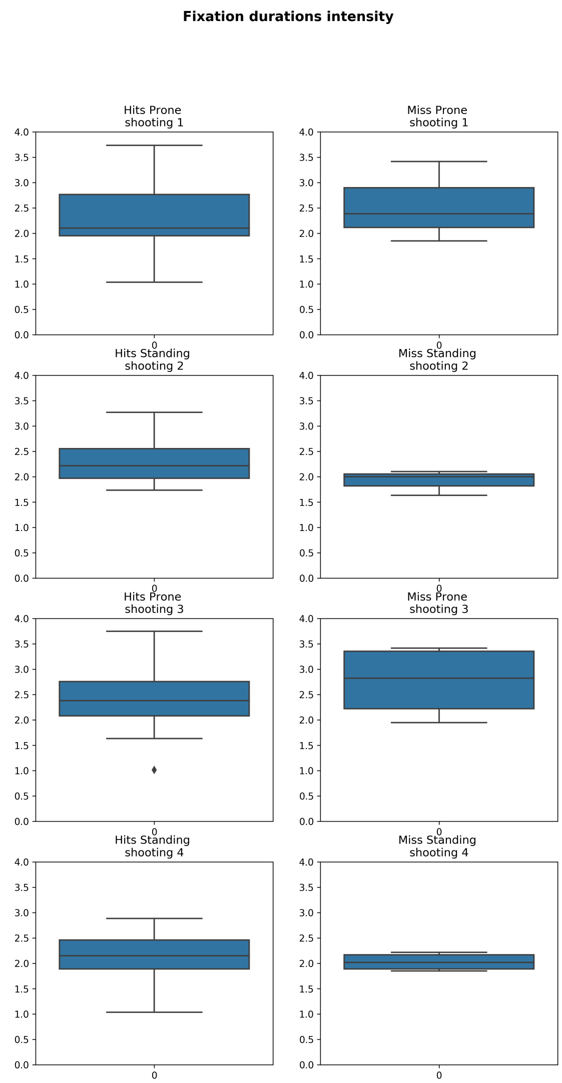

Figure 6: Boxplot of fixation duration as a function of (top) hits (bottom) misses and conditioned on intensity level (increasing left to right) .

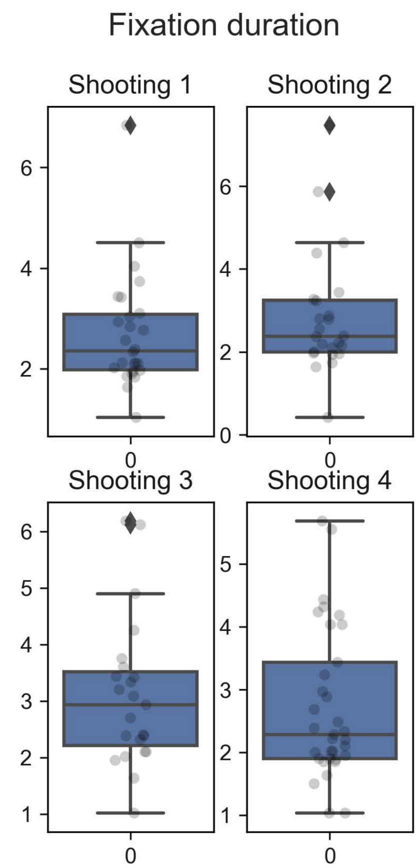

Figure 7: Boxplot of fixation duration as a function of intensity levels.

(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

José Afonso, Júlio Garganta, Allistair Mcrobert, Andrew M. Williams, and Isabel Mesquita. 2012. The perceptual cognitive processes underpinning skilled performance in volleyball: Evidence from eye-movements and verbal reports of thinking involving an in situ representative task. *Journal of Sports Science and Medicine* 11, 1 (jun. 2012), 339–345. https://doi.org/S/N

R.N. Singer A.M. Williams and S.G. Frehlich. 2002. Quiet eye duration, expertise, and task complexity in near and far aiming tasks. *Journal of Motor Behavior* (2002).

Arnold Baca and Philipp Kornfeind. 2012. Stability analysis of motion patterns in biathlon shooting. *Human Movement Science 31 (2012) 295–302* 31 (2012), 295–302.

Andrew T. Duchowski. 2007. *Eye Tracking Methodology: Theory and Practice* (2nd edition ed.). Springer-Verlag New York, Inc., Secaucus, NJ, USA. 334 pages.

Dan Witzner Hansen, Lars Roholm, and Iván García Ferreiros. 2014b. Robust glint detection through homography normalization. In *ETRA '14 Proceedings of the Symposium on Eye Tracking Research and Applications*. Association for Computing Machinery, United States, 91–94. https://doi.org/10.1145/2578153.2578165

Dan Witzner Hansen and Qiang Ji. 2010. In the Eye of the Beholder: A Survey of Models for Eyes and Gaze. *IEEE Transactions on Pattern Analysis and Machine Intelligence* 32, 3 (2010), 478–500. 0162-8828.

Dan Witzner Hansen, Mads Nielsen, John Paulin Hansen, Anders Sewerin Johansen, and Mikkel B. Stegmann. 2002a. Tracking eyes using shape and appearance. In *Proceedings of the 2002 Conference on Machine Vision Applications (MVA '02)*. Nara-Ken New Public Hall, Nara, Japan, 201–204. http://goo.gl/qdLZMn

D. W. Hansen, M. Nielsen, J. P. Hansen, A. S. Johansen, and M. B. Stegmann. 2002b. Tracking Eyes using Shape and Appearance. , 201-204 pages. http://www2.imm.dtu.dk/pubdb/p.php?1222

Dan Witzner Hansen, Lars Roholm, and Iván García Ferreiros. 2014a. Robust Glint Detection through Homography Normalization. In *Proceedings of the 2014 Symposium on Eye Tracking Research & Applications (ETRA '14)*. ACM, New York, NY, USA, 8. https://doi.org/10.1145/2578153.2578165

Mary M. Hayhoe, Travis McKinney, Kelly Chajka, and Jeff B. Pelz. 2012. Predictive eye movements in natural vision. *Experimental Brain Research* 217, 1 (mar. 2012), 125–136. https://doi.org/10.1007/s00221-011-2979-2

Stefanie Huttermann, Daniel Memmert, Daniel J. Simons, and Otmar Bock. 2013. Fixation strategy influences the ability to focus attention on two spatially separate objects. *PLoS ONE* 8, 6 (jun. 2013), 1–8. https://doi.org/10.1371/journal.pone.0065673

C.M. Janelle, C.H. Hillman, R.J. Apparies, N.P. Murray, L. Meili, E.A. Fallon, and B.D.Hatfield. 2000. Expertise differences in cortical activation and gaze behavior during rifle shooting. *Journal of Sport & Exercise Psychology* 22 (2000), 167–182.

J.S.Chia, S.F. Burns, L.A. Barrett, and J.Y Chow. 2017. Increased Complexities in Visual Search Behavior in Skilled Players for a Self-Paced Aiming Task. *Frontiers Psychology* (2017).

A. Klostermann, R. Kredel, and E.J. Hossner. 2013. The "quiet eye" and motor performance: task demands matter! *Journal of Experimental Psychology and Human Perception Performance* (2013).

Michael Land and Benjamin Tatler. 2009. *Looking and Acting: Vision and Eye Movements in Natural Behaviour*. OUP Oxford.

David L. Mann, Wayne Spratford, and Bruce Abernethy. 2013. The head tracks and gaze predicts: how the world's best batters hit a ball. *PLoS ONE* 8, 3 (mar. 2013), 1–11. https://doi.org/10.1371/journal.pone.0058289

Derek T. Y. Mann, A. Mark Williams, Paul Ward, and Christopher M. Janelle. 2007. Perceptual-cognitive expertise in sport: a meta-analysis. *Journal of Sport and Exercise Psychology* 29, 4 (aug. 2007), 457–478. https://doi.org/10.1123/jsep.29.4.457

Diako Mardanbegi and Dan Witzner Hansen. 2012. Parallax error in the monocular head-mounted eye trackers. In *Proceedings of the 2012 acm conference on ubiquitous computing*. ACM, 689–694.

P. McCullagh and J. A. Nelder. 1989. *Generalized Linear Models*. Chapman & Hall / CRC, London.

Fabricio Batista Narcizo and Dan Witzner Hansen. 2015. Depth Compensation Model for Gaze Estimation in Sport Analysis. In *Proceedings of the 2015 IEEE International Conference on Computer Vision Workshop (ICCVW '15)*. IEEE Computer Society, Washington, DC, USA, 788–795. https://doi.org/10.1109/ICCVW.2015.107

Arne Nieuwenhuys, J. Rob Pijpers, Raoul R.D. Oudejans, and Frank C. Bakker. 2008. The Influence of Anxiety on Visual Attention in Climbing. *Journal of Sports and Exercise Psychology* 30, 2 (2008), 171–185.

Roberts Paeglis, Kristaps Bluss, Andris Rudzitis, Andris Spunde, Tamara Brice, and Edgars Nitiss. 2011. NIR tracking assists sports medicine in junior basketball training. In *Proceedings of the International Society for Optical Engineering (SPIE '11)*. SPIE, Bellingham, WA, USA, 1–6. https://doi.org/10.1117/12.889308

Bernardo Rodrigues Pires, Myung Hwangbo, Michael Devyver, and Takeo Kanade. 2013. Visible-spectrum gaze tracking for sports. In *Proceedings of the 1st IEEE International Workshop on Computer Vision in Sports (CVsports '13)*. IEEE Computer Society, Washington, DC, USA, 1–6. https://doi.org/S/N

J.P. Pluijms, R. Cañal-Brulan, M.J.M Hoozemans, and G.J.P Savelsbergh. 2015. Visual search, movement behaviour and boat control during the windward mark rounding in sailing. *Journal of Sports Sciences* 33 (2015), 398–410.

R. Rienhoff, J. Baker, L. Fischer, B. Strauss, and J. Schorer. 2012. Field of vision influences sensory-motor control of skilled and less-skilled dart players. *Journal of Sports Science Medicine* (2012).

Scatt. 2019. https://www.scatt.com/. https://www.scatt.com/. Online; accessed 1. January-2019.

Joan N. Vickers. 1992. Gaze control in putting. *Journal of Experimental Psychology: Human Perception and Performance* 21 (1992), 117–132.

Joan N. Vickers. 1996a. Control of visual attention during basketball free throw. *American Journal of Sports Medicine* 24 (1996), 93–97.

Joan N. Vickers. 1996b. Visual control when aiming at a far target. *Journal of Experimental Psychology* 22 (1996), 342–354.

Joan N. Vickers. 2016. Origins and current issues in quiet eye research. *Current Issues in Sport Science* 1 (2016), 1–11. https://doi.org/10.15203/CISS_2016.101

Joan N. Vickers and William Lewinski. 2012. Performing under pressure: Gaze control, decision making and shooting performance of elite and rookie police officers. *Human Movement Science* 31, 1 (2012), 101 – 117. https://doi.org/10.1016/j.humov.2011.04.004

Joan N. Vickers and A. Mark Williams. 2007. Performing under pressure: the effects of physiological arousal, cognitive anxiety, and gaze control in biathlon. *Journal of Motor Behavior* 39, 5 (aug. 2007), 381–394. https://doi.org/10.3200/JMBR.39.5.381-394