

Quiet Eye research – Joan Vickers on target

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Quiet Eye research – Joan Vickers on target

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ABSTRACT

In this target article (TA; CISS2016_100), Joan Vickers gives an overview of 20 years of research on her discovery that a relatively long lasting fixation before movement initiation enhances complex-motor performance, the so-called Quiet Eye (QE) phenomenon. Vickers' main article (CISS2016_101) is the focus of sixteen peer commentaries (CISS2016_102 – CISS2016_117), authored by sport scientists with a special focus on the QE (**Causer; Farrow & Panchuk; Klostermann, Vater & Kredel; Mann, Wright & Janelle; Schorer, Tirp & Rienhoff; Williams; Wilson, Wood & Vine**), by sport scientists with different research foci (**Baker & Wattie; Davids & Araujo; Frank & Schack; Helsen, Levin, Ziv & Davare; Rodrigues & Navarro**), and by experts in human perception from disciplines beyond sport science (**Foulsham; Gegenfurtner & Szulewski; Spering & Schütz; Watson & Enns**). Finally, critiques, suggestions, and extensions brought forward by the commentators are acknowledged by Vickers in her closing response (CISS2016_118).

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This is a CISS target article, which includes an editorial, an index of contents, a main article authored by Joan N. Vickers, 16 peer commentaries and an author's response. Individual contributions can also be retrieved under the respective dois.

Founded in early 2016, *Current Issues in Sport Science* (CISS) is the official journal of the Societies for Sport Science of Austria (ÖSG) and Switzerland (SGS/4S). As a special feature of CISS, one or two target articles (TA) are published each year. A TA consists of a main article, a number of peer commentaries and a summary response by the main article's author. The main article highlights an internationally recognised researcher, invited by the editorial board to provide a condensed overview of years or even decades of achievements in a specific research topic.

For the very first TA, the CISS editorial team is very proud to present Prof. Dr. Joan Vickers as our main author. It is of the utmost honour to feature such an internationally acclaimed researcher for her discovery of the "Quiet Eye" (QE), a relatively long-lasting fixation before movement initiation that enhances complex motor performance. Since her first publications of this visual-motor dependency in her – numerous cited – studies on golf putting (Vickers, 1992) and basketball free-throws (Vickers, 1996a, 1996b), a multitude of further QE studies have been conducted by Vickers and other research groups (for an earlier overview, Vickers, 2007). All in all, the existing

evidence clearly proves the performance-enhancing effect of a long QE duration as a noteworthy phenomenon in experts' sensorimotor behaviour.

Further, the CISS editorial team appreciates Joan Vickers' TA authorship with her specific positioning in the world of sports-related research as a number of the journal's core objectives perfectly align with Vickers' vision as a sport scientist. These objectives are aimed to bridge gaps – between sport science and more fundamental scientific disciplines, between sport-scientific sub-disciplines, and between scientific theories, empirical investigations and practical applications. In this respect, Joan Vickers can be regarded as an exemplary bridge-builder, as (i) her work is rooted in fundamental science, however she insists on investigating gaze behaviour unconstrained, real-world conditions; (ii) her focus lies on the identification of a gaze-related phenomena, however she connects these behavioural processes with different aspects of expertise, attention, motor control, and neural mechanisms; and (iii) her main interest regards functional determinants of the QE effect, however she does not forget that sport science is an applied discipline – motivating her to transfer gathered insights into practical

interventions and to design and evaluate gaze-training programmes, such as those to enhance performance of top-level athletes. With that being said, Joan can claim to be a prototype bridge-builder indeed.

Fortunately, the sixteen peer commentaries included in this TA package, either by invitation or by submission, present a variety of similarly established scientific perspectives. In this respect, Vickers' main paper is discussed (i) by researchers who have presented own empirical work on specific aspects of the QE, some of them to a remarkable scale (**Causser; Farrow & Panchuk; Klostermann, Vater & Kredel; Mann, Wright & Janelle; Schorer, Tirp & Rienhoff; Williams; Wilson, Wood & Vine**). The remarks of this group are complemented (ii) by those of sport scientists with more general views on perception and action-related issues in the context of complex motor behaviour (**Baker & Wattie; Davids & Araujo; Frank & Schack; Helsen, Levin, Ziv & Davare; Rodrigues & Navarro**) (although, of course, no absolute line can be drawn between i and ii). Finally, Vickers' main article is discussed (iii) by experts in human perception and action who are rooted in disciplines more fundamental than sport science, especially in experimental psychology (**Foulsham; Gegenfurtner & Szulewski; Spering & Schütz; Watson & Enns**). The latter should be particularly noted, as the QE phenomenon seems "non-existent" in the controlled laboratory settings of experimental psychologists, while surfacing only under real-world conditions with highly trained athletes. Hence, the present TA proves that sport science can achieve more than merely adapting concepts from fundamental disciplines. Rather, by discovering and structuring real-world phenomena, sport science itself is capable of making integral contributions to the world of science-and feeding this work forward to fundamental scientific disciplines for further investigation.

Beyond objectives to bridge scientific fields and methods, CISS strives to address an international community. Thus, we have done so with a community of international commentators from five continents, or eleven countries – from Switzerland, Germany, the UK, Portugal, Belgium, the Netherlands, Israel, Canada, the US, Brazil, and Australia. In her concluding response, Joan Vickers replies to the rich body of critiques, suggestions and theoretical, empirical and technical extensions brought forward by this international collective. In doing so, Vickers provides us with a number of challenges and perspectives for future work on the QE. If the discussion and Vickers' response genuinely inspire sport scientists to accept these challenges and to delve deeper into the field of QE research, the ultimate goal of this TA has been achieved. In this case, the QE phenomena seems to be a "current issue in sport science" indeed.

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Figure 1: Joan N. Vickers (University of Calgary)

Competing Interests

The author's role for CISS is Section Editor "movement & exercise science" (2016-2020), Editor-in-Chief-elect (2016-2020) and Founding Editor (2015).

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All relevant data are within the paper.

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Origins and current issues in Quiet Eye research

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ABSTRACT

All sports require precise control of physical actions and vision is essential in providing the information the movement systems needs to perform at a high level. Vision and focus of attention play a critically important role as the ability to direct the gaze to optimal areas in the playing environment, at the appropriate time, is central to success in all sports. One variable that has been consistently found to discriminate elite performers from their near-elite and novice counterparts is the Quiet Eye (QE). In the present paper, I first define the QE, followed by an explanation of its origins as well as the question: why have I pursued this one variable for over 35 years? I then provide a brief overview of QE research, and concentrate on QE training, which has emerged as an effective method for improving both attentional focus and motor performance. In the final section, I discuss some future directions, in particular those related to identifying the neural networks underlying the QE during successful trials.

Keywords:

sport – gaze – expertise – cognition – motor control – attention

What is the Quiet Eye?

Sport is an arena where expertise has traditionally been defined by physical prowess. The bigger, stronger, and taller you are, then the better it is assumed you will be able to perform in most sports. But we have many examples of great athletes who were far from being the biggest, strongest or tallest, when compared to their teammates and opponents. Lionel Messi, Diego Maradona, and Pele are three of the best soccer players in history, but are respectively, 5'7", 5'5", and 5'8" in height (Sibor, 2013). Wayne Gretzky is considered one of the world's greatest hockey players, but he tested at the bottom of his team in speed, aerobics, strength and other physical measures of prowess. Ken Dryden, a competitor of Gretzky explains that "he knew he wasn't big enough, strong enough, or even fast enough to do what he wanted to do if others focused on him. Like a magician, he had to direct attention elsewhere, to his four teammates on the ice with him, to create the momentary distraction in order to move unnoticed into the open ice where

size and strength didn't matter. Gretzky made his opponents compete with five players, not one, and he made his teammates full partners to the game" (Dryden, 1998, p. 98). Gretzky himself put it best: "I couldn't beat people with my strength; I don't have a hard shot; I'm not the quickest skater in the league. My eyes and my mind have to do most of the work" (Gretzky & Reilly, 1990, p. 128). This quote illustrates how cognitive capacities, and specifically the control of the gaze and attention, play an important role in distinguishing good performers from the greatest. In all sporting activities, elite performer are able to focus intently not only on *what* location is most relevant, but also *when* information from that location must be accessed and for how long, relative to the phases of the movement.

The QE has five characteristics that are measured, *in situ*, using a light mobile eye tracker that is coupled to an external motor camera (Vickers, 1996a, 1996c, 2007). For a given motor task, the QE is defined as the final fixation or tracking gaze that is located on a specific location or object in the task space within 3° of visual angle (or less) for a minimum of 100 ms. The onset of

the QE occurs prior to a critical final movement in the task and the offset occurs when the gaze deviates off the object or location by more than 3° of visual angle for a minimum of 100 ms, therefore the QE can carry through and beyond the final movement of the task. The QE of elite performers is significantly longer than that of near-elite or lower skilled performers, meaning those who consistently achieve high levels of performance have learned to fixate or track critical objects or locations for earlier and longer durations irrespective of the conditions encountered. The onset of elite performers is invariably earlier, indicating they have found a way to see critical information sooner, thus enabling the transmission of a higher quality commands to the motor system. The QE of elite performers has an optimal duration given the constraints of the task, meaning it varies in length depending on the specific motor task (for an overview, see Vickers, 2007).

In a typical QE study, the first step is to test elite athletes in a well-known task, thereby establishing norms from which training and other interventions can be based. Critically, the athletes perform, *in situ*, until an equal number of successful and non-successful trials are recorded. Therefore, one must first define success and failure in the *task* as defined by experts, using independent statistics established in the sport. These are very easy to access today in almost any sport. Once sport specific statistics are known, it is relatively easy to define successful and unsuccessful performance in the sport. For example, as I write this paper, the top athlete in golf putting is Jordan Spieth, who averaged 1.7 putts per hole during the 2015 season (PGA Tour, 2016). In archery, Kim Woojin is the current Olympic champ, averaging 9.5 out of 10 (World Archery, 2016). In the basketball free throw, the all-time NBA leader is Steve Nash, who sunk 90.4% of his free throws during a 10 year career (LLC, 2016). In the 2014-2015 NHL season, Carey Price was the best goaltender stopping 93.0% of shots (ESPN, 2016). Because statistics like these exist in sport more than in other domains, the unique QE characteristics of elite performers could be discovered, and distinguished from their lesser skilled, but often more physically gifted “near-elite” teammates. For example, in archery, hits could be defined as those in the 10 and 9 rings (as this level of accuracy can lead to an Olympic medal), whereas anything below 9 would be treated as a miss.

Origins of the QE

I began my quest toward the QE during my PhD program at the University of British Columbia, where I was able to take courses from some of the world’s greatest cognitive scientists, including Anne Treisman (Treisman & Gelade, 1980), and Dan Kahneman (Kahneman, 1973, 2011). Stan Coren (Coren, Ward, & Enns, 2003), a perception psychologist and eye tracking specialist was my research supervisor and taught me how to record the eye movements of elite gymnasts and soccer players who sat, head still in a chin rest and scanned a sequence of slides from gymnastics (Vickers, 1988). Only a few people understood why

I carried out the study, and there were days when I wondered myself, but I realize now I used eye tracking as a way to access to the brain and what today we call the mirror neuron system (Rizzolatti, Fadiga, Gallese, & Fogassi, 1996).

Although my experiences at UBC were exceptional, and laid the foundation for the QE, they do not explain why I have pursued this one variable for so long. Prior to beginning my PhD, I spent five years as a teacher and coach in the public schools, followed by five years as an athletic director and teacher educator at the university level. In those roles I became familiar with the many challenges athletes, coaches and students face. In particular, I became aware of a deficiency in motor learning and control research, which at that time, had not moved out the laboratory and provided little or no assistance to the young teachers and coaches I was teaching who were about to enter the work force. When I started my PhD, I was determined to find a way to conduct experiments in real world sport situations.

My early, applied experiences motivated me to look outside the existing research paradigms, but what has stayed with me all these years is that I know deep down that humans possess the ability to perform at levels way above what they are usually capable of. I know this because I had three experiences myself, as an athlete, in which I performed well above what I had normally achieved. As an undergraduate, I was fortunate to play four years of varsity volleyball and four years of varsity basketball. My first experience occurred during a volleyball game when I served the whole game from the first server position. As the pressure built toward the end of the game, I remember the only thing that was important was to keep my eye on the lower back of the ball where the heel of my hand made contact during the float serves I was delivering. The second occurred in a basketball game when I scored 27 points in a single game (which was 100% above my best result ever), and the last was in alpine skiing when I had a perfect run in deep moguls on a big mountain. As each of the events unfolded I was absolutely sure I had mastered the sport, but it was all gone the next day! Actually it was all gone on the next run. I have asked audiences if they also have had one of these “out of body”, “one with the target”, “in the zone”, “zen” or “flow” experiences and many raise their hands. Research exists on the phenomena, with one approach being the “hot hand in sport” (Gilovich, Vallone, & Tversky, 1985), but overall there is little evidence in support. However, these studies looked at game statistics, whereas the QE is a perception-action, neural-cognitive variable. In this paper I am going to suggest that the QE is the reason the “hot hand” exists, and why having one is a fleeting experience for a mere mortal like me, as well as for most people reading this paper. But if you are an elite athlete, defined as someone who has the very best statistics in the world in a specific sports task, then you possess a “hot hand” (and QE) most of the time.

QE becoming a significant research topic

Insight into the QE first emerged in golf putting (Vickers, 1992), although I did not use the “Quiet Eye” term in that study. The term first appeared in papers on the basketball free throw (Vickers, 1996a, 1996b, 1996c), followed by the volleyball serve reception (Adolphe, Vickers, & LaPlante, 1997; Vickers & Adolphe, 1997) as I wanted to see whether the concept applied to targeting and interceptive timing skills. Today, twenty years after the first QE study was published, a meta-analysis has described the QE as one of three gaze behaviors that consistently differentiates experts from their non-expert counterparts (Mann, Williams, Ward, & Janelle, 2007). On average, experts maintained a QE duration that was approximately 62% longer than non-experts. Recently, Rienhoff, Tirp, Strauss, Baker, and Schorer (2015) have carried out a systematic review of the QE, linking it to Newell’s model of interacting constraints (Newell, 1986). Three electronic databases were searched from inception until February 2015. A total of 580 QE records were found, indicating the tremendous growth in the area over the past few years. In addition, a number of comprehensive reviews of the QE have been completed (see Causer, Janelle, Vickers, & Williams, 2012; Wilson, Causer, & Vickers, 2015).

QE in targeting tasks

In targeting tasks, the function of the gaze and attention system is to locate a target in space and to control the aiming of an object to the target area. In these tasks an object is usually propelled with the hands or feet away from the body in an aiming movement toward a target. Accuracy and consistency in performance are the ultimate goal in tasks such as shooting a basketball, performing a golf putt, throwing a dart, shooting a rifle or bow, or throwing to a receiver. Although the motor behaviors differ markedly in each case, the problem for the gaze and attention system is the same: to focus on the most critical part of the target and acquire specific information so that there is an optimal coupling between the gaze and aiming movements, thus leading to successful completion of the task. The ability to accurately select the correct cues for movement is crucial for successful performance. The additional time needed for a longer QE duration is most often accomplished by having an earlier QE onset, before the critical movement and not necessarily extending the absolute processing period, within the time available.

A recent study in golf putting used an instructional approach to investigate the advantage of an “effect-related” versus “movement-related” focus on golf performance (Klostermann, Kredel, & Hossner, 2014). Expert and near-expert golfers were provided with both movement-related instructions in which their attention was drawn internally to the movement of the arms, and effect-related instructions, which directed their attention to swing and contact with the ball. No overt instructions were given regarding the QE. Putting performance was to a target at

3 m and accuracy was measured using radial error. Performance was significantly better for both groups during the effect-related condition. QE duration was longer for the experts than near-experts. QE offset occurred later for the experts. A new variable called QE efficiency was determined using correlation coefficients between the QE parameters and putting performance. An *inhibition hypothesis* was proposed, which states that the long QE duration could be explained as “the need to inhibit alternative movement variants so that only the optimal variant gets parameterized” (p. 398). Since the golf putt requires exquisite control, often under extreme pressure, the inhibition hypothesis makes sense. Whether this applies to other skills will be interesting to see (for a summary of the optimal QE location, onset, offset and duration in a number of other targeting tasks, see Wilson et al., 2015).

Interceptive timing tasks

In interceptive timing tasks, an object travels toward the performer and the gaze and attention systems are used to read the object as it is delivered, track it as it approaches, and then control it as it is received, for example as it occurs in goaltending in soccer or ice hockey; hitting a baseball or cricket ball; receiving serves in volleyball, tennis or badminton; or receiving a pass in soccer, basketball and many other sports. Interceptive timing tasks have three sequential phases in common: object recognition, object tracking, and object control (Vickers, 2007). During the object-recognition phase, fixations and pursuit tracking are used to study the movements of the object and of the individual propelling the object, as it is pitched, bowled, kicked, shot, or otherwise propelled toward the receiver. During the object-tracking phase, smooth pursuit-tracking eye movements are used to maintain the image of the object on the fovea in order to detect if it spins; accelerates or decreases in speed; changes direction; or is affected by wind, sun, or a host of other factors that can occur. Pursuit tracking differs according to whether object flight is predictable or unpredictable. When the flight of the object is predictable, early tracking is usually sufficient to ensure control of the object at reception. However, when it is unpredictable, early tracking, plus saccadic movements and late tracking eye movements on the object are critical (Land, 2009). During the object-control phase, the object is caught with the hand, kicked to a teammate, hit as in baseball or cricket, passed to a teammate as in volleyball, and so on. Many interceptive timing tasks in sport require the object to be directed to a secondary target at contact.

Predictions of object flight are often made before the object starts moving, such as by the goal keeper in penalty kicks, based on early postural cues of the opponent (Causer & Williams, 2013), which can then be corroborated by early ball flight information. However, in most interceptive tasks, early detection of the target followed by a continuous tracking of the object seems to be the most effective strategy. For example, in a series of studies, Causer et al. (Causer, Bennett, Holmes, Janelle, &

Williams, 2010; Causer, Holmes, Smith, & Williams, 2011; Causer, Holmes, & Williams, 2011) examined the gaze strategies of expert and less-expert shotgun shooters. Analysis of eye movement data showed that expert shooters demonstrated an earlier object pick up, and a longer object tracking (QE duration) when compared to their less-expert counterparts. Successful shots were characterized by similar properties for high and low skill levels compared to unsuccessful shots, demonstrating that this gaze strategy is the most effective.

Researchers have shown similar findings in other interceptive tasks, such as in ice hockey goaltending (Panchuk & Vickers, 2006), table tennis returns (Rodrigues, Vickers, & Williams, 2002) and volleyball serve receptions (Vickers & Adolphe, 1997). Panchuk and Vickers (2006) found QE duration was longer on saves for eight of eight goaltenders, compared to goals. An early onset of QE and longer QE duration is critical for the successful interception of rapidly moving objects: the early QE onset maximizes the tracking time, and enables early flight information to be processed, while a longer QE duration provides sufficient time for flight trajectory information to be accurately calculated (for a summary of the optimal QE location, onset, offset and duration as exhibited by elite or expert performers in interceptive timing tasks, see Wilson et al., 2015).

QE training

Since expert performers have QE characteristics distinct from those with lower skill levels, QE training is designed to help non-experts acquire the most optimal spatial information, thus allowing the neural structures underlying the action to optimally organize. When the spatial information is insufficient or incomplete, then the action is only partially organized and performance suffers. Paradoxically, the type of gaze control that accompanies excellence in motor skills is not itself rapid and dynamic, but instead just the opposite. Even for skills that are rapid and ballistic, like making a save in ice hockey goaltending (Panchuk & Vickers, 2006), the final fixation onset is early, on a specific location (the puck on the stick before it is released) and has a duration longer as the elite performers focuses intently on a specific task location in space well before the final phase of the movement begins.

Since the human brain is a relatively slow visual processor, it is incumbent on the performer to find ways to access complex spatial information earlier and under conditions that can be very difficult to access. QE training studies are designed to help novice to near-expert athletes adopt the QE focus of elite performers earlier, thus accelerating skill acquisition and performance. Origin of the QE norms are derived from research with elite performers. A QE training program is carried out in seven steps:

1. *Define expert QE prototype.* The first step is to isolate the five QE characteristics of elite and near-elite performers in the task during successful and unsuccessful trials. Near-elite

athletes are those with similar physical attributes as the elite (usually a teammate), but with lower statistics in the task during a season of play.

2. *Test trainees in the same task.* The trainee is tested in the same task using a mobile eye tracker and a motion analysis system in conditions similar to those used in step 1.
3. *Provide instruction of the five QE characteristics.* The trainee should be shown the QE video data of an elite QE prototype (derived from step 1). A QE prototype illustrates the results for the elite group for QE location, onset, final critical movement, offset and duration. Carefully teach the trainee the importance of the five QE characteristics, using the frame-by-frame video controls.
4. *Provide QE feedback.* Video feedback is used to show the trainee his/her own QE as collected in step 2. Compare the trainee's QE to the elite prototype using side-by-side QE videos. An important part of this step is to ask trainees questions about their QE location, onset before a specific phase, offset, and duration. How does their QE differ from the elite prototype using frame-by-frame video comparison? The key is to cognitively probe how much the athletes understand about the control of their attentional focus as they perform.
5. *Decision training.* The trainee decides which of the five QE characteristics he/she wants to work on first. This is an important step as it passes control to the athletes in terms of learning how to master their attention. Re-test often using the eye tracker and plot improvements.
6. *Blocked and random training.* Blocked training drills are designed to promote the desired QE focus in repetitive trials with little variation. As the five QE characteristics must be mastered in a variety of game situations, design variable and random drill that are game like. Use bandwidth feedback and questioning as QE control improves (Vickers, 2007).
7. *Assess competitive QE.* Performance in competition should be assessed and follow-up QE tests carried out, as needed, designed to improve the athlete's performance in a variety of real-world competitive situations.

The first study to use QE training was in the volleyball service reception and pass (Adolphe et al., 1997; Vickers & Adolphe, 1997). Initial testing showed that players with higher service reception statistics tracked the ball earlier and for a longer duration. To facilitate early detection of the ball and improve tracking, a number of drills were developed where players were asked to track small objects, identify numbers placed on balls as they were served, and identify numbers when less time was available (i.e., the server was occluded by a blackboard or the receiver had to turn 180° after the serve). One month after completion of the training exercises, players were tested again on court and the results showed that all of the athletes were able to track the ball earlier and longer. Pass accuracy during competition also improved 7% over a three-year span following the study whereas a comparison group of top international

athletes who did not receive the training remained relatively stable over that period of time.

The second study in which we used QE training was with elite and near-elite varsity basketball players (Harle & Vickers, 2001). We found a significant increase in QE duration and free-throw accuracy in the experimental setting in year one, followed in the second year, by an increase in free throw-accuracy in games from 54% to 76% (an increase of 22%, which was significantly higher than two control teams who did not receive a similar training). The amount of improvement in this study was consid-

erable and shows that athletes who are trained to control their gaze, attention and decision making while performing in drills that simulate events within the game achieve gains that are much greater than when physical and/or psychological training are used alone.

Table 1 presents an overview of QE training information used in eight sport and motor activities, and the specific QE characteristics (location, onset, offset, critical movement, and duration) as derived from elite or expert performers in each task.

Table 1: Recommended QE Location, onset before critical movement, offset and duration during QE training in selected motor tasks. The QE norms were derived from research with elite performers in each motor task.

Author(s)	Sport or motor Activity	Who was trained?	QE location	QE onset before which critical movement?	QE offset	QE duration (retention or transfer tests)
Adolphe, Vickers & LaPlante (1997)	volleyball serve reception	national volleyball team	ball as it is being served and during early flight	ball at location of contact by server's hand and during early flight	early if ball flight is predictable; late, before contact, if ball flight is unpredictable	400-500 ms, depending on speed of ball
Harle & Vickers (2001)	basketball free throw	varsity basketball team	front of rim	before shot is initiated	before final extension of elbow and the shooting hand	1.0 s
Vickers, (2007); Vine & Wilson (2011)	golf putting	high and low skilled golfers	back or top of ball	before back-swing	after club/ball contact for 300 ms	2.5 s on short putt; 3.0 s on long putt
Causer, Holmes, & Williams (2011)	skeet shooting	elite olympic shooters	1st clay as soon as it is launched; detect 2nd clay immediately after trigger pull	250 ms before trigger pull	after trigger pull	400-425 ms on each clay
Wood & Wilson (2011)	soccer penalty kick	university level athletes	(A) top left or right corner of net; (B) on ball where foot will make contact	(A) before beginning of run-up; (B) during run-up before back-swing of kicking leg	(A) not reported; (B) not reported	(A) 900 ms (B) 700 ms
Causer, Harvey, et al. (2014); Causer, Vickers, et al. (2014)	surgical knot tying	surgical residents in first month of 5 year program	location in tissue where the first knot is to be placed	before placing the first knot	after all throws (usually 3 or more are completed)	2.5 s
Miles, Vine, Wood, Vickers, & Wilson (2014, 2015a)	throw a ball at a blank wall and catch it before the bounce	typical children; aged 9-10	targeting: "virtual target" on the blank wall; ball flight: ball as it left the wall	targeting: before the underhand throw; ball flight: before the ball left the wall	targeting: after ball hits the wall; ball flight: before the catch	targeting: 700 ms; ball flight: 300 ms
Miles, Wood, Vine, Vickers, & Wilson (2015b)	throw a ball at a blank wall and catch it before the bounce	children with development coordination difficulties; aged 9-10	targeting: "virtual target" on the blank wall; ball flight: ball as it left the wall	targeting: before the underhand throw; ball flight: before the ball left the wall	targeting: after ball hits the wall; ball flight: before the catch	targeting: 500 ms; ball flight: 200 ms

QE in child development

The most recent QE training studies have been in child development, and included typically developing children, as well as those with developmental coordination disorder (DCD) (Miles, Vine, Wood, Vickers, & Wilson, 2014; Miles, Wood, Vine, Vickers, & Wilson, 2015a, 2015b; Wilson, Miles, Vine, & Vickers, 2013). These studies are important as they show that QE training can be used with young children, thus opening up new methods for coaching the developing athlete. These studies also provide a preliminary answer to a question I am often asked when I speak at conferences: Is the QE genetic or acquired? I always respond that I do not know but research needs to be done in the area. In particular, we do not know if some children are born with the ability to focus in an exceptional way from any early age, or if this is an acquired ability that occurs with extensive training and practice. I have taught children with DCD and they find it difficult to perform motor skills and have witnessed the stigma and helplessness they often feel. Therefore another motivation was to see whether we could develop QE training programs that might be beneficial to this group of children. My very first gaze study was in child development, where we found differences in the gaze of children in the top percentile of a motor battery of skills compared to those at the very bottom (Emes, Vickers, & Livingston, 1994). Finally, although extensive DCD research has been carried out, the assumption is that the observed deficit exists primarily at the motor level, rather those related to the gaze and focus of attention.

If you have ever wondered what it is like to have DCD, try this exercise. Stand about 2 m from a blank wall. Look down at a tennis ball you are holding in your throwing hand. Throw it underhand at the wall but do not look up until the ball is about to hit the wall. Try to catch the ball before it hits the floor. Pretty hard, right? We found this is what some children with DCD experience, as opposed to what typically occurs in developing children. On your second attempt, hold the ball in your throwing hand, and look at the wall and in your "mind's eye" create a "virtual target" on the wall. Throw the ball so it hits the target you have created. Catch the ball before it hits the floor. Much easier, right? This is the task we used in three studies in which the participants were typical children and one study in which the children were diagnosed with DCD (Wilson et al., 2013). The throw and catch task we used is a part of the battery of motor skills (Henderson, Sugden, & Barnett, 2007) which combines both a targeting and an interceptive timing component. The participants in all four studies were aged 9-10, equal boys and girls.

In the first study, we found that children who performed in the highest percentile group (in % of successful catches) had a QE duration on their "virtual target" on the wall of about 700 ms *which occurred before they threw the ball*, while those in lowest percentile had a QE duration of about 250 ms, barely the threshold of visual reaction time. In the second study, typical children were randomly assigned to a QE training (QET) group or a technical training (TT) group. The TT participants were pro-

vided with technical information about how to control their arm movements during the throw and catch phases, while the QET participants were in addition taught to fixate a target location on the wall prior to the throw, followed by early tracking the ball prior to the catch. After training, QE duration increased and the percentage of catches increased to 72% for the QET group, whereas the TT group's QE remained the same as the pretest for both groups at around 50%, or chance. In the third study, children with DCD underwent similar QET or TT programs. The QET group increased QE duration and improved catching mechanics, whereas the TT group experienced a reduction in QE duration and no improvement in technique. The fourth study involved typical children and assessed the retention of skills acquired using QET and TT after a two month period. The QET participants had a significantly longer QE duration on the wall, an earlier QE as they tracked the ball, and a high percentage of catches, while the TT group revealed no improvements in QE or catching. Further analyses showed it was the first QE on the wall that was most important, pointing to the importance of anticipation and an early QE focus of attention on a specific target prior to the initiation of the throwing action. Response to these papers has been very positive. It is recommended that QE training programs are developed and applied to other motor tasks important in child development and sport. However, our results do not provide an answer to the question whether QE is genetic or acquired. This is a worthy research question and hopefully one that scientists with a background in child development and genetics will undertake.

QE and performing under high pressure and anxiety

An important characteristic of expert performers is their ability to perform under intense competitive pressure. The QE has also been identified as a gaze affected by high levels of performance pressure and anxiety (Behan & Wilson, 2008; Vickers & Williams, 2007). Vickers and Williams (2007) assessed the QE of elite biathlon shooters separately during high-pressure (national team tryouts) and low-pressure (practice) conditions in which physiological workload increased to 100% of their individual maximum. Anxiety levels were elevated for all the athletes under high pressure, and all but three choked at the 100% workload (shooting 29%). Those that did not choke shot 80% and increased their QE duration on the target by 600 ms. Behan and Wilson (2008) found a similar QE result in a simulated archery task under conditions of elevated cognitive anxiety. Other QE studies have confirmed and extended these results (Moore, Vine, Cooke, Ring, & Wilson, 2012; Moore, Vine, Wilson, & Freeman, 2012; Moore, Wilson, Vine, Coussens, & Freeman, 2013; Vine, Lee, Moore, & Wilson, 2013).

Theoretically, it is thought that high anxiety causes a diversion of processing resources from task-relevant stimuli toward task-irrelevant and/or threatening stimuli, which may be external in the environment or internal through worrying thoughts (Ey-

senck, Derakshan, Santos, & Calvo, 2007; Wilson et al., 2015). According to their *attentional control theory* (ACT), anxiety alters the strength of output so that threat-related stimuli are more likely to capture attention thereby increasing the sensitivity of the stimulus-driven ventral system, at the expense of goal-directed control by the dorsal attention system (Corbetta, Patel, & Shulman, 2008; Corbetta & Shulman, 2002). In terms of QE, this increased sensitivity of ventral attention is likely to disrupt efficient QE processing, and subsequent visuo-motor performance (see Wilson et al., 2015, for a summary of QE anxiety studies completed to date).

What are the neural structures underlying the QE?

With the advent of advanced imaging methods, the neural networks underlying visuo-motor control are increasingly better known, providing a theoretical basis for defining the networks that may be functioning during the QE period (Kolb & Whishaw, 2009, 2013; Liversedge, 2011). Task-specific spatial information is registered first on the retina, then passed through the optic nerve, the lateral geniculate nucleus, and the optic radiations to the visual occipital cortex at the back of the head. Located in the occipital cortex are feature detectors V1-V8 that register what the performer is looking at. V1 is responsible for the initial registration of features, which are then processed by V2 for shape, V3 for angles, V3a for motion, V4 for color, V5 for motion with direction, V6 for depth and self-motion, V7 for stereo motion, and V8 for further color-responsiveness. V1 to V8 processing is highly individualized, influenced by the type of training received, by current conditions and by a host of other factors. Once an object, person or location is registered, visual information travels rapidly forward along two visual networks, the dorsal attention network (DAN) and the ventral attention network (VAN) which run in parallel (Astafiev, Stanley, Shulman, & Corbetta, 2004; Corbetta et al., 2008; Corbetta & Shulman, 2002). The DAN is faster than the VAN and projects from the occipital lobe to the parietal lobe and forward to the frontal lobe in a journey in which the frontal eye fields and areas in the frontal lobe sustain focus on critical cues in space. During the QE the primary function of the DAN is thought to focus attention on specific locations in space, as well as to sustain intentions generated internally. With practice and the development of expertise, it is thought that the DAN system blocks or suppresses distracting or anxiety-producing stimuli that may intrude from the VAN system. The VAN projects forward through the temporal lobes to the frontal areas, and includes the hippocampus and amygdala. Both the hippocampus and amygdala are responsible for encoding memories (both good and bad). The hippocampus converts short-term memories to long-term and distributes them throughout the brain in areas involved in their origin, while the amygdala is the seat of emotional control. An athlete who has had a particularly bad experience may have negative memories registered by the hippocampus and amygdala. Following DAN/VAN processing motor commands

are developed in the frontal cortex and passed on to the motor cortex, which initiates the action (Callaert et al., 2011; Woolley et al., 2010). During the complete visuo-motor process outlined above (from retina to motor cortex) the lower centers in the basal ganglia and cerebellum are also on-line and take over automatic and other forms of control. As is evident from the description above, visuo-motor control dominates the brain, both in terms of its structures but also its processes.

Four lines of evidence

Research evidence that confirms the brain undergoes extensive change as a result of training in sport is in its infancy. Studies that do exist fall into four categories. EEG/ERP (electroencephalography/event related potentials) studies determine cortical processing differences as elite and novice athletes prepare to execute a skill, such as the golf putt or shooting in archery. MRI (magnetic resonance imaging) studies on high and low skilled athletes require the athlete to passively lie in the scanner in an effort to identify structural differences caused by extensive training in a specific sport. fMRI (functional magnetic imaging) studies attempt to identify the neural structures of elite and novice athletes as they watch an event from their sport, for example a video of a motor task that is temporally or spatially occluded. Participants are required to make a decision, for example, to identify the direction of a serve by pressing a button. Other fMRI studies require athletes performing a simulated sports task, for example, using a joystick to shoot at a target in archery. As will be shown in the following, very few studies have imaged the brain during the QE period.

The first, and perhaps only study to assess the QE and EEG used event-related potentials (ERP) to pinpoint the locus of attention and temporal activation during the preparation of putts performed by low (LH) and high (HH) handicap golfers (Mann, Coombes, Mousseau, & Janelle (2011). They measured a specific type of ERP called the *Bereitschaftspotential*, which is a moment of heightened processing which precedes an actual, intended, or imagined event by 1 s to 1.5 s thereby indexing anticipatory attention and movement preparation. Electrodes were placed over C3 and C4 in the left and right motor cortex, as well as the P3 and P4 in the left and right parietal areas. The LH group not only performed better on the putting task, but also had a longer QE duration relative to the HH group, accompanied by greater cortical activation in C3 (right motor cortex) and C4 (right parietal lobe). Mann et al. (2011) state that during the QE period, highly skilled golfers "allocated more attention to the visuo-motor components of the putting task than their HH counterparts ... [which] reflects attentional processes that permit the assessment, organization, and recall of the requisite motor program from memory" (p. 231).

Second, Jäncke, Koeneke, Hoppe, Rominger and Hänggi (2009) scanned four groups of golfers using MRI: 10 professional golfers (handicap 0), 10 highly-skilled golfers (handicap range 1–14), 10 golfers at the intermediate level (handicaps 15–36),

and 10 individuals with no golf experience. Significant differences were found between the two higher skilled groups when compared to the two lower skilled. The authors found that neuro-anatomical changes had been induced by intensive practice in golf. The high skilled groups had larger volumes of grey and white matter in the right and left fronto-parietal networks, including premotor and parietal areas. In addition, they had lower volumes of fibers running from the thalamus to the frontal lobe, which regulates emotion, attention, and basic movement processes, suggesting less reliance on working memory and more on automated control processes. In a second MRI study, novice golfers were trained for 40 hours of golf practice and play and compared with a control group who received no practice in golf (Bezzola, Merillat, Gaser, & Jäncke, 2011). The pre/post MRI comparison showed significant increases associated with the DAN network, specifically in areas of the supplementary area and motor cortex, as well as the pre-motor cortex and left and right inferior parietal lobes. There was no measure of the QE in these studies.

Third, in a series of three studies, fMRI was used to identify the neural areas activated in viewing and responding to video sequences of participants filmed from the view of the athlete receiving serves in tennis and in badminton (Wright, Bishop, Jackson, & Abernethy, 2010, 2011; Wright & Jackson, 2007). Elite and novice participants determined the direction of the serves as quickly as possible by pressing a directional button. Experts showed greater activation in brain areas associated with visual attention and the analysis of body kinematics, specifically superior parietal cortex, the middle and superior temporal sulcus, which control smooth pursuit processing, as well as object recognition, motion detection, and depth perception. Conversely, the novices had higher activation in the occipital cortex, suggesting a greater influence of bottom-up processing based on the perception of distinct features rather than an overall top-down understanding of what was being viewed. There was no measure of the QE in these studies.

Finally, the overall goal of a study by Gonzales et al. (2015a, 2015b) is to carry out an fMRI study in which a valid archery simulator activates the brain structures and processes used during the QE period. Two of three experiments have been completed so far. In study 1, expert and novice archers took shots to a regulation target set at 30 m, and in study 2 shots were taken using a computer simulator and joystick. Results were similar in the two tasks. Experts were more accurate than the novices, as expected, and had a longer mean QE duration and earlier onset. The authors conclude that the longer QE durations may facilitate the integration of information for the formulation of a motor program, as part of a feed-forward/feed-back system. In the fMRI study, Gonzalez et al. (2015b) have hypothesized that enhanced activation of the dorso-fronto-parietal network will occur in expert archers more than in non-experts, that is associated with top-down processing and the allocation of attention to relevant stimuli and the suppression of distractors in the ventral stream due to bottom-up processing. They do not specify whether this will occur for the experts and novices over

all trials (using radial error, i.e., hits and misses combined), or whether the QE will differ for experts and novices on accurate trials, as opposed to misses. If I were to predict the outcome, I would expect significant differences for the experts on hits versus misses, as hypothesized above, but not for novices, as they have not developed the neural networks that will allow them to be accurate over a number of trials, which will be relatively easy for the experts in the simulator condition. If QE is determined when accuracy is calculated using hits and misses combined (i.e radial error), the results will not be as clear as when an absolute measure of accuracy is used (i.e 10 hits versus 10 misses), as normally occurs in QE studies. Results are forthcoming in 2016.

Conclusion

At the outset I talked about three experiences I had in sport when I performed at a level way above anything I had achieved in the past, experiencing for fleeting moments what is commonly called the “hot hand” in sport. As a result of those experiences, I knew that some secret power resides within all of us on occasion, but is probably present in elite athletes and other experts most of the time for reasons we did not understand. Now 35 years later, the QE may provide an objective measure of the “hot hand” in sport. With the attainment of sports expertise, measurable changes occur in the visuo-motor networks and QE as a consequence of extensive training and real world competition. Because the QE onset occurs prior to the final critical movement, and is of longer duration when performance is higher, the QE period represents the window of time when the neural networks are organized prior to and during motor execution. In this view the neural networks underlying high levels of performance are “fed” very precisely with external visual information, and it is this information that is central to organizing the complex neural systems underlying control of the limbs, body and emotions. An analogy I often use describes the QE as a “GPS system” that feeds the brain with the optimal spatial information needed for the action to be effectively organized, initiated and controlled. When the location, onset before a critical movement, offset and duration of the QE are all optimal then the resultant performance is superior; when any one of these QE dimensions is non-optimal then performance will suffer.

My last point is that, to date, the QE has been isolated in approximately 28 motor tasks, which means there are many QE discoveries yet to be made when one considers the many sports that humans participate in. Although understanding the neural and other processes underlying the QE is important, it is also vitally important that we continue to isolate the QE of elite performers in sport, medical, law enforcement and other motor tasks, followed by developing QE training programs that are effective with different age and skill levels, as well as for disability groups and rehabilitation programs.

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Data Availability Statement

All relevant data are within the paper.

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Sssh! We're talking about the Quiet Eye – comment on Vickers

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Over the past two decades, the Quiet Eye (QE) has emerged as a consistent characteristic of expert perception in sport and other skilled domains (e.g., surgery). As noted in Vickers' (2016) target article, the QE reflects the stability of a performer's gaze in the period immediately before movement in an aiming task. The value of QE for differentiating both among performers of different skill levels and between successful executions and failures seems clear, as reported by several reviews (e.g., Rienhoff, Tirp, Strauss, Baker, & Schorer, 2016; Vickers, 2007; Vine, Moore, & Wilson, 2014). In fact, in their meta-analysis, Mann, Williams, Ward, and Janelle (2007) highlighted the QE as one of the most consistent perceptual-cognitive effects in sport expertise research.

After 20 years of study into this phenomenon (largely led by Vickers and her colleagues), we believe the QE concept is at a

ABSTRACT

Over the past two decades, the Quiet Eye (QE) has emerged as a consistent characteristic of expert perception in sport and other skilled domains. The value of QE for differentiating both among performers of different skill levels and between successful executions and failures seems clear; however, we argue that research on QE is at a cross-roads and that future research should consider greater movement into five areas: replication, explanation, extension, integration and application. Greater attention to these areas may help to ensure that the full potential of QE is realized in sport and beyond.

Keywords:

perception – cognition – sport – Quiet Eye – expertise

crossroads. On the one hand, research in this field has clearly established the relevance of QE in the domain of sport and it could certainly become a dominant concept in athlete training and development. On the other hand, however, the QE almost undoubtedly applies to other areas of human performance. How does research move forward over the next 20 years to further legitimize this concept and expand its relevance in sport and beyond? In order to capitalize on the potential of QE for informing our understanding of aspects of skilled perception and for developing practical strategies to improve perceptual performance in sport and elsewhere, we argue for specific movement in five areas: replication, explanation, extension, integration and application.

Replication

Replication, although seemingly unattractive to journal editors who wish to focus on publishing new and novel findings, is a cornerstone of scientific inquiry. Over the history of QE research, very few studies have been 'straight up' replications of results. Importantly, while the QE effect appears robust in reviews and meta-analyses, there have been inconsistencies in results between studies and research labs (c.f., Glöckner, Heinen, Johnson, & Raab, 2012; de Oliveira, Oudejans, & Beek, 2006, 2008). These inconsistencies highlight the need for continual replication of previous work by different teams of researchers and with different tasks, sports and skill levels. Lack of replication can limit our understanding of the depth and breadth of this effect and can be a significant limitation for conducting and accurately interpreting meta-analyses.

Explanation

As noted above, there are several proposed explanations of the QE. In order to move into a more advanced level of understanding and application, researchers of this phenomenon need to determine the precise mechanism(s) driving this effect. Various ones have been proposed, ranging from a) QE facilitating a general quiescence of the psychomotor system, b) QE allowing greater time for response programming and c) QE allowing superior attentional control through inhibiting environmental distractors (see Rienhoff et al., 2016). It will also be important to determine (if possible) the optimal QE duration for different tasks (see Rienhoff et al., 2016). It is conceivable that QE may not have an optimal duration for a task; the optimal duration may in fact depend on specific task constraints. Optimal QE duration could vary, for example, across variations of the same task. When shooting a basketball, optimal duration may depend on task constraints like type and structure of the defense, speed of play, and distance to the basket. Similar to movement execution outcomes, there may be a variety of gaze solutions that depend on interactions between the performer and task. Studying this possibility would provide valuable insights into intra- and inter-individual variability in QE.

Extension

To date, most work on the QE has focused on stable, closed-ended aiming tasks (e.g., basketball free throw shooting, darts, etc.). However, the relevance of this stable gaze strategy for open-ended tasks is only beginning to be explored (e.g., Panchuk & Vickers, 2006). While the application of this effect to athlete development and performance is clear, extending the effect to other areas of human health and performance may prove fruitful. While research has explored the implications of QE in populations with developmental coordination disorder (DCD; Miles, Wood, Vine, Vickers, & Wilson, 2015), the potential

to extend research to other populations is promising. For instance, there has been some research considering gaze behavior of individuals with autism spectrum disorder (ASD, a core characteristic of which is lack of eye contact), however, research has neither considered specific perceptual skills (i.e., QE) nor how play and movement can be used to improve eye contact in social situations. The usefulness of QE training for children with DCD (Miles et al., 2015) suggests that QE research and interventions have tremendous potential for improving fundamental movement skills for other populations with developmental disorders. Moreover, the utility of the QE concept toward understanding and improving seemingly mundane, yet vital activities of daily living for quality of life, remains largely unrealized.

Integration

As our understanding of perceptual-cognitive expertise advances, it seems clear that perceptual-cognitive phenomena do not operate in isolation. In an effort to determine how QE integrates with other elements of perception, cognition and learning, researchers have begun exploring how QE relates to other concepts, such as focus of attention (Rienhoff, Fischer, Strauss, Baker, & Schorer, 2015), fields of vision (Rienhoff, Fischer, Strauss, Schorer, & Baker, 2012), and transfer of learning (Rienhoff et al., 2013). More work of this nature could be quite revealing regarding how the QE might be best utilized. For example, how does the structure of practice influence QE? Does blocked practice hinder the development of QE and does high contextual interference practice promote its development? Can QE be facilitated with an implicit learning approach and if so, which one (implicit or explicit) is superior for learning and performance? Answers to these questions would help situate QE amongst other well-supported motor behavior concepts.

Application

In our opinion, this is the area with the potential for the largest 'real world impact'. In our work with high performance sport teams, one of the most beneficial elements of the QE phenomenon is how easily it can be applied in practical situations. Unlike some motor learning concepts, the QE is quickly understood by coaches, trainers and athletes, and can rapidly be put into action in sports with stable, closed aiming tasks. That said, our understanding of how QE develops across an athlete's participation in sport is largely unknown, outside of short-term intervention studies (e.g., Moore, Vine, Cooke, Ring, & Wilson, 2012; Vine, Moore, & Wilson, 2011). How and when is the QE acquired across athlete development? Are there particular windows of development that are best suited for QE training? Is QE more likely to develop in a highly specific (i.e., specialized) environment or is it better facilitated through more variable, diversified environments? As with many aspects of skilled perception, understanding the time-course of development would allow for

more appropriate interventions to promote more rapid acquisition of this skill at the correct point of development.

Conclusion

Vickers' (2016) target article will assist with the continued expansion of the QE concept. Greater attention to the issues above may help to ensure that its full potential is realized in sport and beyond.

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The future of Quiet Eye research – comment on Vickers

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ABSTRACT

The Quiet Eye (QE) phenomenon has a robust literature base. However, the specific mechanisms by which the QE enables athletes to be more accurate are still not fully understood. Furthermore, QE has been shown to negate the negative effects of anxiety, but similarly, the specific role it plays is unknown. A more systematic and strategic approach to future research is needed to delineate the different theories and develop a stronger, more concrete understanding. There is also the question of QE training, which appears to have a significant impact on performance in a relatively short time period. Limitations to current studies as well as suggestions for future projects are outlined. Technological advances are also discussed in relation to enabling researchers to better understand the neural underpinnings of the QE advantage.

Keywords:

eye-trackers – technology – Quiet Eye – anxiety – training – attentional control

Introduction

Expertise in sport, as well as other temporally and spatially demanding domains, requires a set of refined perceptual-cognitive skills in order for an athlete to be both efficient and effective (Causer & Williams, 2013). Specifically, the orientation of visual attention has been shown to differentiate between skill-levels and also task outcome in a number of aiming and interceptive tasks (Vickers, 2011). Seminal research by Joan Vickers (1996a, 1996b, 1996c) established a robust link between the duration of the final fixation on a target or object before execution of a critical action and success. Subsequently, there have been a plethora of studies examining this Quiet Eye (QE) phenomenon and trying to understanding its role in sporting expertise (Wilson, Causer, & Vickers, 2015). However, there are many questions that remain unanswered.

Why is Quiet Eye effective?

Despite the consistent and robust literature base now present on QE, researchers are still undecided as to what makes the QE critical for successful performance (Vine, Moore, & Wilson, 2014). In the earlier studies, researchers proposed QE played a functional role in motor programming, however, since then there has been evidence of its role in online control of action (Causer, Hayes, Hooper, & Bennett, 2016; Vine, Lee, Walters-Symons, & Wilson, 2015). Other proposed roles of QE include: external focus of attention, emotional regulation, distractor control, and quieting of the psychoneuromuscular system. In order to determine the QE advantage, a systematic program of work is required to differentiate the relative influence of each of these possible roles.

Furthermore, task demands have already been shown to influence the 'need' for QE, with more cognitively demanding tasks more likely to benefit from longer QE durations (Klostermann,

Kredel, & Hossner, 2013). Therefore, the transfer of QE characteristics to other, more dynamic scenarios involving decision-making and interaction with opponents or team mates is also required (Wilson et al., 2015), specifically looking at how QE metrics interact with other perceptual-cognitive skills, which enable athletes to utilize postural cues, recognize tactical patterns and make complex decisions based on complex environmental information (Causer & Williams, 2013).

Quiet Eye and anxiety

A popular area of research is examining how QE can negate the potentially negative effects of anxiety (Wilson, 2008). It appears that individuals who are able to maintain a longer QE under high-anxiety are more likely to sustain performance (Causer, Holmes, Smith, & Williams, 2011). However, it is not fully understood in which way this longer QE reduces the effects of anxiety on performance (Wilson et al., 2015). The popular opinion is that the longer final fixation enables the individual to minimize the influence of external distractors, which in turn enables athletes to focus on the primary task (Moore, Vine, Cooke, Ring, & Wilson, 2012). Findings are typically linked to Attentional Control Theory (Eysenck, Derakshan, Santos, & Calvo, 2007), which outlines the effect anxiety has on performance efficiency and effectiveness. It is thought that a longer QE is an example of an efficient gaze strategy, which maximizes attentional resources on the principal task. However, further research is needed to provide a more comprehensive understanding of the mechanisms by which QE enables certain athletes to overcome anxiety. Furthermore, it is also important to determine how different types of anxiety influence the performance on tasks of varying skill-levels, ages, and for individuals from other domains.

Quiet Eye training

As described in Vickers (2016), after the initial descriptive findings of QE had been reported, researchers proceeded to attempt to train these characteristics in order to replicate the expert advantage (Vine et al., 2014). However, despite the effectiveness of many of these training programs, there are some limitations that should be considered. For instance, in many of the respective studies, there are limited acquisition trials, short retention periods and multiple training interventions (instructions, gold-standard eye movement, feedback of self), which makes it difficult to ascertain which manipulations are most effective (Causer, Janelle, Vickers, & Williams, 2012). It is also difficult to compare between many of the training studies due to the different practice structures, feedback and instruction procedures and research designs (Broadbent, Causer, Williams, & Ford, in press). With a more comprehensive understanding of the mechanisms involved, and the underlying neural events that occur during the QE period, more effective training programs can be developed.

Effective QE characteristics are associated with high-level expertise, which has been developed over years of deliberate practice (Ericsson, Krampe, & Tesch-Römer, 1993). However, researchers are expecting athletes to circumvent these practice hours by giving them explicit instruction on how to orientate their visual attention. Therefore, a more precise study of how QE evolves over the lifespan of an athlete is needed to determine whether QE training, although effective in the short term, is a viable option for the long-term development of visual attention.

Neural underpinnings of Quiet Eye

There have been some attempts to determine the neural correlates of QE, which may give researchers a better understanding of the link between performance and QE (Gonzalez et al., 2015). A combination of neurophysiological techniques, such as fMRI and TMS, can be used to determine causal relationships between behavior and specific anatomical regions (Mann, Coombes, Mousseau, & Janelle, 2011). However, the specific task demands may influence the relative contributions of the attentional networks, which would make generalization of findings difficult. Despite this, researchers should look to enhance their understanding of the networks activated during QE and how the expert brain differs to less-skilled athletes. This would enable researchers to better understand how QE training can lead to brain plasticity specific to aiming.

Advances in Technology

In many of the early QE studies, a limiting factor in enabling more detailed conclusions to be drawn was the eye-trackers themselves (Panchuk, Vine, & Vickers, 2015). Typically with low sampling frequencies, poor mobility and low spatial resolution, researchers were forced to use self-paced, unrepresentative laboratory-based tasks, which limited the applied implications that could be made (Ericsson & Williams, 2007). Furthermore, this limited accuracy can lead to discrepancies between temporal aspects of QE (onset, dwell, offset), which may impact on instructions used for training programs (Gonzalez et al., 2015). However, with the significant advancement of eye-tracking technology over the last few years, it is now easier to develop more representative task, or collect data *in situ*, which enable coaches and athletes to access more reliable and meaningful data (Vickers, 2009). Furthermore, the high-sampling frequencies now available in mobile eye trackers can enable a more in-depth analysis of the specific eye movements occurring in the final aiming action. For example, high-resolution eye-trackers can enable researchers to examine saccades and microsaccades, as well as providing a more accurate definition of what constitutes a stable QE (Gonzalez et al., 2015).

Summary

In summary, the discovery of the QE period has had a significant impact on both motor control and learning theory as well as the applied arena for improving sports performance. Moving forward, researchers should seek to better understand the specific mechanisms by which the QE advantage is acquired and understand the long-term learning of QE characteristics. Furthermore, with the perpetual improvement in technologies, researchers should continue to refine their understanding and definition of what the QE advantage entails and how it can be expedited effectively over an athlete's lifespan.

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What could an ecological dynamics rationale offer Quiet Eye research? Comment on Vickers

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ABSTRACT

In this commentary, we respond to suggestions in previous Quiet Eye (QE) research that future work is needed to understand how theories of ecological psychology and nonlinear dynamics might frame empirical and practical work. We raise questions on the assumptions behind an information processing explanation for programming of parameters such as duration, onsets and offsets of QE, and we concur with previous calls for more research considering how visual search behaviours, such as QE, emerge under interacting personal, task and environmental constraints. However, initial work needs to frame a more general ecological dynamics explanation for QE, capturing how a process-oriented approach is needed to address how perceived affordances and adaptive functional variability might shape emergent coordination tendencies, including QE, in individual performers.

Keywords:

Quiet Eye – ecological dynamics – task constraints – organismic constraints – affordances – intra-individual variability – inter-individual variability

Introduction

Joan Vickers' (2016) target article describes how her highly influential research programme on Quiet Eye (QE) over the years was predicated on experiential knowledge, empirical data and theoretical ideas, to develop understanding of how skilled individuals control gaze and attention to perceive 'critical information' for performance. This approach is aligned with proposals of Greenwood, Davids and Renshaw (2014), that an elaborate cross-fertilisation of experience, theory and data can enrich practitioners' understanding of how to facilitate athletes' pick up of information to regulate functional actions. This type of integrative approach may lead researchers and practitioners towards different explanations, nuances, emphases, outcomes

and applications, depending on the theoretical perspective utilised to frame studies and interpret data.

Vickers describes QE as a 'perception-action, neural-cognitive variable', and Rienhoff et al.'s (2015) systematic review showed that published research has been dominated by assumptions and terminology predicated on an information processing perspective. Good progress has been made seeking answers to questions on the 'optimal' duration of QE and its relationship with perception, cognition and decision-making. Most studies typically average measures across participants and intra-individual variability in performers is rarely discussed. Performance is studied with a correlational approach used to associate average values of QE durations and times of onset and offset in groups with different outcomes.

Vickers (2016; see also 2007), and Rienhoff et al. (2015) have pointed to the relevance of a constraints-based approach (Newell, 1986) to QE, suggesting how tasks, sport disciplines, individual characteristics and environmental features may shape QE parameters. Williams, Janelle and Davids (2004) originally proposed this approach to understanding visual search patterns more generally, arguing that they need to be framed and studied as emergent behaviours continually shaped by interacting constraints. Rienhoff et al. (2015) located 581 published papers on QE, identifying 51 papers construed as investigating effects of constraints on QE. This body of work focused mainly on the categories of person, task and environmental constraints to describe effects on QE outcomes.

Rienhoff et al. (2015) commendably concluded that further work is needed to study the QE phenomenon from the perspectives of ecological psychology and nonlinear dynamical systems, theoretical approaches that we have integrated into an 'ecological dynamics' framework for studying emergent behaviours in sport and physical activity (Araújo, Davids & Hristovski, 2006).

Developing an ecological dynamics rationale for QE effects: some key issues

How might an ecological dynamics framework interpret findings from QE research and what accents, priorities and interpretations might it focus on in attempting to explain effects? This is a major question requiring a detailed position paper to elucidate how key concepts in ecological dynamics can be used to identify mechanisms and interpret findings. Although this task is beyond the scope of the current commentary, clearly concepts like affordances (invitations for actions), self-organisation under interacting constraints and adaptive variability are likely to be prominent in an ecological dynamics rationale. For example, such an elucidation could focus on understanding how QE behaviours emerge from interacting constraints of performer, task and environment, focusing on the role of adaptive variability in skilled individuals perceiving affordances in performance environments (Dicks, Davids & Button, 2008). Here, we outline key questions that an ecological dynamics framework can address in future work.

Although QE characteristics may vary according to task constraints, how do interacting constraints shape this, and other, visual search behaviours? For example, how is useful information revealed as such for an individual performing a given task? How to decide what is the critical spatial location that QE needs to target in each task? Vickers (2016, p. 2) clarifies that the role of QE is to extract "critical information sooner, thus enabling transmission of higher quality commands to the motor system", providing "a way to access to the brain". But how can relevant spatial information be distinguished from non-relevant information, before the information extracted by QE is transmitted to the brain? This is an important question because the explanations about the usefulness of QE rely on the assumption that

gaze is fixated on "relevant cues". Information from these cues will then "feed" neural networks, allowing these brain structures to organize (programme) a motor response. For example, how does a dorsal attention network distinguish what is distracting or what is anxiety-producing for each individual (Vickers, 2016, p. 7)? Indeed, the explanation presented by Vickers (2016, p. 8) is that "the neural networks underlying high levels of performance are 'fed' very precisely with external visual information, and it is this information that is central to organizing the complex neural systems underlying control of the limbs, body and emotions."

The problem, we believe, is that the starting point is missing in an information processing explanatory framework: How does the brain tell the eye where to look (and perform the QE)? How is the action that allows the body to search for relevant cues and perform a QE "programmed by the brain"? A possible answer to these questions implies a clear understanding of the role of constraints and information in explaining how intertwined processes of perception, cognition and action subserve goal-achievement in athletes (Araújo et al., 2006). And this explanation cannot be confined to how task constraints and information are represented in the brain, because this will always postpone the answer to the question concerning how these task constraints and information sources were selected in the first place.

An ecological dynamics framework that formally includes both the individual (with his/her body and brain) and the environment (including task constraints), would not place QE as the sole explanation for expert performance, as implied by Vickers (2016, p. 4) when she writes: "when the spatial information is insufficient or incomplete, then the action is only partially organized and performance suffers." There are many sources of information relevant for expert performance beyond patterns of energy detected by the visual system, such as those detected by haptic systems (Kim et al., 2013). The view that "visuo-motor control dominates the brain" (Vickers, 2016, p. 7) is too restricted for an ecological dynamics viewpoint, which advocates that there are more variables than gaze in explaining expert performance in complex adaptive systems (Davids, Araújo, Seifert, & Orth, 2015). Otherwise, designing practice task constraints would be a relatively straightforward task for coaches and practitioners: just emphasise an average value of QE in each specific sport.

This is one reason why it may be timely for QE research to focus on the role of interacting constraints. This application cannot be restricted to the categorisation of circumstances in which QE is used. Rather an interacting constraints model can be used to theoretically inform experiments and practice on behaviours *before QE emerges*. To explain that an expert performer is already "in the right place at the right time", an ecological dynamics perspective can address how QE needs to be understood beyond an 'organismically-biased' perspective (Davids & Araújo, 2010).

Considering athletes performing a task as complex adaptive systems mitigates against imputing so much importance to

one perceptual variable, which leads to researchers seeking 'optimal' values of QE durations, onsets and offsets. It is doubtless a characteristic of visual search behaviours, but ecological dynamicists seek to understand how intentions, perception and actions are intertwined in a given task with specific informational and physical constraints to support goal achievement in athletes. From an ecological dynamics perspective, current research on QE seems too 'outcome-oriented' (especially averaged across participants in groups). A preferred emphasis in future ecological dynamics work may be on an individualised, process-oriented approach, which would raise questions like: How does QE relate to emergent coordination tendencies of an individual athlete as he or she attempts to satisfy changing task constraints? How do skilled performers adapt and vary QE parameters during performance to support coordination of their actions with important environmental events, objects, surfaces and significant others? Rather than looking for optimal values, it would be important to look for 'critical threshold bandwidths' which could be distinguished according to task constraints and individuals, within and between expertise levels, while studying emergent actions in sport performance.

As a starting point, the concepts of affordances, self-organisation and emergent behaviours make it likely to expect that there may be functional variability in QE characteristics between individuals as they accept 'invitations for actions' under different task constraints.

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Using Quiet Eye training in an elite sport context – comment on Vickers

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ABSTRACT

While the mechanisms underpinning the Quiet Eye (QE) phenomenon are of growing interest to researchers, the translation of QE concepts to the real-world of athlete training and development form the backbone of QE's popularity. This commentary focuses on the challenges associated with applying QE research findings into the daily training environment of elite athletes. In particular we consider: a) how one defines optimal QE behavior in elite athletes; b) how we handle the explicit nature of QE instruction and feedback; and c) how we explain skill failure despite optimal QE behavior.

Keywords:

gaze behavior – Quiet Eye – applied sport – expertise

Introduction

Vickers (2016) presents a compelling overview of the history and origins of her interest in the Quiet Eye (QE) and the growth of a program of research that has spanned three decades and sparked curiosity amongst researchers across the world. The prevalence of this research and longevity of interest in the topic is likely a testament to the fact that it crosses the boundaries of theoretical and applied research so readily. As Vickers (2016) notes there have been efforts to not only characterize QE in a multitude of tasks (see. Rienhoff, Tirp, Strauss, Baker, & Schorer, 2016, for an overview) but also to explain the mechanisms that underlie this phenomenon (e.g., Mann, Coombes, Mousseau, & Janelle, 2011) and to answer the question of how these mechanisms can be translated for the benefit of performers across a range of skills (e.g., Panchuk & Vickers, 2013). While the target article touches on all of these areas and identifies possible re-

search avenues in development, anxiety, and neural activity and imaging, given our interest in applied sport, we will focus this commentary on questions that have arisen from our own experience in using QE training as a tool for improving sport performance.

We have used the QE training approach advocated in the target article in our own published work (Panchuk, Farrow, & Meyer, 2013) as well as when consulting with athletes across a variety of sports (e.g., golf, shooting, basketball) to great effect. There is no question that QE training can be an effective method of eliciting behavioral change and improving performance in athletes. Applied work, however, presents a number of challenges that are not typically encountered in laboratory-based experiments (e.g., lack of an expert QE prototype, limited time to complete interventions). Working with these sometimes difficult challenges has led us to consider how QE training, specifically with highly-skilled athletes, should be carried out with respect

to: a) what we consider optimal QE behavior in elite athletes, b) how we handle the explicit nature of QE instruction and feedback, and c) how we explain skill failure despite optimal QE behavior. In the following sections, we will consider each of these questions within the context of traditional QE training.

The expert QE prototype

The first step in the QE training process is to 'define the expert QE prototype'. While this typically involves referring to existing research or comparing skilled and lesser skilled athletes, it is not always possible to do this if time is an issue or when the athlete being trained is the expert in their sport. In these circumstances, a degree of flexibility in the training approach is necessary and it may be preferential to compare the athletes' performance when they are successful versus unsuccessful. In a similar vein, researchers also need to appreciate the individual differences between performers since what is optimal QE behavior for one performer may not be optimal for another. Expert QE prototypes, used to establish norms for training, are often determined by averaging data across a number of elite performers. For example, in golf, it is assumed the optimal QE duration is between 2-3 seconds (e.g., Vine, Moore, & Wilson, 2011). As a general rule this does not pose any serious issues, however, in the context of elite sporting performers, the use of grouped data may mask the individuals who perform outside of these norms yet are still successful. The debate surrounding the use of grouped or individual data is not unique to QE research but it does pose interesting questions for researchers and practitioners. Given that one of the hallmarks of elite performers is their unique ability to use visual information to support exceptional performance, it begs the question whether the idiosyncrasies observed in their QE behavior (which fall outside of what is deemed prototypical) actually underpin their phenomenal capabilities. In these cases, would it not be detrimental to prescribe training in accordance with the prototype? Or is it still desirable to train the athlete to the norms of the group?

QE instruction and feedback

In the target article, a rather detailed and explicit instructional approach is recommended for the training of a performer. Key features of this approach include the detailing of the five QE characteristics with frame by frame video training followed by explicit feedback and probing of the trainee to attain how much they "understand about the control of their attentional focus as they perform" (Vickers, 2016; p. 4). In the applied setting, "information minimization" is often sought by athletes and coaches alike. This desire is consistent with the aims of the implicit motor learning literature (e.g., Masters, 2013). Consequently, does the performer really need to understand the five QE characteristics? If QE location was the limiting factor, then we would

advocate only focusing on this aspect preferably via methods that reduce the explicit nature of any guidance provided. For example, for golf putting we have previously asked golfers to tell us the color of a marker placed under their ball. The logic being that such an instruction would ensure the golfer needed to maintain a longer fixation on the key QE location (Panchuk & Vickers, 2013). Such an approach is consistent with previous implicit QE training approaches conducted in both sport and surgical domains (e.g., Vine & Wilson, 2011; Wilson et al., 2011) where a key focus is that the attentional skill is passively acquired by the performer in an attempt to inoculate against stress. Recourse to explicit training approaches is considered a hindrance to such an outcome.

QE and skill failure

Those working in the applied space quickly appreciate that there are no silver bullets for improving performance – and QE training is not an exception. While we are not questioning the efficacy of QE training, one of the challenges of using QE training in elite populations is explaining to an athlete or coach why a performance was unsuccessful even though QE location, onset, offset, and duration were optimal. Given that QE does not account for all of the variance in performance (Vine & Wilson, 2010, 2011), the conversation with a coach or athlete about training becomes easier if we have an understanding of what other factors influence performance and how they interact with QE. While understanding the mechanisms (e.g., neural activity) underlying the QE effect is valuable, it is just as important to appreciate other contributors to performance. Hence, we would suggest approaching QE testing and training from an interdisciplinary point-of-view by collectively capturing multiple facets of performance (gaze, movement coordination, psychological state, etc.) as such an interdisciplinary approach should provide further insights which were beneficial for applied practitioners.

Summary

In summary, the QE phenomenon has profoundly influenced the training of athletes attentional control skills. This commentary has focused on the issues of application surrounding QE research. To this end, we encourage continued work investigating the most effective methods possible for transferring enhanced attentional control skills to competitive performance. Particularly fruitful directions would include the continued development of implicit learning techniques to develop QE and the greater use of interdisciplinary research teams so that the complex relationships between attention and movement control can be better understood.

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Functions of a quiet and un-quiet eye in natural tasks – comment on Vickers

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It is an intriguing possibility that one of the factors determining expertise in sport is our overt visual attention. Research into the Quiet Eye (QE) has now spanned many different situations (Vickers, 2016). The finding that a final fixation with a long duration is associated with sporting success has been replicated both within and between individuals (Mann, Williams, Ward, & Janelle, 2007). In this commentary, I will describe how progress in this field relates to what we know about the functions of gaze in the laboratory and in real world actions.

The un-quiet eye

The irony of any paper about the QE is that the eye is not really “quiet” at all. Our illusion of continuity is so strong that many people express surprise when watching the darting saccades that are common in most visual tasks. In the laboratory, fixations tend to last somewhere between 100 ms and 500 ms dur-

ABSTRACT

The Quiet Eye (QE) is an interesting phenomenon that has implications for the links between cognition and eye movements as well as for the question of how we examine these links in real world tasks. The gaze behaviour observed in sports and other active tasks is varied in form and function. Although fixation duration has a specific definition in laboratory tasks, in sport and naturalistic actions it is not as easy to interpret. I discuss what we can learn from gaze in natural behaviour and how both quiet and “un-quiet” eyes may have highly specific functions in different tasks.

Keywords:

gaze – eye movements – cognition – attention

ing tasks like reading or image viewing (Rayner, 2009). Even during fixations the eyes are subject to “fixational eye movements” such as microsaccades (forming a continuum of oculomotor activity with saccades; Martinez-Conde, Otero-Millan & Macknick, 2013). It has recently been reported that experts make larger microsaccades when watching video clips of table tennis, indicative of increased attention to items in the periphery (Piras, Raffi, Lanzoni, Persiani, & Squatrito, 2015).

In the laboratory, saccades are a readily-interpreted response to the limits of the fovea. Thus, fixations are an indication of where people are extracting information from and what they are doing with this information. Longer fixation durations are normally indicative of more difficult – or less efficient – information processing. As a result, expertise in such tasks is often associated with shorter rather than longer fixation durations. For example, novice or less-skilled readers have greater average durations (Rayner, 2009). Gegenfurtner, Lehtinen and Säljö (2011) conclude in their meta-analysis that experts generally

make *shorter* fixations when looking at visual information. To understand this apparent discrepancy with QE research it is helpful to consider studies of active vision from outside the lab.

From the lab to the golf course

QE research presents several challenges compared to conventional lab-based cognitive psychology. Researchers must deal with a participant who is free to move, and technical limitations mean that analysis is often dependent on video coding. QE research has succeeded in overcoming these challenges, along with research into natural gaze behaviour by Land, Hayhoe and colleagues (e.g., Land & Hayhoe, 2001). With mobile eye trackers cheaper and more user-friendly than ever before, the number of researchers investigating gaze in active tasks is only going to increase.

Despite the difficulties, I (as well as others) have argued that it is crucial to study visual behaviour outside the constrained situation of the psychological laboratory (Foulsham, 2015; Tatler, Hayhoe, Land, & Ballard, 2011). In Foulsham, Walker and Kingstone (2011), we compared gaze in people walking outdoors with those watching videos of the same scene while sitting in the laboratory. People fixated task-relevant features such as the path more frequently in the real world than on video. Participants also moved their eyes less within the head frame-of-reference when walking in the real world, perhaps due to their freedom to make head movements and the participant's locomotion through the environment. There are interesting parallels here with QE research. It may be that, when walking, we are all "experts", skilled at dwelling in the right place at the right time (for "non-experts", see Kretch, Frenchak, & Adolph, 2014, who measured gaze in infants learning to walk). The study of gaze in walking also makes clear that defining "fixations" in real world actions is more difficult than when the head is fixed in laboratory conditions. This is partly due to the lower temporal resolution of mobile eye trackers, but also because of difficulties with excluding smooth pursuit, tracking gaze, and reflexive movements which keep the eyes central while the head is moving. The spatial (within 3°) and temporal (> 100 ms) limits of QE gaze may seem somewhat arbitrary, and it will be interesting to

see whether advances in technology can lead to a more physiologically precise definition.

Figure 1 shows an example of the range of gaze behaviour made during real tasks. In this (unpublished) study, several golfers were recorded on a real course executing different shots. QE-type behaviour could be detected in the fixations on the ball and club before striking the ball. However, a range of other interesting behaviours were on display during the pre-shot routine. Golfers often looked at targets between the tee and the desired position on the fairway, a scanning process which continued during practice swings. Before and after the shot, gaze was used for other purposes: to guide the hands when manipulating ball or tee, or to track the ball in motion. The visual information being acquired and the processing occurring is different in each case, and difficult to study within the laboratory.

The function of eye movements in natural tasks

The variation in gaze during sports is no surprise if one looks at the literature from natural behaviour. The key insight from these experiments is that gaze is highly specific to a particular task and sub-task (Foulsham, 2015; Land & Hayhoe, 2001). For example, during Land's tea-making experiments, some fixations were associated with guiding the hand when reaching; others with manipulating items (e.g., putting the lid on the kettle); and others with monitoring a state of the environment (e.g., waiting for the kettle to fill). That participants can seamlessly switch between the appropriate types of gaze behaviour demonstrates a high level of learned control. Such control, and exquisite timing, must also be hallmarks of the trained athlete. The examples from natural behaviour teach us that it is only possible to fully interpret the function of gaze patterns, and measures like fixation duration, within a more detailed description of the task and the motor acts involved. Expertise and extended processing are normally associated with shorter fixations in laboratory tasks, where stimuli and processing difficulty can be controlled, and it is easier to draw conclusions about a single fixation. In sport, walking and tea making, longer gazes are often associated with the monitoring of dynamic information in the environment, as well as with over-learned, predic-



Figure 1: Point of gaze (circular cursor) at three moments during a golf shot. The function of fixation may be quite different when picking up a tee (left), lining up before a shot (middle) and tracking the ball after the shot (right).

tive behaviour which allows skilled actors to deploy gaze early. It is important that researchers are now probing the QE experimentally, in order to determine the functional consequences of a longer final look (Gonzalez et al., 2015; Vine, Lee, Walters-Symons, & Wilson, 2015). As with other natural behaviours, the timing of QE onset and offset, and therefore also of “un-quiet” periods, is likely to be the crucial factor. Ultimately, the discoveries from such experiments will be specific to particular sports and actions, and the QE must fit within a more detailed description of the task at hand.

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In my mind's (quiet) eye: a perceptual-cognitive approach to the Quiet Eye – comment on Vickers

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Introduction

The quiet eye (QE; Vickers, 1992, 1996) has become a widely researched phenomenon across a variety of sports and motor tasks (for reviews, see e.g., Vickers, 2007, 2009, 2016). It is currently considered a critical action-related variable, being a major factor of perceptual-cognitive expertise that differentiates experts from non-experts (e.g., Mann, Williams, Ward, & Janelle, 2007). It is therefore surprising that our insight into its functioning, into the underlying mechanisms of the QE, has remained scarce to date. While research on the QE has grown, covering cross-sectional research designs (e.g., expert novice paradigm with QE as dependent variable; e.g., Vickers, 1992) as well as longitudinal research designs (e.g., learning paradigm with QE

ABSTRACT

In her article on the origins and current issues in quiet eye (QE) research, reviewing an impressive body of research, Vickers (2016) concludes amongst others that it is important to understand the neural and other processes underlying the QE. Interestingly, the debate on the mechanisms of the QE has received growing interest only recently, with hypotheses from two main theoretical approaches (i.e., cognitive and ecological ones) evolving. What is missing as part of this discussion, however, are perceptual-cognitive approaches and their potential explanatory value with respect to the QE. Following a short summary of the current debate on the theoretical underpinnings of the QE and the main hypotheses that have been proposed so far, we introduce a perceptual-cognitive approach to the QE, and discuss recent findings that point to a perceptual-cognitive explanation of the QE.

Keywords:

effect anticipation – effect representation – mental representation – CAA-A

as independent variable; e.g., Vine & Wilson, 2010), focusing on behavioral, cognitive, and neural aspects, the discussion of the theoretical underpinnings has taken a back seat until recently (e.g., Gonzalez et al., 2015).

Current debate on how the QE works

Following Vickers (2009), Klostermann (2014) and Gonzales and colleagues (2015) have augmented the discussion on what exactly is reflected by the QE. So far, cognitive and ecological approaches (formerly known as motor and action approach: Meijer & Roth, 1991) have been introduced as theoretical accounts for the specific mechanisms of the QE.

The most prominent suggestion so far has evolved from the cognitive domain and draws on the schema theory (Schmidt, 1975). According to this hypothesis, the QE serves to program movement parameters in order to prepare subsequent movement execution (*programming hypothesis*; e.g., Williams, Singer, & Frehlich, 2002). In contrast to the cognitive approach, the ecological approach draws on the theory of direct perception (Gibson, 1979). According to the *affordance hypothesis* (e.g., Oudejans, van de Langenberg, & Hutter, 2002), the QE reflects the attuning of affordances prior to their realization, not requiring any cognitive engagement. Aiming at an integrative approach, Klostermann (2014) has recently introduced the *inhibition hypothesis*, with reference to Neumann (1992). According to this hypothesis, alternative parameter specifications are inhibited during the QE, allowing one parameter specification to come into effect. In sum, several hypotheses have been proposed as potential explanations for the QE, focusing on seemingly dichotomous aspects of the motor action. Surprisingly, while hypotheses from both the cognitive and the ecological domain exist, theories from the perceptual-cognitive domain and their potential explanatory value have not been discussed in the light of the QE so far. It might, however, prove valuable in the explanation of what the QE is and how it works.

A perceptual-cognitive approach to the QE

Following what is often referred to as a crisis in the motor domain (Abernethy & Sparrow, 1992; Schack & Ritter, 2013; Summers, 1998), with researchers from cognitive and from ecological approaches agreeing that they disagree, a third class of approaches has gained in importance not only in movement science and psychology, but as well in cognitive robotics (for an overview, see Schack & Ritter, 2013): Perceptual-cognitive approaches discuss motor control in the light of action-based cognition. Specifically, the goal-directedness of actions, the anticipation of perceptual effects, and effect representations are of particular importance for action control according to this class of approaches (for an overview, see Schack & Tenenbaum, 2004a, 2004b).

According to perceptual-cognitive approaches (e.g., theory of anticipative behavioral control: Hoffmann, 1993; simulation theory: Jeannerod, 2001) and the original idea of a bidirectional link between an action and its effects (i.e., ideomotor theory: James, 1890), actions are primarily guided by cognitively represented perceptual effects. Drawing on seminal work of Bernstein (1967) and his idea of a model of the desired future, motor actions can be considered as being stored in memory as well-integrated representational networks or taxonomies comprised of perceptual-cognitive units that guide action execution (cf. cognitive action architecture approach/CAA-A; for an overview, see Schack, 2004; Schack & Ritter, 2009). Moreover, these networks of *basic action concepts* (BACs) are suggested to change throughout the process of motor learning, resulting

in action-related structure formation through perceptual-cognitive scaffolding. From research conducted in the realm of the CAA-A (e.g., Schack & Mechsner, 2006), experts as compared to novices hold structured representations with groupings of BACs reflecting the functional phases of the motor action (cf. Göhner, 1992, 1999; Hossner, Schiebl, & Göhner, 2015). Recently, action representations have been shown to functionally adapt in the direction of an elaborate representation during motor learning, thereby relating more so to biomechanical task demands (Frank, Land, & Schack, 2013).

With respect to the QE and the ongoing theoretical discussion, we think that it is important to consider as well perceptual-cognitive approaches. Drawing on Bernstein's (1967) notion of the desired future and the cognitive action architecture approach (Schack, 2004), the QE may be considered as reflecting the time to create a model of the desired future across all levels of action organization and across all perceptual-cognitive components (nodes) of the action architecture. Accordingly, the desired effects are planned based on the action effect representation available, and thus serve to select, execute, and control an action. From this point of view, it might be the effect anticipation based on the effect representation available that is reflected by the QE. Recent research indicates that the representational networks of a motor action develop alongside of the QE during learning (Frank, Land, & Schack, 2016). Participants trained on a golf putting task over the course of three days. Putting performance, the mental representation structure of the putt, and the QE were measured prior to and post practice as well as after a retention interval. In contrast to a no practice control group, both representational networks as well as QE durations developed functionally alongside of performance improvements over the course of learning. Interestingly, the degree of elaborateness in representation structures related to the length of QE durations after learning, with better developed representation structures relating to longer QE durations. This finding extends research on differences in QE behavior by providing insight into QE changes over the course of practice, with the QE developing alongside of representational networks of motor action in long-term memory, relating to one another after learning. From these findings, the more elaborate information-processing during movement preparation, as expressed by longer QE durations, seems to be related to more elaborate underlying effect representations in long-term memory.

This finding supports the notion that the QE reflects cognitive processing (e.g., Gonzalez et al., 2015; Klostermann, Kredel, & Hossner, 2014; Williams et al., 2002). More importantly, however, this study provides initial evidence that the QE reflects critical action-related information processing based on the effect representation available. To that effect, the QE is likely to reflect a predictive, perceptual-cognitive mode of control initiating a cognitively demanding process of motor planning. In contrast to the programming hypothesis, however, it may be not the parameterization of motor commands in the first place, but the anticipation of perceptual effects that are crucial to successful motor planning and execution. Although the results indicate

that the more elaborate information processing during movement preparation is based on more elaborate mental representations in long-term memory, it must be noted that we did not directly test for underlying mechanisms in the study reported above. Future studies are needed to look more closely at the causality of this relationship, and the mechanisms of the QE.

Conclusion

This commentary covered a short summary of the current debate on the theoretical underpinnings of the QE and the main hypotheses that have been proposed so far, followed by the proposition of a perceptual-cognitive approach to the QE. In contrast to merely cognitive or merely ecological approaches, this approach takes into account cognitive as well as ecological aspects, by focusing on the cognitively represented perceptual effects of the action. Accordingly, the anticipation of these effects is suggested to be reflected during the QE. In order to advance the current discussion on the theoretical underpinnings of the QE, researchers (including ourselves) should put more effort into designing studies that tackle the underlying mechanisms of the QE and its components (e.g., duration, onset, offset) in more depths and in relation to the action, thereby disentangling various explanations and testing competing hypotheses against each other. Crossing boundaries between seemingly distinct theoretical approaches from movement science, cognitive psychology, and neuroscience will necessarily result in controversial but hopefully as well fruitful discussions toward more integrative accounts of the QE phenomenon.

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Visual expertise and the Quiet Eye in sports – comment on Vickers

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Introduction

Since 1992, Joan Vickers has been very successful in establishing a lively and productive research tradition that examines the Quiet Eye (QE) in sports (Vickers, 1992). The Quiet Eye is the critical period when the eyes remain relatively still (within 3° of visual angle) before an athlete executes a movement, for example, when elite basketball players fixate the front of the rim before finally shooting a free throw (Vickers, 2016). Numerous studies indicated that QE correlates with high performance in a number of tasks (see the meta-analysis by Mann, Williams, Ward, & Janelle, 2007). In our own meta-analysis of visual expertise (Gegenfurtner, Lehtinen, & Säljö, 2011), in which we tested the predictive validity of expertise theories, QE is missing as a conceptual framework – a mistake perhaps. Our study demon-

ABSTRACT

Research on the Quiet Eye (QE) has progressed brightly over the past years. Fixating on a task-relevant location before movement onset has been identified as a significant correlate of expert performance in many sport domains. In this commentary, we propose that visual expertise, including the QE, is socially mediated. Studying social mediation opens the opportunity to conceptualize expertise as a relational phenomenon that is accomplished through interactions with other people and with changing environmental affordances. Drawing on examples from basketball, soccer, and golf, we elaborate on this situational interpretation and propose that visual expertise in sports is contingent on the social dynamics of the game; is reflexively aligned to the social group; and changes as the social context changes. Future QE research can extend units of analysis to study how trajectories of expertise are socially mediated and unfold over time.

Keywords:

visual expertise – Quiet Eye – fixation – sports – expert performance – social mediation

strated meta-analytically that expertise changes the amount, the speed, and the visual span of information processing in domains such as sports, medicine, and transportation. Experts compared to novices had more fixations of longer duration on task-relevant areas; fewer fixations of shorter duration on task-redundant areas; shorter times to first fixate task-relevant areas; and a longer saccadic length (Gegenfurtner et al., 2011). QE complements and extends these expertise differences with a particular focus on the temporality of attentional resource allocation in visuo-motor coordination; it highlights how significant a few milliseconds of gaze can be before an action is executed.

Visual expertise research is, to some extent, reductionist. We isolate a particular process or variable as unit of analysis from the larger expert activity to make expert performance research-

able (Säljö, 2009; Szulewski, Gegenfurtner, Van Merriënboer, & Howes, 2016). For example, we use an eye tracker to define constantly occurring micro-movements of our eyes as a singular “fixation” and then study the frequency of fixations, their durations, or the time between fixation onset and the initiation of a movement (Panchuk, Vine, & Vickers, 2015). The underlying assumption is that visual expertise is an individual capacity that resides inside the mind or brain of an elite performer (Gruber, Jansen, Marienhagen, & Altenmueller, 2010; Seppänen & Gegenfurtner, 2012; Szulewski, Roth, & Howes, 2015). In recent years, there has been an increasing interest in studying the social and cultural sources that correspond with individual displays of expert performance (Gegenfurtner, Siewiorek, Lehtinen, & Säljö, 2013; Stoeger & Gruber, 2014). In such situated interpretations of expertise, professional vision is conceptualized as a relational phenomenon, accomplished through interactions with other people and with environmental affordances (Goodwin, 1994). In this commentary, we would like to offer a few reflections on QE, and on visual expertise more broadly, as it relates to the social context within which the practices of elite athletes are situated. Drawing on examples from basketball, soccer, and golf, we propose that visual expertise is contingent on the social dynamics of the game; is reflexively aligned to the social group; and changes as the social context changes.

Visual expertise is contingent on the social dynamics of the game

Basketball is a team sport. Each match is different. Within a match, the players on the court need to quickly and aptly react to a multitude of situations. Some of these situations require a QE. For example, Harle and Vickers (2001) indicated that QE is critical when shooting free throws as shooting accuracy significantly improved when participants were trained to fixate one spot on the hoop before shooting a free throw. The allegedly best QE in the US American National Basketball Association (NBA) of all time has Steve Nash, “who sunk 90.4 % of his free throws” (Vickers, 2016, p. 2). Perhaps unsurprisingly, Nash was voted Most Valuable Player in 2005 and 2006. The Most Valuable Player in 2000, Shaquille O’Neal, was famous for performing poorly in free throw situations; although he allegedly trained to fixate one spot on the hoop before shooting a free throw, his shooting accuracy was relatively low. His expertise was evident not in free throw situations, but in offense situations, in which he frequently scored field goals with a right-handed jump hook shot. The Most Valuable Player in the years 1987, 1989, and 1990, Earvin “Magic” Johnson, was famous for yet another kind of visual expertise: his no-look passes. Without looking at his fellow teammates, he passed the ball at incredible speed, a skill that can be attributed to superior parafoveal processing. Our point here is not to compare Nash, O’Neal, and Johnson, but that different levels of speed and interactional complexity during the game require different adaptations of visual expertise (Klostermann, Kredel, & Hossner, 2013; Szulewski, Fernando,

Baylis, & Howes, 2014). The practices of expertise are situationally contingent on the social dynamics as the player interacts with his or her teammates on the court.

Visual expertise is reflexively aligned to the social group

Practices of visual expertise are not only situationally contingent on the dynamics within a game. They also vary between games, competitions, and seasons. For example, one of the best soccer players of all time is Lionel Messi (Vickers, 2016) who was voted the world’s best player five times between 2009 and 2016. He is the most successful scorer in Spain’s Primera División, where he scored more than 300 goals for this team FC Barcelona. Scoring such a high number of goals as a striker suggests he has the ability to use visual cues of the defenders’ and goal keepers’ movement patterns. Extrapolating this information from the array of visual stimuli on the field helps anticipate opponents’ intentions and future events (Mann et al., 2007). When playing in the Spanish league, Messi scores consistently high even if the opponents, his teammates, the match tactics, the head coach, weather conditions, or the pitch condition change. When playing for the national team of Argentina, however, Messi scores fewer goals per match. Indeed, there are many examples of players who performed very well for one team and rather poorly for another team. One possible reason for those performance differences is the big-fish-little-pond effect (Marsh & Seaton, 2015). Other possible reasons relate to different social affordances when team contexts change. Excellence tends to cluster in groups; in soccer and other team sports, this includes supporting staff such as managers, physical therapists or managers (Stoeger & Gruber, 2014) which can promote the emergence and continual display of outstanding performance. As Stoeger and Gruber (2014) indicate, exceptionally high performing professionals typically have support staff who are exceptionally good themselves in their supporting roles. These networks of athletes and support teams form a rich social platform for professional excellence. The practices of visual expertise are thus reflexively aligned to the social group within which they are enacted.

Visual expertise changes as the social context changes

The observation that changes in the social group can create changes in the way elite athletes perform leads to our last reflection: expertise changes when the social context changes (Gegenfurtner, 2013; Lehtinen, Hakkarainen, & Palonen, 2014), not only in team sports, but also in individual sport disciplines such as golf. Tiger Woods is the most successful golf player of all time. Between 1998 and 2009, he was 11 years the number one in the official world golf ranking. Among others, his exceptional performance in putting can be attributed to his QE on the

green (Frank, Land, & Schack, 2016; Vickers, 1992). Over an exceptionally long time, Tiger Woods was able to outperform other golf players. In November 2009, his social context changed dramatically when he was involved in scandals and therapies. In the months and years after, his golf performance was considerably lower than in former years – until 2013, when he stabilized his performance and was again ranked as the world's best golfer. This case tends to indicate that expertise is not an isolated event inside the mind; rather, individual perceptions of how stable and psychologically safe one's social context is shape lifetime trajectories of expert practices (Gegenfurtner & Seppänen, 2013; Lahn, 2011; Laine & Gegenfurtner, 2013; Lehtinen et al., 2014).

Conclusion

QE research has been very productive and lively since 1992 (e.g., Vickers, 1992; 2016). In this commentary, we proposed that the practices of visual expertise, including keeping a QE, are intrinsically a social activity and mediated by the situational and contextual affordances within which expert performance unfolds. Extending cognitive units of analysis to examine how the trajectories of expertise are socially mediated can be a useful strategy for further lines of inquiry as QE research heads into a bright and prosperous future.

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Is a 'quiet eye' all it takes to be successful?

Comment on Vickers

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Introduction

First of all, we would like to compliment Joan Vickers with the Quiet Eye (QE) research she inspired so many researchers with. Her recent review paper on issues related to QE research (Vickers, 2016) provides an excellent platform for examining both the behavioral and neural aspects of oculomotor control. The cortical circuits controlling oculomotor function and upper limb movements are highly interconnected. Oculomotor control (in general) and QE (in particular) are believed to be mediated by a parieto-frontal network. However, little is known about the nature of interactions between key areas of this network as well as between this parieto-frontal network itself

ABSTRACT

Inspired by the pioneering work of Joan Vickers, Quiet Eye (QE) research has gained increased attention from researchers in disciplines ranging from Sports Science to Neuroscience. A recent target article by Vickers (2016) provides an overview of QE research relating to expert performance, oculomotor control, attention, anxiety, and child development. In this commentary, we provide a neuroscientific perspective on QE and optimal oculomotor control and discuss their possible underlying brain mechanisms. We focus primarily on the role of the parietal-frontal network and question its involvement in visuomotor transformations and processing of an efference copy. To address these issues, we discuss the potential benefits of adapting transcranial magnetic stimulation techniques to QE research. In addition, a brief perspective on QE research in patients with neurodegenerative disorders and aging is provided.

Keywords:

attention – goal-directed reaching – gaze – efference copy – visuo-motor transformation – parieto-frontal network

and other brain structures important for controlling the planning and execution of goal-directed movements such as the basal ganglia and cerebellum. Other aspects of QE literature that have been addressed in Vickers' paper aim to tackle the link between QE, memory and attention as well as the use of QE training as a means to improve oculomotor control in patient populations. Our commentary will focus primarily on questions related to brain mechanisms underlying QE and discuss future target groups that could benefit from QE training. Throughout this commentary, we will formulate some challenging research questions we do not know yet fully the answers for.

Potential brain mechanisms

One possible explanation for the benefits of long QE durations on successful motor performance is that it provides the necessary time for organizing the neural structures that are responsible for planning and controlling actions. Visually-guided movements require sensory information about the target to be extracted and transformed into an appropriate motor command. Thus the amount, or quality, of visual information about the target appears critical in this sensorimotor transformation process. A possible mechanism underlying QE effects on motor control is that a longer fixation duration provides more time to prepare the motor command, send it forward and process online feedback, but also allows to gain more detailed visual inputs about the target through the fovea. Another likely mechanism is that longer QE duration may provide the generation of a better-defined efference copy of the intended movement.

Can stable gaze (and longer QE duration) prior to movement initiation be taken as a prerequisite for optimal visuo-motor transformations? A large number of transcranial magnetic stimulation (TMS) studies in humans corroborate the view that a cortical circuit connecting the posterior parietal cortex (PPC) to the premotor cortex subserves sensorimotor transformations underlying reaching movements (Davare, Andres, Clerget, Thonard, & Olivier, 2007; Davare, Rothwell, & Lemon, 2010; Koch et al., 2010; Tunik, Frey, & Grafton, 2005; for a review, see Davare, Kraskov, Rothwell, & Lemon, 2011). This circuit connects the medial part of the intraparietal sulcus (mIPS) and parieto-occipital junction (POJ) to the dorsal premotor cortex (PMd). Using state-of-the-art dual-coil TMS paradigms, it has recently been shown how transfer of visuo-motor information is processed in parieto-frontal networks during grasping movements (Davare et al., 2010). It is also possible to probe POJ-M1 connections with dual-coils paradigms during reaching movements (Vesia, Bolton, Mochizuki, & Staines, 2013). Since optimal visuo-motor transformations are expected to optimize the definition of the motor plan before movement initiation, the use of dual-coils TMS paradigms would provide an elegant way to address this question.

Is QE associated with the formation of an efference copy? There is evidence to suggest that visuo-motor transformations occur in the parieto-frontal pathways through the generation of an efference copy (Loh, Kirsch, Rothwell, Lemon, & Devare, 2010; Medendorp, Goltz, Crawford, & Vilis, 2005). The efference copy is necessary for optimal transformation of the target coordinates from a gaze-centered into a hand-centered reference frame (Medendorp et al., 2005; for a review, see Vesia & Crawford, 2012). In the context of eye-hand coordination, for example, information about the efference copy of eye motor commands can be used for defining hand motor commands. In addition, the efference copy generated by networks projecting onto the frontal eye field (FEF) may be effective for optimizing fixation on the target. Evidence from functional magnetic resonance imaging (fMRI) studies describing expert vs. novice differences in brain activity during sport-related anticipation could provide

some hints about the brain network involved in this process (Wright, Bishop, Jackson, & Abernethy, 2011; Wright & Jackson, 2007). Interestingly, evidence from those studies suggests that early stage occlusion during anticipation results in increased activation across both posterior and anterior components of the action observation network rather than the cerebellum and the basal ganglia. Importantly, interactions between areas of the action observation network (see Rizzolatti & Sinigaglia, 2010, for a review) and the parieto-frontal network can be studied with TMS.

Future target groups

Beyond pinpointing specific mechanisms underlying the QE phenomenon at the neural level, future QE research should focus particularly on the investigation of special target groups.

Expert versus novices: QE training is expected to enhance performance of goal-directed movements by optimizing preparatory gaze. Modulation in brain activation from novice (untrained) to expert (trained) performance in young and older adults should be investigated. Besides training-induced changes in preparatory gaze, QE training is expected to optimize information processing and interregional communication between areas of the parieto-frontal network as well as between the parieto-frontal network itself and subcortical brain structures (e.g., the cerebellum, a candidate region for formation of efference copy). Yet, very little research has been conducted to explore the association between performance gains and practice-related changes in the reorganization of the aforementioned brain network. The question also remains open about the specific mechanisms that might be most affected by QE training. Documenting shifts in brain activation from unskilled to skilled performance before and after QE training by using fMRI and TMS would allow addressing these issues.

Aging and pathological functioning: Recent research suggests that generic oculomotor training might have a positive impact on postural stability in people with cerebellar ataxia (Bunn, Marsden, Giunti, & Day, 2015) as well as on gait in progressive supranuclear palsy (Zampieri & Di Fabio, 2009). In several studies, optokinetic stimulation and gaze stabilization were used as elementary components in vestibular rehabilitation to improve static balance (Bunn et al., 2015; Chen, Hsieh, Wei, & Kao, 2012; Morimoto et al., 2011). Crowdy, Kaur-Mann, Cooper, Mansfield, Offord, and Marple-Horvat. (2002) investigated the effect of rehearsal of eye movements on locomotor performance in cerebellar patients. They reported an improvement of stepping regularity and accuracy in the two cases and a decrease in stance and double support phase durations in one patient only. Improved oculomotor control was shown by a reduced occurrence of saccadic dysmetria, measured as a significant increase in the ratio of single to multi-saccadic eye movements. An earlier study of Crowdy Hollands, Ferguson, and Marple-Horvat (2000) showed that the amount of locomotor problems observed in cerebellar patients during visually guided stepping

is linked to the severity of their oculomotor abnormalities. Despite the heterogeneity in level of dysfunction between the participants, a significant improvement in the accuracy of steps as a result of eye movement rehearsal was found compared to repeated walking alone. All studies mentioned above investigated the effect of generic oculomotor training on balance and lower limb functionality. Given the importance of visually guided goal-directed aiming in aging and in pathological functioning such as Multiple Sclerosis and Parkinson, it is remarkable that, to the best of our knowledge, no research has been conducted on this topic.

Conclusion

While our commentary makes some assumptions about the brain network underlying QE, the actual brain structures responsible for processing sensory information during longer QE durations are yet to be uncovered. This issue could be addressed by using neuroimaging techniques such as fMRI, electroencephalography (EEG), and TMS. These three techniques are complementary because they allow not only to define these brain networks (fMRI and EEG) but also to determine the causal role of each brain area in sensory processing, movement planning and execution (TMS). To date, no studies using a combination of these techniques has been conducted to highlight the brain mechanisms underlying preparatory gaze behavior and QE in goal-directed movements. Furthermore, inference about the effect of age on the neural mechanisms underlying the benefits of QE on movement performance and training is therefore imperative.

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Tackling Quiet Eye issues on a functional level – comment on Vickers

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Over the last decades, positive effects of a gaze strategy called the Quiet Eye (QE) have been found for motor performance on an inter- and intra-individual level. As elaborated by Vickers (2016), this phenomenon highlights the relevance of the tight coupling between perception and action for superior motor behaviour. The QE's functionality has been shown for a large range of motor tasks like dart throwing and golf putting (for a recent overview, see Rienhoff, Tirp, Strauss, Baker, & Schorer, 2016); and, first and foremost, Joan Vickers has a large share in unravelling this phenomenon (Vickers, 2007). However, a number of recent studies revealed that the relation between the QE and performance is not as monotonic as suggested (for recent overviews, see Gonzales et al., 2015, Wilson, Casner, & Vickers, 2015). Thus, instead of isolating the QE in further motor tasks or of searching for QE correlates on a neural level – as both suggested by Vickers (2016) – we would find it more fruitful to

ABSTRACT

Joan Vickers (2016) pinpoints the Quiet Eye's (QE) relation to superior learning and performance in numerous motor tasks. On this basis, this commentary emphasises that future research should particularly focus on underlying mechanisms to increase our understanding of the QE phenomenon. To this end, we suggest to pursue a functional approach that tackles the QE on a behavioural level by advancing theoretical as well as methodological aspects. Consequently, (a) an *inhibition hypothesis* will be outlined that supposes the QE to "shield" the parametrisation of the optimal task solution against alternative movement variants; (b) an algorithmic approach to the study of gaze behaviour will be introduced that maximises data quality and minimises manual analysis effort; and (c) a peripheral perspective on the QE will be depicted suggesting QE functionalities beyond foveal information processing.

Keywords:

perception-action coupling – gaze behaviour – inhibition hypothesis – peripheral vision – eye tracking technology

elaborate theoretical frameworks on the behavioural level that allow to experimentally test specific predictions in order to extend our understanding of the mechanisms underlying the QE. This commentary will outline such a framework by suggesting an explanation on a functional level, presenting respective empirical and measuring methods and providing an outlook on future research questions by introducing a "peripheral perspective" on the QE.

An inhibition hypothesis

In QE literature, different mechanisms are offered for the explanation of the phenomenon's functionality (for a recent overview, Gonzalez et al., 2015). The explanatory power of these mechanisms, however, seems to be limited to specific

demands (e.g., online vs. offline control) and constraints (e.g., situations of increased anxiety) of the motor task (Klostermann, 2014; Klostermann, Kredel, & Hossner, 2013). As, from our point of view, this state of diversity is rather unsatisfactory, we have elaborated a functional mechanism that parsimoniously accounts for the broad variety of current research findings. Drawing on Neumann's (1990) functional approach to the study of attention, this mechanism features an inhibition function such that the QE supports the parametrisation of the optimal solution for a given perceptual-motor task by inhibiting alternative movement parametrisations. Based on this hypothesis, predictions were established that offer an explanatory potential for the current state of research. This is especially true for the classical finding of prolonged QE durations in experts as motor learning is rather accompanied by an economisation of behaviour which would imply a shortening of the QE period with growing expertise rather than its lengthening. In contrast, on the basis of the *inhibition hypothesis*, it is assumed that expertise is hallmarked by a densely explored task space, resulting in increased inhibition demands and, thus, in a prolongation of the QE interval.

On an empirical level, results in favour of the *inhibition hypothesis* could be presented as an experimentally evoked increase in task demands over movement preparation (Klostermann et al., 2013) and movement execution (Klostermann, Kredel, & Hossner, 2014) affected the efficiency of long QE durations (see also Williams, Singer, & Frehlich, 2002). However, further research is required that specifically addresses the suggested "shielding" of the optimal movement variant, for instance, by experimentally varying inhibition demands.

Regarding the theoretical level, it needs to be added that the assumed inhibition mechanism needs further specification. Since the functionality of the attentional selection-for-action mechanism proposed by Neumann (1990) is fundamentally rooted in the idea that, in a real world, humans can achieve only one action goal at a time, it seems to make a lot of sense to marry the proposed inhibition function with current theoretical approaches on the effect-relatedness of motor control processes, in particular, with the idea of internal forward models (e.g., Wolpert & Miall, 1996) which would perfectly match concepts focusing on prediction also in the domain of human vision (e.g., Enns & Lleras, 2008). However, details of this marriage have still to be sorted out in order to come up with clear-cut predictions that are open for empirical testing.

Advanced designs and technologies

For the rigorous study of functional mechanisms underlying the QE phenomenon, first, research designs needs to be shifted from the classical correlational to an experimental approach allowing for the independent manipulation of the QE duration as well as other variables derived from the respective explanatory framework. To this end, we have introduced an experimental paradigm which is based on the external pacing of a throwing

movement and the temporally aligned presentation of cues (i.e., the target disc) being able to experimentally manipulate the QE duration (e.g., Klostermann et al., 2013).

Second, to perform meaningful inference statistics, compared to classical QE studies which are based on a manual allocation of a gaze vector to an area of interest, a massive increase of trials per participant and condition and of participants per group is inevitably. Consequently, we have proposed a technological shift towards an automated vector-based gaze analysis, which uses light-weight and high-frequency mobile eye-tracker hardware embedded in a motion-capture system enabling us to synchronously capture gaze behaviour and kinematics of the participant (Kredel, Klostermann, & Hossner, 2015). To allow for a thorough automation of the eye-tracking data collection and data analysis, gaze needs to be represented mathematically (i.e., as a gaze vector), which requires to track the position and orientation of the eye tracker in real-time inside a laboratory frame-of-reference. Beyond, we implemented a custom software application fusing the kinematic and eye-tracking data (i.e., eye rotation angles) thereby providing additional functionality for the automated management of experimental setups. With this system, the highly subjective and tedious manual data analysis can be replaced by an automated, objective data-to-stimulus assignment process since the gaze vector can be automatically assigned to static or moving objects with known positions related to the laboratory frame-of-reference (e.g., a target that has to be hit). Additionally, due to the simultaneous recording of the participants' movement behaviour, this gaze analyses can be directly related to respective performance variables.

A peripheral perspective

Most notably, the advanced analysis procedure sketched before is not limited to a one-to-one assignment of a single stimulus to a foveal gaze point. In fact, it can be extended by mathematically specifying the biological characteristics of the visual periphery around the calculated gaze vector allowing for a many-to-many assignment of stimuli to foveal and peripheral regions. Obviously, this procedure offers a useful approach for the further disentanglement of potential QE mechanisms by extending the analysis beyond the collection of foveal data.

The necessity to extend the study of functional gaze strategies beyond the boundary of foveal vision is certainly true for situations in which crucial information can originate from a number of locations as it is the case, for instance, in combat or team sports. For example, in karate where the attacks can be realised with both arms and legs, the defender needs to monitor several cues at the same time. As, due to tight time constraints, it may be dysfunctional to fixate relevant cues in consecution, a central fixation in-between these locations and using peripheral vision might be more beneficial (Williams & Elliot, 1999). In a recent study, we were able to show that participants when monitoring four moving targets over a longer

period of time used exactly such a “pivot-point” gaze strategy (Vater, Kredel, & Hossner, 2016). Since, due to the motion sensitivity in the peripheral visual field, participants were able to detect motion changes even at large eccentricities, these results suggest a general functionality of a visual stabilisation. Thus, the QE might not only be beneficial in situations that require precise foveal information processing. Instead, a long final fixation might also be functional in situations that require an “anchoring strategy” – on the basis of the inhibition hypothesis, for shielding the optimal movement variant (e.g., the most precise pass to the best positioned teammate) against inferior alternatives. Hence, it seems worth considering to extend the purview of QE research beyond the boundary of foveal information processing as it has been exclusively done so far (cf. Vickers, 2016, Table 1: QE location).

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Quiet Eye: The efficiency paradox – comment on Vickers

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Introduction

The publication of Joan Vickers' seminal Quiet Eye (QE) papers (Vickers, 1996a, 1996b, 1996c) offered the promise of a widely generalizable, distinguishing psychomotor metric of expertise. A voluminous body of empirical and applied work has emerged over time, consistently supporting the QE as a reliable covert index of performance excellence (Vickers, 2016). In short, the QE has stood the test of time. Qualitative (Causer, Janelle, Vickers, & Williams, 2012; Wilson, Causer, & Vickers, 2015) and quantitative reviews (Mann, Williams, Ward, & Janelle, 2007) have reiterated the QE as a robust discriminator of expertise and precursor of successful performance. Despite extensive empirical support and widespread perceptual training programs, the underpin-

ABSTRACT

The extant literature abounds with evidence in support of the foundational tenets advanced in Vickers' pioneering papers describing the Quiet Eye (QE). Central among her seminal findings is the rather counterintuitive finding that experts and expert performance are characterized by an extended QE period. A longer QE has been oft-replicated across both self-paced and externally-paced tasks, but seems at least superficially inconsistent with broadly accepted notions that increasing levels of expertise are afforded by greater automaticity and efficiency. This "efficiency paradox" is considered in the context of theorized processes that occur during the QE. Answers to questions concerning the mechanisms underlying the extended QE hold great promise for advancing our understanding of the QE specifically, as well as expertise based differences in visual attention more broadly.

Keywords:

efficiency paradox – cortical efficiency – motor preparation – attention – emotion

nings of the QE period remain poorly understood, and in some ways, counterintuitive.

The efficiency paradox

Perhaps the most robust phenomenon in all performance-related visual search research is the nearly ubiquitous finding that experts and expert performance are consistently characterized by an earlier onset and longer QE. From both scientific and intuitive perspectives, endorsement of a "longer is better" recommendation seems rather crude, and the principal mechanisms associated with this recommendation remain speculative. Simply stated, it seems illogical to expect that a longer is better adage is advantageous across performance situations

where efficiency is paramount. Research examining the many underlying attributes of expertise has generally concluded that experts are more efficient, effective, and accurate in recognizing task-specific patterns, more proficient at making decisions, maintain superior procedural and declarative information, have a profound reservoir of retrievable contextual cues, and possess an unparalleled ability to foreshadow events and outcomes (Holyoak, 1991, Stakes & Allard, 1993, Mann et al., 2007). If efficiency, strictly speaking, enables experts to perform greater, more detailed work in relation to the total energy expended, how then does the QE represent and/or enable efficiency? Is it simply because the QE acts to reduce the number of fixations and fixation locations during the moments leading up to performance execution? Furthermore, why is a prolonged duration of the QE period necessary for the expert advantage to emerge? We briefly explore this paradox in the context of the literature examining the relationships between QE and cortical efficiency, motor preparation, and emotion regulation.

Cortical efficiency

From a purely visuomotor perspective, the QE may serve to maximize efficiency, as reflected in cortical patterns indicative of elite performance (Janelle et al. 2000; Janelle & Hatfield, 2008). Research has consistently reported cortical quieting in the left hemisphere as compared to the right (at temporal, mid-frontal, occipital, and parietal regions) when performing visuospatial and motor coordination tasks (e.g., Crews and Landers 1993; Haufler, Spalding, Santa Maria, & Hatfield, 2000; Janelle & Hatfield, 2008). Elite athletes generally make fewer fixations of longer duration, suggesting a level of information processing efficiency that permits more time to be spent on task-relevant cues and less time in search of these cues (Mann et al., 2007). As such, time to movement onset – otherwise said, decision-action time – should be reduced in the expert. A prolonged QE may permit a similar advantage. Task-salient cues are prioritized during visual search, particularly during the final fixation. During this time, cortical resources are likely reallocated away from analytical processing and irrelevant sensory cues and toward the visuospatially dominant perceptuomotor processes that are critical for effective motor programming and execution. Why the efficiency paradox? Neural efficiency refers to the attainment of superior performance along with simultaneous spatial localization or a reduction in brain activity (Costanzo et al., in press). Studies of motor planning in expert golfers have demonstrated that brain activation during the pre-shot routine is radically different from that of less skilled performers (Mann, Coombes, Mousseau, & Janelle, 2011, Milton, Solodkin, Hlustik, & Small, 2007). The expert brain arguably uses less energy to cope with the task demands by converging activation on smaller brain areas and/or less global activation. Irrelevant brain processes are inhibited while essential brain regions exhibit elevated activity as needed, compared to that observed in less-expert performers. Incidentally, a link between cortical

efficiency and the QE duration has been demonstrated (Mann et al., 2011). Although the experts were more proficient, it is unlikely we can argue they were more efficient based on the QE data reported.

Motor preparation

Conceptually, the QE period is thought to represent the time needed to organize the visual parameters and neural networks responsible for the orienting and control of visual attention (Vickers, 1996a, 1996b). Vickers (1996a, 1996b) has relied heavily on basic cognitive neuropsychological evidence to advance postulates on the cerebral architecture that underlies the QE period. Leveraging the early work of Posner and Raichle (1991), who proposed a three-component network for visual attention, Vickers suggested that the QE period has implications for motor preparation. The orienting network affords shifts in attention, while the executive network works to identify the most salient cues for goal directed behavior, and the vigilance network functions to support focused attention by enabling the orienting system and suppressing the processing of irrelevant stimuli. A secondary effect, therefore, of the vigilance network may be the reorganization of the neural networks responsible for maintaining visuospatial processing and the activation of the appropriate motor program. Preparatory activity in the milieu of sensorimotor alterations involves an integrated neural conduit linking perception to action (Toni & Passingham 2003). The QE appears to functionally represent the time needed to organize the neural networks and visual parameters responsible for the orienting and control of visual attention (Mann et al., 2007; Vickers 1996a, 1996b).

Given this contention, we are again faced with the paradoxical notion that the QE period, a discernible measure of expertise, is consistent with the increased efficiency associated with expert performance. During the preparation and movement phases of skill execution, the visual attention centers (i.e., occipital and parietal cortex) propagate the necessary directives to the motor regions of the cortex (i.e., motor cortex, premotor cortex, supplementary motor area, basal ganglia, and cerebellum). Consequently, the cortical areas responsible for execution of a motor task may in turn benefit from the reallocation of resources during the QE period, allowing for the development of a more refined motor program that results in better performance and greater expertise levels. The question remains, whether the QE period is the cause or the effect of this reorganization, and why such parameterization should not occur more quickly for experts.

Emotion regulation

A large body of knowledge has emerged lending support to the debilitating effects of anxiety on performance, processing efficiency, and cue utilization. As an extension of this work, several researchers have suggested that the QE period may reflect the regulation of emotional states (Janelle et al., 2000; Mann et

al., 2011; Vickers, Williams, Rodrigues, Hillis, & Coyne, 1999) and the needed reinvestment of greater information processing to sustain performance. That is, the extended QE duration that is characteristic of experts may in fact represent the time needed to accommodate the detrimental effects of anxiety/arousal on the recruitment of task specific resources. Consistent across a variety of reports, the QE duration is influenced by modulations in cognitive stress, physiological arousal, or pressure. Importantly, QE duration has consistently been reported as longer for elite compared to subelite performers across conditions (Causser, Holmes, Smith, & Williams, 2011; Mann et al., 2007; Wilson et al., 2015). The notable differences in QE under adverse conditions and between skill levels supports an emotion regulation function, or a function that is, at minimum, susceptible to emotional reactivity. Apparently, efficiency in emotion regulation, which may indeed occur more quickly, does not speed the QE, but rather permits preservation of the processes that occur during an extended QE period.

Implications

Considering the collective evidence summarized here, a trend begins to emerge suggesting the QE may be representative of a covert pruning process that requires additional time to align the perceptual cognitive systems with the motor systems to execute a skill at its highest level. Why experts take more time to navigate the processes that are theorized to underlie the QE remains unknown. The “efficiency paradox”, as we have called it, is perplexing. Moving beyond a superficial understanding of what the QE is, and what happens during the QE will require creative research designs, innovative approaches, and mechanistic manipulations. Exploration of remaining questions spurred by Vickers’ seminal work will not only allow a more complete understanding of the QE, but will aid in advancing the knowledge base and training recommendations to facilitate the acquisition and refinement of expert performance across multiple performance domains.

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What information is being acquired during the period of Quiet Eye? Comment on Vickers

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ABSTRACT

Sports and athletes' highest performance offer a fascinating scenario to investigate perceptual-motor expertise. The remarkable work of Joan Vickers has captured this opportunity and built a valuable experimental paradigm. Our commentary emphasizes what information is being acquired during the period of Quiet Eye (QE), capable to produce successful performance. First, an extended notion of visual system that includes posture is presented. It is suggested that QE would represent a collective postural effort (resulting from movements of eyes, head, trunk, and whole body) to acquire the relevant information available in the optic flow. Second, the contribution of neural structures and functioning for vision and attention is discussed. Models of neural networks of attention and two visual systems are described with respect to QE and some questions about action parameters and motor programs are raised.

Keywords:

Quiet Eye – information acquisition – posture – attention – neural networks

Introduction

Sports and athletes' highest performance offer a fascinating scenario to investigate perceptual-motor expertise. The remarkable work of Joan Vickers has captured this opportunity and built a valuable experimental paradigm. Since its original proposal 20 years ago (Vickers, 1996), research on the phenomenon of Quiet Eye (QE) has evolved consistently, offering a cognitive approach to the success of motor skills based primarily on eye movements data. Vickers (2016) showed that QE has become a comprehensive topic of research, covering the following aspects: differences between expert and non-expert (near-expert, intermediate or novice) athletes, targeting and interceptive actions, training for QE enhancement, child devel-

opment and pressure or anxiety situations. Additionally, a more precise identification of neural networks related to QE is offering a complementary interpretation and convincing generalization regarding this topic.

QE occurs when gaze is relatively stationary on a location or moving object (according to a maximum 3° of visual angle and minimum 100 ms criterion) prior to movement initiation. QE is expected to facilitate information processing; its duration reflects the time needed to program and fine-tune a response; long durations of QE extend the period of critical preparation, which involves response selection and the fine tuning of movement parameters for motor programming (Gonzalez, Causer, Miall, Grey, Humphreys, & Williams, 2015). During this period, it is argued that "task-specific spatial information" (Vickers, 2016,

p. 7) is acquired to accomplish the definition of motor program parameters, with the goal-directed, dorsal attention network (DAN) being responsible for focusing and sustaining attention to relevant cues at particular locations, and the stimulus-driven, ventral attention network (VAN) encoding memories and controlling movement-related emotions (Corbetta, Patel, & Shulman, 2008). As a result of practice and expertise, DAN is thought to block or suppress distraction or anxiety-generated stimuli that may arrive from the VAN system (Gonzalez et al., 2015; Vickers, 2016).

We have organized our comments to emphasize what information is being acquired during the period of QE, capable to produce successful performance. Furthermore, an extended notion of the visual system is discussed, including posture as well as the contribution of neural models of vision and attention.

Posture supporting QE

We would like to discuss how gaze behavior may be associated with balance control as well as theoretical aspects involved in this relation. Other perspectives, as alternative to the information processing approach proposed by Vickers (1996, 2016), could add new elements to QE analysis. Not just the visual search pattern itself, but how experts can make use of the obtained information is crucial to understanding expertise and talent development (Savelsbergh, Haans, Kooijman, & van Kampen, 2010). A perception-action perspective suggests that movement control is based on a continuous coupling to available perceptual information, which is presumed to evolve over time (Savelsbergh & van der Kamp, 2000; Savelsbergh, Onrust, Rouwenhorst, & van der Kamp, 2006). For instance, the Gibsonian notion of visual system (“eyes-in-the-head-on-the-body-resting-on-the-ground”; Gibson, 1979, p. 205) favors the simultaneous consideration of gaze and postural data during motor actions.

Continuous and predictable saccadic and smooth pursuit eye movements improve postural stabilization during quiet stance (Aguar et al., 2015; Rodrigues et al., 2013; Rodrigues et al., 2015); in more dynamical contexts, increased postural stability due to motor learning has been reported in a variety of motor skills, such as rifle shooting (Era, Kontinen, Mehto, Saarela, & Lyytinen, 1996) and manual rhythmic movements (Amado, Palmer, Hamill, & van Emmerik, 2016). Interestingly, expertise of ball cascade jugglers seems associated with parsimonious oculomotor and attention pattern (“gaze-through” strategy) with fixations at the scene’s central location, weaker frequency locking between point-of-gaze and ball movements, reduced dependency to visually tracking ball motion, and improved anterior-posterior body sway stabilization (Dessing, Rey, & Beek, 2012; Huys & Beek, 2002; Huys, Daffertshofer, & Beek, 2004; Rodrigues et al., 2016), which is in line with experts’ higher capability of decoupling postural control and arm movements (Amado et al., 2016).

Considering that postural adjustments seem to support opti-

mal gaze behavior during complex actions, QE could be interpreted as a period of extraction of relevant visual information (e.g., time-to-contact variables; Lee, 1998, 2009) from optic flow. Although optic flow results from translational components of head movements in space and eye movements add rotational components to the flow on the retina (Cutting, 1996; Kim, Growney & Turvey, 1996; Kim, Turvey & Growney, 1996), a process of minimization of rotational consequences to the flow, called gaze stabilization (Daniel & Lee, 1990), seems advantageous to optimizing translational information acquisition with respect to the perceiver. As human visual input depends on the dynamics of all body parts, QE is constrained by posture. On the other hand, QE would represent this collective postural effort (resulting from movements of eyes, head, trunk, and whole body) to acquire the relevant information available in the optic flow, needed to successful performance.

Brain, vision, attention, and QE

To analyze the role of brain functioning in perception and action, we would like to briefly discuss models regarding processes of vision and attention. As shown above, Vickers (2016) emphasized the neural bases of attention, referring to functions of DAN and VAN (Corbetta et al., 2008). Also based upon neurological evidence, Milner and Goodale (1995, 2008) proposed a model of two visual systems, advancing from previous work (Livingstone & Hubel, 1988; Schneider, 1969; Trevarthen, 1968; Ungerleider & Mishkin, 1982). This model posits a separate ventral visual system for the purposes of object perception and representation in space and a second dorsal system, which uses this visual information in formulating an effective response. Visual inputs of each system are transformed for different purposes – one for representing visual information and another for using vision to guide action (Milner & Goodale, 2008). Despite the apparent independence of the two streams, coordinated action is dependent upon a high degree of cooperation between the two pathways, with enhanced attentional activity probably around movement initiation (Milner & Goodale, 1995); the transfer of high-level visual information between the two streams probably occurs in an early stage of this process. A first prerequisite of an action is selecting a goal object to be addressed, when the object is “flagged” due to enhanced attention, during processing by the ventral stream; a second prerequisite is to convey whatever “top-down” knowledge about the object is needed to supplement the “bottom-up” sensory information used by the dorsal stream (Milner & Goodale, 1995).

According to this general view, QE period would be under control of the ventral vision-for-perception system, mentally representing environmental information, and the motor action would be regulated by the dorsal vision-for-action system, within the three-dimensional space. For example, in a table tennis forehand stroke task, participants visually tracked the ball (QE) and stabilized eye and head around the time of ball-bat

contact; Milner and Goodale's model accommodate evidence from both early information acquisition to predict a ball's future trajectory and action planning, and late movement adjustments based on image expansion information (Rodrigues, Vickers, & Williams, 2002).

Models of both Milner and Goodale (2008) and Corbetta et al. (2008) characterize visual and attentional processing in the brain, which results in perceptuo-motor behaviors, such as QE. Although we acknowledge the importance of combining neuroimaging (event related potentials, transcranial magnetic stimulation, functional magnetic resonance imaging) and other technologies to better explain the links between gaze and performance in future studies (Corbetta et al., 2008), data from investigations on neural networks and perceptuo-motor behavior represent distinct levels of analysis. Yet, knowledge on neural structure with respect to QE is important and welcome; it does not necessarily imply improvement of QE explanatory power. For instance, the referred models do not describe the information content obtained during QE which generates successful performance.

The use of a more detailed description of neural structures underlying the QE by Vickers (2016), emphasizing the role of attention during the process of information acquisition to action control, has left some open questions. How are these attention networks connected to the process of providing parameters to a motor program? How does the better understanding on these neural structures affect the rationale of setting parameters for a motor program during QE, originally presented by Vickers (1996)? The "GPS"-like (Vickers, 2016, p. 8), optimal spatial representation, supposedly acquired during QE, should feed the motor program to be subsequently triggered; however, the notion of motor program was replaced by the term "brain" in the present version of QE perspective. Which are the theoretical consequences of this change?

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Quiet Eye: The next generation – comment on Vickers

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ABSTRACT

In this commentary on Joan Vicker's target article (2016), we first recognize the work she has done in the last 35 years. We then provide examples of differentiations of the Quiet Eye (QE) that might be necessary to fully understand the multifacetedness of the phenomenon. Here we propose, as in our current review (Rienhoff, Tirp, Strauss, Baker, & Schorer, 2016), for the QE a differentiation by the mechanisms behind it. We suggest another categorization in the research on training the QE. Additionally, we provide further areas of research that are interesting for the future, namely the QE across life-span and the (in)dependence of the perceptual-motor processes.

Keywords:

perception – expertise – elite sport – motor behavior – learning – training

A recognizing introduction

In her target article, Joan Vickers (2016) impressively summarizes 35 years of research starting with a practical perspective. Her discovery of the Quiet Eye (QE) as a perceptual motor phenomenon is an impressive accomplishment as is her pioneering work to bring the QE to the rising attention it has received in the last decades. She has published an impressive number of articles, brought this area of perceptual expertise to an interdisciplinary community and into the real world of applied coaching. Her fundamental research inspired many researchers around the world to investigate perceptual motor expertise and the specific phenomenon itself. For example, researchers have recently begun to look further at the mechanisms of the QE phenomenon (Rienhoff et al., 2016; S. Vine, Moore, & Wilson, 2014). In this commentary, we provide examples of further de-

lineations of the QE that might extend our understanding of the multifacetedness of this phenomenon and provide intriguing areas of future research.

Differentiating eye-movements for QE categories

To gain a deeper understanding of the way the QE works we might need to categorize and differentiate research on QE (Rienhoff et al., 2016). Vickers (2016) presents one by the tasks at hand. Recently, an ecological approach has been introduced by Rienhoff and colleagues (2016) to differentiate research on QE. Another fruitful categorization might be to use a sensory-physiological one. In her target article, Vickers presents studies in which either fixations (e.g., Vickers, 1996) or smooth pursuit tracking (e.g., Vickers & Adolphe, 1997) are the dependent vari-

ables, which are both summarized as QE. But necessarily one needs to differentiate between the functions of fixations and smooth pursuit eye tracking in visual perception (Holmqvist et al., 2011). The main difference is that a fixation is a position measurement and smooth pursuit tracking a movement measurement of a participant's gaze (Holmqvist et al., 2011). Concerning the QE research, duration (on-/ offset) and position measures are the main measurements. Investigating an eye-movement like smooth pursuit tracking enables to additionally measure directions, movement durations, velocities, accelerations and amplitudes (Holmqvist et al., 2011). These differences of two eye-behaviors might reflect the mechanisms behind the QE. For example, smooth pursuit tracking might be used to find an anchor for peripheral vision, while a fixation in an aiming task might be used to stabilize the movement system etc. This differentiation may be fruitful and we have begun a series of studies exploring these possibilities.

Future research might need to look at a combination of all of the possible categorization by perceptual processes or others to gain further insight. While the dependent variable might remain the QE as defined by Vickers (Vickers, 2007), single cells investigations of varying combinations might be necessary to explain mechanisms like the standing still hypothesis (Moore, Vine, Cooke, Ring, & Wilson, 2012), which is related to postural stability and neuromuscular quiescence, the pre-programming hypothesis (Moore et al., 2012; Vickers, 2007; S. J. Vine & Wilson, 2011), which associates the QE duration with a period of cognitive preprogramming of the movement, or the inhibition hypothesis (Klostermann, 2014) with a focus of explaining longer QE durations by an inhibition of alternative movement possibilities.

Differentiating the needs of athletes in training

As Vickers noted, a large number of studies have focused on the trainability of the QE (for an overview, S. Vine et al., 2014). Vickers (2016) classified a seven step QE training system on the basis of using QE prototypes of elite athletes. This approach is in line with research concerning motor performance, which assumes that there exists one 'optimal' technique for each sport (Irwin, Hanton, & Kerwin, 2005; Jones, Bezodis, & Thompson, 2009; Sherman, Sparrow, Jolley, & Eldering, 2001). However, Cavanagh (1987) argued that performers in particular elite sports use a diversity of techniques with considerable deviation to achieve the same outcomes. Due to that assumption, future research needs to investigate whether performer-dependent QE training differences exist. It might well be, that QE training for novices has to be different to the type of training advanced athletes need to do.

Additionally, as will be argued below, some research (Tirp, Steingröver, Wattie, Baker, & Schorer, 2015) has shown that perceptual and motor learning do not precede in parallel. In the context of QE training, it might be necessary to have a closer look at its impact on the motor result. Moreover, to gain deeper

insight into the influence of QE training, one needs to consider the intervention duration necessary to obtain a positive effect in both QE duration and motor outcomes. Due to the fact that different interventions and instructions have been used in previous studies, future research should try to classify the training instructions to ensure a better comparability between different QE training studies.

Perceptual-motor characteristics

The QE is a phenomenon that looks by definition at perceptual-motor performances. An implicitly made assumption is that perceptual-motor learning precedes in parallel with the QE. Several studies have shown the trainability of the QE (for an overview, S. Vine et al., 2014); however, fewer studies have focused on the trainability of the QE and the motor result in association. Two studies which focused on the synchrony of perceptual-motor learning in real and virtual realities were done by Tirp and Schorer (in preparation) as well as by Tirp et al. (2015). Results indicated an asynchronous learning of perceptual and motor performance. Additionally, this does not imply the role of the cognitive system, which should not be under-estimated. For example, Castaneda and Gray (2007) postulated that a focus on skill executions positively affects motor learning processes. In the context of perceptual-motor learning, the focus of attention used by the performer might differ in either perceptual (e.g., QE) or motor learning (e.g., basketball free throw) parameters. Future research needs to integrate the cognitive with the perceptual and motor system in order to expand our knowledge in these key areas.

Development and maintenance of QE in the life-span

As Vickers (2016) proposed, the development of QE is an engaging area of research. Surprisingly, little has been done in the maintenance of QE as athletes' age. In a series of studies, Rienhoff et al. (2013) and Fischer et al., (2015) demonstrated that the role of QE in two different expertise groups and three different age groups might vary. In contrast to younger experts, showing the expected pattern of results, master athletes lose the QE and have shorter durations compared to novices in the same age group while still showing superior results. This is not only in contrast to younger age groups in QE (Rienhoff et al., 2016; Vickers, 2016), but also in contrast to previous findings on perceptual expertise in master athletes (Horton, Baker, & Schorer, 2008; Schorer & Baker, 2009). Together, these studies provide an interesting first step towards our understanding of the development of the QE phenomena across the lifespan, which might have implications not only for elite sports but also for everyday activities.

Conclusions

The target article by Vickers (2016) nicely shows the amazing progress that has been made in this field of research. These first steps were important to describe the effect but future steps need to be more precise to cover the multifacetedness of the phenomena. This might only be possible by differentiating QE expertise research by the potential mechanisms behind it. Our current review provides some avenues to explore (Rienhoff et al., 2016), but there are certainly other perspectives that might be even more useful for gaining further insights into the QE. As another possible perspective, we propose the variation by categorizing the underlying eye-movement processes. The same line of argumentation holds for the current training research. A clear differentiation between levels of expertise of the learner might be needed to develop skill-adapted training programs. From our point of view, these differentiations are an important mission for the next generation.

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How eye movements improve vision and action – comment on Vickers

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ABSTRACT

The review by Joan N. Vickers (2016) describes evidence for a link between eye movement behavior and performance in a wide range of motor tasks. Central to the review is the observation that elite athletes hold gaze steady within a fixed range of the target earlier and for longer durations as compared to novices, an ability referred to as 'quiet eye' (QE). However, the functional significance of QE for performance in targeting and interception tasks has not yet been established. We summarize findings from laboratory studies providing direct evidence for perceptual benefits of smooth pursuit, fixational and predictive eye movements and outline potential mechanisms underlying these benefits. Recent improvements in mobile eye tracking might lead to validation of these findings in sport settings and to a more refined definition of QE.

Keywords:

Quiet Eye – smooth pursuit eye movements – predictive eye movements – saccades – microsaccades – visual motion – sports vision

Eye movements enhance vision

As vision scientists we appreciate Joan Vickers' (2016) target article drawing attention to the importance of eye movements for control of actions in sports. We share with the author an interest in adding to the understanding of how vision guides and modulates motor behavior, and how eye movements, in turn, contribute to the effectiveness of the visual system. Humans use different types of eye movements to bring and hold objects of interest close to the fovea, the area of highest visual acuity in the eye. Smooth pursuit eye movements help us track moving visual objects. Quick displacements of gaze called 'sac-

ades' allow us to scan a visual scene. These movements are interspersed with periods of relative stability known as 'fixations' during which visual information can be acquired.

Vickers refers to any relative stability of the eye focused within three degrees of a critical location as 'Quiet Eye' (QE), whether this is during fixation on a stationary object or pursuit of a moving object. Vickers (2016) reports that elite athletes fixate or track locations of interest earlier and for longer durations as compared to novices or near-elite athletes. The underlying claim is that because experts have better QE performance this ability must have beneficial effects on performance in sports and other motor activities. It is Vicker's merit to have intro-

duced QE to the Sport Sciences community decades ago, when mobile eye tracking was in its infancy. Research on QE has had a significant impact on athlete development and training, and has advanced tools and technologies for improving vision and movement in sports.

Yet, it is unclear what mechanisms underlie beneficial effects of eye movements. Does QE boost performance by enhancing visual processing of target information? Or does it serve to ignore distracting context information? Or is QE simply a byproduct of improved prediction?

The benefit of smooth pursuit

Many studies have addressed the question whether and how pursuit eye movements enhance or impair vision. We systematically manipulated eye movements to assess whether and how accurate pursuit (a 'dynamic QE') improves the ability to predict motion trajectories (Spering, Schütz, Braun, & Gegenfurtner, 2011). Observers viewed a small object (the 'ball') moving across a computer display while their eye movements were recorded at high resolution. When the ball disappeared from view, observers had to predict its trajectory and estimate whether it would have hit or missed a line segment (the 'goal') if it had continued to move. Observers performed better when they were instructed to track the ball with their eyes than when they were asked to fixate the goal, and more accurate pursuit (higher velocity gain and smaller position error) resulted in better perceptual performance. Because we kept retinal motion information constant during pursuit and fixation, we could rule out visual processing differences as a source of pursuit benefits. Instead, our results indicate that such benefits are due to the act of moving the eyes vs. fixating (see also Brenner & Smeets, 2011; Uchida, Kudoh, Muramaki, Honda, & Kitazawa, 2011). When we move, our brain generates a corollary discharge, a neural copy of the movement command and sends it back to the sensory system (Crapse & Sommer, 2008). This efference copy provides an internal report of our own movements and has important motor and sensory functions: it enables monitoring of on-going movements and informs our ability to predict future sensory events (Chen-Harris, Joiner, Ethire, Zee, & Shadmur, 2008; Wolpert & Miall, 1996). Accordingly, pursuit and saccadic eye movements do not produce beneficial effects in patients with known deficiencies of efference copy function (Spering, Dias, Sanchez, Schütz, & Javitt, 2013; Thakkar, Schall, Heckers, & Park, 2015). We propose that use of efference copy information is one possible mechanism through which smooth pursuit (dynamic QE) can boost vision; another possible mechanism might be the narrowing of direction bandwidth during pursuit (Debono, Schütz, Spering & Gegenfurtner, 2010).

The role of predictive eye movements

The target article does not consider other aspects of eye movements with demonstrated beneficial effects on sports performance, such as predictive eye movements (Diaz, Cooper, Rothkopf, & Hayhoe, 2013; Hayhoe, Mc Kinney, Chajka, & Pelz, 2012; Land & McLeod, 2000). Pursuit and saccades reveal prediction of future events and reflect our ability to use cognitive expectations to guide motor behavior (Kowler, 2011). When a moving stimulus is temporarily occluded, observers' pursuit slows down but recovers in anticipation of target reappearance (Bennett & Barnes, 2004). In sports such as table tennis or cricket, athletes initially track the ball but then make a saccade to the anticipated bounce location 100-200 ms ahead of its impact (Land & Furneaux, 1997; Land & McLeod, 2000). Professional players initiate predictive saccades earlier, more accurately and more reliably than novice players. Studies in virtual-reality settings have identified ball and flight parameters that determine the kinematics of predictive eye movements by systematically manipulating properties of the pre- and post-bounce trajectory (Diaz et al., 2013). Such predictive eye movement strategies presumably allow players to extract information about the location and time of the bounce in order to estimate the post-bounce trajectory and to plan their next move, thus contributing to sports performance. Whereas the neurological framework presented in the target article for how the brain controls vision and movement is somewhat sparse, much is known about the neurological underpinnings of eye movement control in general (Krauzlis, 2005) and of predictive eye movements in particular (de Hemptinne, Lefèvre, & Missal, 2008; Kim, Badler, & Heinen, 2005). We argue that prediction might be another possible mechanism underlying QE performance, enhancing the ability to keep the eye on the target.

The eye is not quiet during 'QE'

The term 'QE' implies a stable gaze, but the eye is never motionless. Even when fixating on a stationary object the eye makes miniature eye movements such as 'microsaccades'. Due to methodological limitations (see next section), these miniature eye movements have not been investigated in actual sport tasks. However, many laboratory studies have shown that microsaccades improve visual perception: they control fixation, reduce perceptual fading and enhance spatial acuity (Martinez-Conde, Otero-Millan, & Macknik, 2013; Rolfs, 2009; Rucci, Iovin, Poletti, & Santini, 2007). Even though we do not yet know much about the role of microsaccades during active performance, we can assume that microsaccades are critical in maintaining a vivid percept of our visual environment, including when playing sports or performing other motor tasks such as driving (Benedetto, Pedrotti & Bridgeman, 2011). Because microsaccades can be considered as saccades on a smaller spatial scale we can assume that they allow observers to optimally sample visual information from critical target locations in the

environment, akin to regular saccades (Martinez-Conde et al., 2013). Following this logic, the beneficial effect of QE may be due to the actual instability of the eye during fixation, rather than fixational stability.

Methodological limitations and future directions

Most studies on QE employed mobile eye-tracking technology. These eye trackers are highly suitable for in situ testing, but the price to pay for mobility is low temporal and spatial resolution. Until recently, the highest tracking rate that could be achieved was 60 Hz (resulting in an eye position image approx. every 17 ms). Given the fast dynamics of eye movements (for example, an average saccade takes only around 30 ms to complete), the spatio-temporal accuracy of eye movement signals obtained with mobile tracking is low. Based on existing QE studies we cannot know how accurately an observer fixates or tracks an object. By definition, for QE the eye has to be within a 3-degree range of the target. Given that visual acuity drops to 50% of its maximum when a target is located 2 degrees away from the fovea (Land & Tatler, 2009) this range is too large to make accurate predictions about the role of eye movements for performance. It is also unclear how a low position error (i.e., QE) is achieved, whether through smooth tracking or catch-up saccades. Even results regarding the onset and duration of QE are questionable. The advent of mobile eye tracking technology at a higher frame rate (mobile eye glasses with 120 Hz tracking capability are now available) will help address this problem. At the same time, comparisons between experts and novices can be achieved in laboratory or immersive virtual-reality settings using more accurate eye trackers. Such studies could and should be used to study the functional role of eye movements in more detail.

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The Quiet Eye in life and lab – comment on Vickers

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We confess to some envy of Vickers (2016), for her fortune in discovering the phenomenon of the quiet eye (QE) so early in her career, wisdom in recognizing its importance, and dedication in pursuing it for so many years. Given the QE's ubiquity and consistency in elite sports, one would expect analogous phenomena in other domains. Our laboratory studies of visual searches by typical undergraduates have produced two candidates. Moreover, we speculate that theoretical mechanisms we have proposed to account for our data may contribute to a better understanding of the QE in athletics.

The first set of studies concerned a phenomenon known as the *rapid resumption* of search (Lleras, Rensink, & Enns, 2005). This occurs when participants search for targets among displays that are presented for brief intervals interspersed with blank intervals, simulating what happens when a viewer glances away from a scene and then back again. Targets are detected with extraordinary speed following the reappearance of an inter-

ABSTRACT

Inspired by Vicker's (2016) comprehensive review of the quiet eye (QE) in athletics, we review two sets of findings from laboratory studies of typical university students performing visual search tasks. These studies also point to a relationship between longer fixation durations and improved performance, in keeping with the QE in elite athletes. The lab studies also suggest a possible underlying mechanism: longer fixations enable improved predictions of both perceptual and action outcomes. Because these predictions depend on cycles of reentrant visual processing, they benefit from additional processing time. We also caution that under some circumstances longer fixations can be detrimental in visual search, and suggest that this may have analogues in sport.

Keywords:

visual search – prediction – forward model – reentrant processes – attention

rupted display: only 200 ms, in comparison to 500 ms or longer following the onset of a completely new display. These rapid responses point to a form of memory (of the initial glance at the display) that was reactivated when the expected sensory experience was reinstated. A clear link with fixation duration was apparent: rapid resumption was more common on trials with longer display times (Lleras et al., 2005), and the fixations immediately prior to rapid resumption were longer than those prior to responses made at normal speeds (van Zoest, Lleras, Kingstone, & Enns, 2007).

The second set of studies investigated a *passive advantage* in search (Smilek, Enns, Eastwood, & Merikle, 2006). In these studies, participants were randomly assigned to perform the same search task under either *passive* instructions, which instruct participants to "use your intuition...let the target pop into your mind", or *active* instructions, which tell participants to "be active...deliberately direct your attention." Passively instructed

searchers were, on average, 20 % faster than actively instructed searchers, and this passive advantage is also tied to fixation duration: passively instructed searchers made longer initial fixations after the search display appears (Watson, Brennan, Kingstone, & Enns, 2010).

Why are longer fixations correlated with better performance on these visual search tasks? We propose that they allow the generation of better predictions for both perception and action, and that this may also explain the advantages associated with the QE in elite athletes. Predictions in the action realm are often referred to as *forward models: models* because they involve the construction of mental simulations, and *forward* because they make predictions about future actions, permitting the consequences of these actions to be tested before their execution (Wolpert & Flanagan, 2001). This is critical for overcoming the considerable lag time between physical events and their registration and processing by the nervous system. For example, a simple version of forward modeling prevents our visual experiences from changing radically every time we make a saccade since neuronal activity in the lateral intraparietal area is updated to reflect the expected post-saccadic retinotopic locations of stimuli (cf. Colby, 1998). Better predictions can lead to better action selection, whether the action is the interception of a football or simply a saccade to an optimal location in visual search.

Forward models are not only critical for linking vision to action; they appear to be equally important for perception itself, where what is perceived is often influenced as much by what one is expecting as what is on view (Di Lollo, Enns, & Rensink, 2000; Enns & Lleras, 2008). Following this perspective, we interpret visual search as a series of prediction-comparison cycles. During a fixation, searchers are making predictions about likely target identities and locations, in other words, forward models of the sensory input expected after saccading (or even only covertly attending) to a location. These models are then compared to the actual input received after the saccade (or attention shift). This continues until the input from one fixation is recognized as matching the target, and a motor response is made.

According to this interpretation, the ultra-rapid responses made during an interrupted search indicate that an accurate prediction has already been generated following the first display presentation. During the following presentation, the searcher only has to perform the comparison of the incoming visual information to this already-existing prediction before making a motor response. It seems that this prediction solely concerns the target and its immediate neighborhood, as rapid resumption is eliminated by changing the target location, but unaffected by completely scrambling the location of distractors outside of a small window around the target (Jungé, Brady, & Chun, 2009; Lleras, Rensink, & Enns, 2007).

In a similar vein, the main oculomotor predictor of response speed in our study of the passive advantage was the number of fixations performed *after* the target had been fixated but *before* responding. Passively instructed participants made fewer of these unnecessary fixations, consistent with their having

generated a superior prediction of the target's location prior to fixating it, and then being able to more rapidly recognize the target upon fixating it (Watson et al., 2010).

We can also speculate on why longer fixations enable enhanced predictions. According to our predictive account of vision, perception *within* each fixation itself involves a cycle of comparisons that takes place even more rapidly than the *between*-fixation cycle we have just described. At any moment in a fixation, the visual system has generated a representation from the information that was available from the fixation's onset. This is fed back to early visual areas, and compared to the new visual information that continues to arrive, which refines subsequent representations, until the end of the fixation (cf. Di Lollo et al., 2000). Longer fixations may simply enable more reentrant processing cycles, which then contribute to better forward models both in the realms of perception and action.

Finally, we note that a QE may not always be advantageous. Improved predictive capabilities are only useful if these predictions are based on the most relevant information, but in many tasks relevant information lies outside the useful field of view of a single fixation. This entails an inherent trading relationship between longer fixations, which allow enhanced predictions about the information that is currently being fixated, and more frequent saccades, which increase the chances that relevant information will be fixated. Consistent with such a trading relationship, we found substantial overlap in search efficiency between actively and passively instructed groups, with some actively instructed participants having response times that were comparable or even better than some passively instructed participants (Watson et al., 2010). We suggest that these participants were trading the disadvantage of shorter fixations with the advantage of making saccades to more new locations. In follow up studies, we examined visual search in large-field displays (a real-world messy office, and large photos of this office displayed on a computer screen), and reversed the passive advantage: actively instructed searchers were faster than passively instructed searchers, and made more frequent saccades and head movements to acquire the widely distributed visual information (Brennan, Watson, Kingstone, & Enns, 2011).

Similar active advantages may occur in sports. One study, for example, found that experienced soccer players were superior at anticipating pass destinations while watching a video clips taken from a full 11 on 11 game, and that they made more fixations of shorter duration (Williams, Davids, Burwitz, & Williams, 1994). A previous study using a similar methodology found longer fixations to be advantageous, but this study used set plays such as free kicks, or situations involving far fewer players (Helsen & Pauwels, 1992). We suggest that the QE may be advantageous for tasks that require monitoring relatively few locations that are close to each other, but disadvantageous when multiple task-relevant objects must be monitored over relatively large visual angles, which occurs frequently in team sports.

We close by congratulating Vickers (2016) for a thoroughly enjoyable overview of research on a single variable — the QE —

that has had astonishing longevity and broad impact. We look forward to the continued development of QE theory, both as it applies to sports in real life situations and in the laboratory. We hope our speculations are of interest to others, like us, who want to tie these domains together.

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Quiet eye vs. noisy brain: The eye like the brain is always active – comment on Vickers

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As highlighted by Vickers (2016), the scientific study of Quiet Eye (QE) has grown substantially since her identification of the phenomenon two decades ago. This growth is due to the prevailing robustness of empirical findings and her significant innovation in continuing to create novel situations and contexts to examine the phenomenon. The body of work outlined by Vickers (2016) has inspired many scientists and is of the highest quality in regards to the level of sophistication of the methods employed and the intellectual rigor of the ideas examined. Moreover, research on the training of QE has the potential to have significant impact on performance and learning across many domains. In this short reply to her review article, I focus my attention on just a few key areas which in my mind would benefit from further research endeavour.

ABSTRACT

The Quiet Eye (QE) period is a pervasive phenomenon in many aiming tasks. The number of published reports exploring the QE has grown substantively following the seminal work by Vickers (e.g., 1992, 1996). However, our understanding of the mechanisms underpinning the phenomenon remains limited. There is an abundance of descriptive data, yet few attempts to use experimental manipulations to identify causal mechanisms and even fewer efforts to employ neuroscience methods to identify areas of the brain activated during the QE. We can only speculate in regards to the extent to which the phenomenon is linked to motor programming, on-line visual control, arousal control, or other possible mechanisms, which may work together or in isolation. While early attempts to employ QE training methods have reported significant benefits, the absence of a mechanistic explanation necessitates caution in currently recommending widespread use of such interventions.

Keywords:

aiming – mechanisms – eye movements – perceptual training

What is the QE? Methods and definition

Vickers (2016) suggests that QE should be measured in situ. While collecting data in situ may present the optimal scenario, the phenomenon may be reproduced in the laboratory using more controlled experimental tasks (see Gonzalez, Causer, Miall, Grey, Humphreys, & Williams, 2015b). Provided that the QE is reliably reproduced in the laboratory and the task retains an action component linked to gaze behaviour it should be possible to explore the underlying mechanisms under more controlled settings. This latter approach may be desirable, if not essential, if we are to better isolate the mechanisms involved in the QE using neuroscience methods. The use of fMRI, EEG/ERP and TMS methods remains problematic when whole body movements are involved. While data collection in situ needs to

continue, we may need to accept the fact that more controlled tasks are needed to enhance our theoretical understanding of this phenomenon.

Another limitation is that the definition of QE has emerged from the operational capacities of the main measurement system used to quantify the phenomenon (i.e., the ASL mobile eye system). Consequently, the definition is somewhat arbitrary rather than being linked to any underlying mechanism (see Gonzalez, Causer, Miall, Grey, Humphreys, & Williams, 2015a). The mobile eye system has a measurement error of ± 1 degree and a sampling rate of 50 or 60 Hz. The operational definition of QE is that the gaze remains within a visual angle of 3 degrees from the target for a minimum period of 100 ms. The issue is that the eye is never actually 'quiet'; it is always on the move since there are continuous drifts, tremors and microsaccades (see Gonzalez et al., 2015a). We have limited understanding of what, if any, functional role these small and rapid eye movements have and the extent to which they may impact on the QE. High resolution eye trackers now sample at upwards of 500 Hz with a spatial resolution under 0.1 degrees. Although it may be difficult in the short term to use such high resolution systems in situ, they may certainly be used effectively under more controlled laboratory conditions. Advances in measurement sensitivity may enable us to revise and refine our operational definition of the QE.

As highlighted by Vickers (2016), we need clear and objective criteria to define the links between QE and performance. However, I disagree with Vickers (2016) that the QE period should only be discriminating on 'hits' and 'misses'. If the QE is strongly associated with aiming performance it should be able to differentiate performance in a continuous rather than a dichotomous manner. For example, in archery, a longer QE should be evident on a shot that scores 7 compared to another that scores 8 (out of 10) not just 'hits' and 'misses'. Similarly, the QE should be able to discriminate a putt that falls 10 cm short of the hole from one that rolls 2-3 metres past the target rather than those which are holed or not. The use of regression analyses rather than traditional difference testing may offer greater sensitivity in examining the links between QE and performance across the board. We need to better identify how sensitive the QE measure is and to what extent can it predict various levels of performance on aiming tasks.

Is the QE relevant across all tasks? Limiting scope and identifying mechanisms

The seminal work on QE used targeting tasks such as golf putting and the basketball free throw. In such instances, the target is often static, but not always so as in shotgun shooting (e.g., Causer, Holmes, & Williams, 2011), and there is nothing to focus on other than the target. Clearly, during an aiming task one assumes that information is being extracted from the target which facilitates performance. However, it may be that focusing on the target may be less important than maintaining a

stable gaze. Is there a change in performance if gaze is diverted slightly off centre yet remains stable?

The greatest shortcoming in this area of study is the paucity of work that has attempted to better identify the mechanisms that underlie the QE phenomenon. It has been suggested that the QE period reflects motor programming, on-line motor control, and arousal or attention control, yet all of these suggestions remain largely uncorroborated (Gonzalez et al., 2015a). Some researchers have used experimental manipulations to test theoretical assumptions (e.g., Klostermann, Kredel, & Hossner, 2013; Williams, Singer, & Frehlich, 2002), whereas others have used neuroscience methods to identify neural activity during the QE period (e.g., Mann, Coombes, Mousseau, & Janelle, 2011). Yet, more theoretically-driven research is needed using cross-disciplinary approaches if we are to enhance our understanding of the QE period. Limited benefit may be gained from more descriptive reports using different population groups and tasks. The issues of identifying causal mechanisms are compounded in tasks that involve interception of objects in flight and interactions with teammates and opponents. It could be argued that the QE is only relevant in aiming tasks with limited applicability to other tasks. For example, in sports like soccer and tennis it has been well reported that elite athletes are more likely to use 'visual pivots' to extract information from multiple locations (Ripoll & Fleurance, 1988). These visual pivots are thought to highlight the optimal location to anchor the fovea while using the parafovea and periphery to extract information from the display (e.g., Williams & Davids, 1998; Vaeyens, Lenoir, Williams, Mazyn, & Philipparets, 2007). In such situations, a longer QE period may be observed but its duration may be unrelated to motor programming, on-line motor control or the control of arousal. The longer fixation may merely be indicative of the need to extract multiple sources of information from different areas of the display; which highlights the classical differentiation between 'looking' and 'seeing'. We need to better delimit the scope and generalisability of the QE. Our potential to do so is strongly associated with our ability to better understand the mechanisms that contribute to the QE and how these change as a function of the spatial and time-dependent networks involved (Gonzalez et al., 2015a).

What is being trained?

The potential value of QE training has been highlighted (e.g., Causer et al., 2011; Causer, Vickers, Snelgrove, Arsenaault, & Harvey, 2014). Yet, not all researchers have embraced the 7-step QE training programme outlined by Vickers (2016). Moreover, the QE training programme proposed in the review article seems more closely aligned with the Decision-Training programme proposed by Vickers in her earlier work (e.g., Vickers, 2007) rather than QE training per se. Moreover, it could be argued that steps 1, 2 and 7 which are outlined in Vickers (2016) are not part of the training programme, but rather are more reflective of the experimental design and methods/measures employed.

In regards to the remaining steps (i.e., 3, 4, 5 and 6), not all papers report using these as part of the training programme (e.g., see Causer et al., 2011). It appears that steps 5 and 6 have not been used by other researchers to train QE. A more typical approach has been to merely use video instruction and feedback to highlight differences between QE periods that are perceived to be more or less optimal. This latter approach has resulted in significant changes in QE characteristics, as well as some transfer from practice to competition, suggesting that only variants of steps 3 and 4 may be crucial in QE training.

We should be cautious in recommending widespread use of QE training programmes. While it is clear that our interventions can change some characteristics of the phenomenon at the behavioural level (e.g., longer duration or earlier onset of QE) our lack of theoretical understanding makes it difficult to determine what is actually being trained at the mechanistic level. How do we know whether any increase in the QE period through training is indicative of enhanced motor programming, a reduction in on-line motor control demands or merely reflective of changes in attention or arousal control? It may be that interventions with different foci are needed to improve each component. In order to be able to fully endorse the benefits of evidence-based practice, we need to better identify the different underlying mechanisms and then develop training programmes that specifically enhance these mechanisms. Clearly, such training programmes not only need to be well-designed, using appropriate control groups and transfer measures, but process tracing measures need to be collected (e.g., fMRI or experimental manipulations employed) to improve understanding of what actually changes as a result of these interventions. In conclusion, the immense contribution made by Vickers to this area of study is acknowledged. She has identified the phenomenon and provided strong leadership in moving knowledge and understanding forward. However, despite her substantive and exceptionally valuable contribution, much scope remains for further work to improve understanding of what goes on during the QE and how this knowledge may be used to create systematic, evidence-based training programmes.

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Say it quietly, but we still do not know how Quiet Eye training works – comment on Vickers

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It is a testament to her energy and enthusiasm that Joan Vickers has championed the impact of the Quiet Eye (QE) for 25 years. However, to focus on just the longevity of the endeavor would do a disservice to the originality of her early studies (Vickers, 1992, 1996), and the insights that she first derived from her vision-in-action approach. Much of what Vickers alluded to in these early studies has since been supported via developments in our understanding of the cognitive neuroscience of visual attention (e.g., Corbetta & Shulman, 2002). However, while the findings reviewed by Vickers (2016) are robust (notwithstanding potential publication bias issues), there is still a lack of understanding as to the specific mechanisms by which QE and QE training exert their performance advantage.

ABSTRACT

The Quiet Eye (QE) construct, first reported by Prof Joan Vickers 25 years ago, has proved to be an enduring perceptual cognitive variable. Not only does it reliably differentiate more from less proficient performance, but it appears to provide an insight into how competitive pressure impacts upon the planning and control of visually guided skills. Perhaps the most exciting findings from an applied perspective are the performance advantages conferred from QE training. In this commentary we suggest that QE research needs a period of consolidation, rather than expansion if the mechanisms underpinning these performance effects are to be better understood. We need to manage the difficult balancing act of ensuring consistency in definitions and methods, while recognizing the importance of inter and intra- task (and individual) variability. This may require different experimental and analytical methods than those currently used.

Keywords:

attention – online control – pre-programming – anxiety – gaze

QE training

The authors of this commentary have invested more time than most on testing the efficacy of QE training in populations as varied as children with developmental coordination disorder (Miles, Wood, Vine, Vickers, & Wilson, 2015) to experienced sporting performers (Vine, Moore, & Wilson, 2011; Wood & Wilson, 2011); in tasks as varied as laparoscopic surgery (Wilson et al., 2011) to machine gun shooting (Moore, Vine, Smith, & Wilson, 2014). We have consistently found a significant performance advantage compared to groups receiving typical movement-related instructions, whether this be in terms of immediate or delayed retention, or in transfer to more demanding (stressful) conditions. However, it is less clear *why* these ef-

facts arise and whether there are similar mechanisms at play in each case.

Even when multiple process measures are examined, the picture is still often unclear.

For example, in a golf putting task, we found that a QE trained group of novices revealed post-training improvements that were not apparent in the control group: significantly better performance; smoother putting mechanics; longer QE durations; and greater decreases in cardiac and forearm muscular activity (Moore, Vine, Cooke, Ring, & Wilson, 2012). However, only one of the putting kinematic variables was found to mediate the group differences in performance under pressure. So if longer QE durations are not explaining the group differences in performance, what does this say about the mechanisms underpinning QE training (and the role of QE in general in supporting performance)? How much of the benefit simply comes from what QE training does *not* focus on (i.e. technical, movement-related instructions)?

What has become clearer is that QE training has to be considered as more than just a visuomotor intervention. Moore, Vine, Freeman, and Wilson (2013) found that group-based differences in performance under pressure *were* mediated by a psychological interpretation of the stress they experienced (the ratio of the demands of the situation to their resources to cope). Other studies have shown that QE training acts as a more implicit form of motor learning (Vine, Moore, Cooke, Ring, & Wilson, 2013) and improves perceptions of psychological control when anxious (Wood & Wilson, 2012). Therefore, the positive QE training results might be telling us more about generic psychological and physiological changes that occur via the taught pre-performance routine, rather than any specific role for QE itself. To further our understanding of how QE might impact upon performance will therefore require novel experimental designs and a departure from replication studies. For example, there is a need to consider: appropriate control groups (Why just technical-training comparisons?); and transfer tasks (Are there any cross-over benefits?); the exploration of QE dose-response relationships (Is an optimal threshold duration enough?); the manipulation of the timing and location of the QE period (What degree of variability can be withstood before performance disruption occurs?); and the role of different phases of the QE (Is early or late information more important?).

Neural structures underlying QE

The main concern we have about putting all our eggs in the neuroscience basket is that we may not really learn more about the underpinning mechanisms that we cannot estimate from what we already know about the cognitive neuroscience of goal-directed, visually-guided movement in general (e.g., Land, 2009). All routes point towards a critical role for the dorsal lateral prefrontal cortex (e.g., Corbetta & Shulman, 2002) as Vickers (2016) outlines in her target article. Will confirming this knowledge really help us improve our QE training interven-

tions – especially when we know that tasks will have to be deconstructed beyond recognition to enable valid brain imaging (Walsh, 2014)? Indeed it is somewhat ironic to think that Vickers adopted her vision-in-action approach 25 years ago in order to move away from a ‘watching performance on screen’ approach. The functionality of brain imaging will improve at an incredible speed, enabling more ecologically valid insight into the neural processes underpinning perception and action. In the meantime, there is still much to learn from improved experimental methods and novel analysis techniques.

Uncovering the QE in other tasks

Vickers (2016) points out that the QE has been isolated in nearly 30 tasks, with varying spatial and temporal demands. When a concept can be shown to be critical in so many tasks, it becomes harder to specify how it achieves its benefits. Therefore, we would argue that rather than seeking to isolate the QE for a range of new tasks, we need to better understand the role of the QE in tasks where we already know ‘something’. For example, in golf putting the late portion of QE appears to be critical in supporting performance (Vine, Lee, Walter-Symons, & Wilson, 2015), whereas in interception tasks early information is more important (e.g., Miles et al., 2015). What might these differences tell us about a consistent role for QE in underpinning performance? Does simply reporting a total QE duration (as done in most studies) provide sufficient explanatory power? One key requirement for QE theory development is therefore the use of consistent definitions and analysis methods. Sometimes, QE is defined up until the initiation of movement (e.g., in golf putting, Mann, Coombes, Mousseau, & Janelle, 2011; and basketball, Vickers, 1996) whereas other times, the duration is defined as extending throughout movement (e.g., in golf putting; Vine et al., 2011; and basketball, Harle & Vickers, 2001). Similarly, more work is needed to understand how technique variations (e.g., high vs low style of shooting in basketball) impact on QE. Both styles of shooting might have different QE locations, timings and durations, but could serve the same general function; providing the motor system with visual information as late as possible in the movement (cf. Oudejans, van de Langenberg, & Hutter, 2002).

As well as inter-individual differences in expert-QE, there is also little consideration of intra-individual (functional) variability in terms of optimal QE locations, timings and durations (cf. Seifert, Buttons, & Davids, 2013, in limb movement). Most research still publishes grouped data, whereas we know that experts can use different visuomotor strategies for the same task. For example, Jordan Spieth (mentioned by Vickers, 2016, as the best clutch putter in golf) switches between two completely different approaches to the visuomotor control of putting: either fixating the ball (a ‘typical’ QE) or fixating the hole as he putts. What do the differences (and similarities) between these strategies tell us about how he uses vision to plan and guide movement? Do such variations potentially account for the non-

significant QE-performance findings that have been found in the published literature (and non-published data sets)? Would QE training that focuses on fixations to either target reveal similar performance advantages (Lee, 2015)?

Conclusion

The current commentary is written from the position of a critical friend. We too have invested much of our careers on trying to understand the influence of anxiety on motor performance through disruptions in QE, and the potential benefits of QE training for effective and efficient skill acquisition; and we have frequently fallen short in our attempts to better understand the QE. There is much exciting work being carried out across a number of groups; but 'replication' studies in new tasks, and the publication of pretty brain pictures while participants lie in scanners, is unlikely to push the field forward. Admittedly, the type of experimental designs that might elucidate QE mechanisms *are* challenging and *will* require much deliberation compared to the 'easier pickings' of replicating current designs in different populations. However, we believe that this challenge needs to be embraced in order to push this field forward. The exciting news is that there are still plenty of questions left to be answered in the next 25 years of QE-related research.

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All relevant data are within the paper.

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The Quiet Eye: Reply to sixteen commentaries

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TA RESPONSE

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Below I respond to the 16 commentaries on the Quiet Eye (QE) from eminent scientists in the field. Some come from researchers who have published many QE papers, while others come from other fields that offer new insights and directions for future studies. I want to thank Ernst Hossner for his leadership in bringing the target paper, the peer commentaries and this response forward at this critical time in the evolution of the QE. Below I address a number of exciting possibilities and challenges the QE faces, as identified by the reviewers and myself. Two main themes run through my response, the first describes the extensive progress QE research has made in the past and the incredible future that lies ahead, as identified by the commentators. Second, after 20 years of QE research, a number of commentators mention that the QE is at a critical crossroads, and I agree. In the latter part of the paper I explain that many of limitations mentioned by some of the commentators is due to two causes: the failure to recognize that the QE's origin is in the expertise paradigm, and second, there has been gradual departure from the early methods used to detect the QE, and the adoption of more traditional motor learning and control

ABSTRACT

The future of the QE is discussed in terms of its origin in the expertise paradigm, the urgent need for QE theory development, the potential of an ecological dynamics framework providing an interpretation of QE findings, and the success of QE training and its ability to facilitate emotional control and motor success. Important methodological issues are discussed and recommendations made for future studies. In particular, a call is made to detect the QE of elite performers during pure states of accuracy, as it is only in this way that norms in specific sports and motor activities can be established for the five QE characteristics (QE location, QE onset, QE movement phase, QE offset and QE duration), which are the bases of QE training.

Keywords:

expertise – sport – perception-action – cognition – motor control

(ML&C) methods and their reliance on motor error scores as the sole measures of performance accuracy, without recognition of the standards of excellence from the sport or profession being investigated. Given these themes, the following topics are discussed, as identified by the commentators and myself:

- (1) Brief review of the QE
- (2) The foundation of the QE lies in the expertise paradigm
- (3) QE theory development: neural, perceptual and cognitive evidence
- (4) A bridge with ecological psychology
- (5) QE training is effective, but we don't know why
- (6) The QE facilitates emotional control and motor success
- (7) Some important methodological issues
- (8) The QE at a crossroads: The QE paradigm is distinct from the ML&C paradigm
- (9) Recommendations for future QE studies
- (10) Conclusions

Brief review of the QE

The QE (Vickers, 1996a, 1996b, 2007, 2009, 2016) is measured, *in situ*, using a light mobile eye tracker that is coupled to one or more external motor camera(s). For a given motor task, the QE has five perceptual-motor characteristics that are objectively measured. Each is presented below, along with the specific perceptual and cognitive characteristics that are central to attaining the highest level of expertise:

- First, the QE is the final fixation or tracking gaze that is located on a specific location or object in the task space within 3° of visual angle (or less) for a minimum of 100 ms. The QE therefore provides objective evidence of the location of the gaze in space. The QE also provides critical information about selective attention processes used by performers, especially as they move from novice to expert in a motor task.
- Second, the QE onset of elite performers occurs earlier, providing evidence of superior anticipation and potential feed-forward of the motor commands.
- Third, the onset of the QE is timed to occur before a critical phase of the movement, thereby providing evidence of enhanced perceptual-motor coordination. Central to the QE is perfect timing.
- Fourth, the QE offset occurs when the gaze deviates off the object or location by more than 3° (or less) of visual angle for a minimum of 100 ms, therefore the QE can carry through and beyond the final movement of the task or occur earlier before the movement is completed. The offset is thus sensitive to specific task constraints, such as objects moving through the visual field, or compressed time periods in which an action must occur. For this reason, the QE offset may be early or late and capable of providing evidence in support of efference copy/corollary discharge, open or closed loop control, and other models of motor control.
- Fifth, the QE duration is longer for elite performers, indicating a period of sustained visual focus and concentration which is needed to optimally organize the billions of neurons in the brain that are used to plan, initiate, and control the movement.

The foundation of the QE lies in the expertise paradigm

My search for the QE was greatly influenced by the expertise paradigm, a point that needs to be emphasized at the outset. I was especially influenced by the research of Chase and Simon (1973), Bloom (1985), Starkes (2003), Ripoll (Ripoll, Bard, & Paillard, 1986; Ripoll, Papin, Guezennec, Verdy, & Philip, 1985) and Ericsson (Ericsson, Krampe, & Tesch Römer, 1993). Ericsson (2003) explains that the expertise paradigm has gone through distinct phases of research, beginning with a “general theory of expertise” proposed by Chase and Simon (1973) and followed by the “expert performance approach” of Ericsson (1996) and

Starkes and Ericsson (2003). The QE is based more on the latter approach, which focuses on objectively measuring “superior performance in tasks that capture expertise in the domain” (Ericsson et al., 2009, p. 3). Although the expert performance approach is generally accepted (Abernethy, Farrow, & Berry, 2003), Ericsson (2003, p. 373) argues that “only a small number of researchers currently conduct research with the focus on capturing the essence of expert performance in sport”. I agree with Ericsson in terms of QE research, where there has been a tremendous growth in studies that describe group differences based on skill level, training, type of pressure and other topics, but only a few studies report the QE when the highest level of accuracy has been achieved. Ericsson (2003, p. 379) explains that “the expert performance approach does not seek to avoid the complex contexts of naturally occurring phenomena. Instead, the approach strives to re-create the conditions and demands of representative situations with sufficient fidelity where experts can repeatedly reproduce their superior performance”.

The QE method was developed with many of the requirements noted by Chase and Simon, Starkes, Ripoll, Ericsson and others (as cited above). Whenever possible, the QE data is recorded, *in situ*, using a light mobile eye tracker coupled to one or more external motor camera(s). During QE studies elite and near-elite athletes are tested on repetitive trials until equal numbers of hits and misses are achieved (usually 10 trials of each). The explanatory power of the QE therefore lies in providing concrete measures of the perceptual-cognitive abilities that are present during accurate trials compared to inaccurate, as defined by the sport or profession being investigated. Because the five characteristics of the QE outlined above are obtained as the task is performed under conditions similar to the real world, objective evidence is obtained about the specific *spatial awareness* (QE location), *anticipation and selective attention* (QE onset), *perceptual motor-coordination* (timing with critical phase of movement), and *optimal control* relative to external task constraints (QE offset). Finally, during states of success, a period of *sustained focus and concentration* (QE duration) is needed on a specific location in the task space to organize and control the extensive perceptual motor neural networks underlying optimal motor performance.

QE theory development: neural, perceptual and cognitive evidence

Development of a potential theory for the QE was by far the major topic mentioned, with comments and evidence drawn from neuroscience, perception and cognition by a number of commentators. **Helsen, Levin, Ziv, and Davare** provide a description of the neural architecture that may be involved in the QE. Their hypothesis is not only that the QE provides more time for organizing the parameters controlling a skill, but that “a longer [QE] fixation duration provides more time to prepare the motor control response, send it forward and process online feedback

... [thereby providing] the generation of a better-defined efference copy of the intended movement" (p. 2). Efference copy has traditionally been defined as a copy of the intended action commands sent forward from the higher centers that are designed to modulate feedback from the ongoing action. For example the "tickle" experiment (Blakemore & Wolpert, 2000) is used as evidence as it has been shown you cannot tickle yourself, as you prepare an inhibitory response called corollary discharge, however, if someone else tickles you it is difficult to suppress the tickle sensation. **Helsen et al.** argue that both efference copy and related corollary discharge commands are programmed during the QE period, using a neural circuit that includes the posterior parietal cortex, the motor cortex, and the frontal eye fields which maintains fixation on a meaningful target. This system is described as central to generating transformations from visual inputs to the motor commands.

Mann, Wright, and Janelle, in a related commentary, tackle one of the most intriguing aspects of the QE in that optimal performance is characterized by a long duration QE, even as the movement times may be very fast. **Mann et al.** are among the first to propose a novel "efficiency paradox" which is characterized by "neural efficiency, ... simultaneous spatial localization ... [and] a reduction in brain activity" (p. 2). "Experts and expert performance are characterized by an extended QE period. A longer QE has been oft-replicated across both self-paced and externally-paced tasks, but seems at least superficially inconsistent with broadly accepted notions that increasing levels of expertise are afforded by greater automaticity and efficiency" (p. 1). Many involved in coaching, teaching and sports vision training assume that if athletes move quickly then their brain and visual systems must also be working at an even faster pace. But QE studies show the reverse is the case. Elite ice hockey goaltenders facing pucks coming at them at 150-200 km/h, have a QE duration on saves that averages almost a second on the puck before flight, followed by a rapid movement of the stick, blocker or foot that averages less than 200 ms (Panchuk & Vickers, 2006, 2009; Panchuk, Vickers, & Hopkins, 2016). Additional evidence comes from QE studies in which elite athletes consistently "fixate fewer locations of longer duration, suggesting a level of information processing efficiency that permits more time to be spent on task relevant cues and less time in search of these cues" (Mann et al., 2007). EEG studies in which the QE was assessed reveal a quieting of the left hemisphere in elite shooters and golfers; the expert brain uses less energy and is radically different from that of less skilled performers (Mann, Coombes, Mousseau, & Janelle, 2011).

Mann et al. propose two reasons for their efficiency paradox, the first related to the cerebral architecture and models of information processing, and the second related to emotional regulation. They state that the "extended QE duration that is characteristic of experts may in fact represent the time needed to accommodate the detrimental effects of anxiety/arousal on the recruitment of task specific resources" (p. 3). **Causser** also asks if "a longer QE is an example of an efficient gaze strategy, which maximizes attentional resources on the principal task"

(p. 2). Consistent across a variety of reports, the QE duration is influenced by modulations in cognitive stress, physiological arousal, or pressure. This point of view is also supported by extensive QE research showing a long duration QE insulates biathlon and shotgun shooters from high levels of pressure, anxiety and physiological arousal (Causser, Bennett, Holmes, Janelle, & Williams, 2010; Causser, Holmes, Smith, & Williams, 2011; Vickers & Williams, 2007); golfers during high pressure and challenge and threat states (Moore, Vine, Cooke, Ring, & Wilson, 2012; Moore, Vine, Wilson, & Freeman, 2012), and basketball players under high levels of pressure (Vine, Moore, & Wilson, 2011) to name a few studies. **Mann et al.** state that the QE may be representative of "a covert pruning process that requires additional time to align the perceptual cognitive systems with the motor systems to execute a skill at its highest level" (p. 3). Bridgeman (2007) also provides evidence that once a re-fixation is initiated, which occurs often in high arousal states, then motor efference commands and accompanying corollary discharge feedback contingencies are cancelled, or at best compromised. Corbetta, Patel, and Shulman (2008, p. 306) provide MRI evidence that

survival can depend on the ability to change a current course of action to respond to potentially advantageous or threatening stimuli. This "reorienting" response involves the coordinated action of a right hemisphere dominant ventral fronto-parietal network that interrupts and resets ongoing activity and a dorsal fronto-parietal network specialized for selecting and linking stimuli and responses. At rest, each network is distinct and internally correlated, but when attention is focused, the ventral network is suppressed to prevent reorienting to distracting events.

Within this context, QE processing, when optimal, would occur earlier and for a longer duration in the dorsal fronto-parietal network, and when non-optimal be interrupted by the ventral network and re-oriented to information that is detrimental to performance.

Watson and Enns provide new insights and clarity that are very welcome. First, they distinguish between looking and seeing in the context of eye tracking and explain that *looking* requires moving the gaze to new locations using saccades, while *seeing* requires a fixation of sufficient duration to distinguish targets from non-targets (Watson, Brennan, Kingstone, & Enns, 2010). I find these definitions very helpful, as there has been a lack of consensus in the use of these terms in eye tracking studies in the past. They then introduce a new finding called "rapid resumption of search", which may explain why a longer QE duration occurs during accurate motor performance. Their recent evidence shows that humans resume an interrupted visual search much faster than when they start a new search (Enns & Lleras, 2008). Once the same target has been fixated then it is detected with extraordinary speed, in only 200 ms compared to 500 ms, when a new display is searched. If a new target is fixated, then the "rapid resumption of search" is abolished.

I attempted to relate these findings to two QE training studies that have been completed in the soccer penalty kick (Wood & Wilson, 2011, 2012). When an athlete performs a penalty kick, either a keeper-independent or keeper-dependent gaze strategy can be pursued (Kuhn, 1988; Navarro, van der Kamp, Ravnaud, & Savelsbergh, 2013; van der Kamp, 2006). During the keeper-independent strategy, the kicker ignores the goaltender, and instead fixates a location on the goal (usually a corner) and decides in advance where the ball will go. During the in-run he or she then focuses only on the ball during the kick, thus ensuring solid contact. In contrast, when a goalie-dependent strategy is used, the penalty kicker fixates the goaltender throughout in an effort to gain an advantage.

Wood and Wilson's (2011, 2012) QE training studies taught penalty takers how to use the keeper-independent strategy. At the beginning of the trial, the athletes were taught to select a corner of the goal they planned to shoot at and fixate for a long duration using QE-A. This was followed by a second fixation, QE-B, which was on the ball before and as the kick was executed. Results of the two studies show that the QE-trained groups had significantly longer QE-A and QE-B durations than a control group, and were more likely to aim optimally and further from the goalkeeper, whereas those in the control group aiming more toward the goaltender. **Watson and Enns** (p. 2) provide evidence into why this strategy worked as they speculate that

longer fixations enable enhanced predictions ... [using a] predictive account of vision [in which] perception *within* each fixation itself involves a cycle of comparisons that takes place ... rapidly. ... At any moment in a fixation, the visual system has generated a representation from the information that was available from the fixation's onset. This is fed back to early visual areas, and compared to the new visual information that continues to arrive, which refines subsequent representations, until the end of the fixation. ... Longer fixations may simply enable more reentrant processing cycles, which then contribute to better forward models both in the realms of perception and action.

Relating these findings to QE-A and QE-B, minor perturbations (under 3° of visual angle) usually occur in fixations during the in-run and kick (due to stepping and the dynamic nature of kicking) that could be subjected to a "rapid resumption of search" that is very fast, allowing a continuation of QE-A or QE-B as planned. However, if the penalty taker chose to fixate the goaltender during the in-run, then this would abolish the use of the "rapid resumption of search", which would take more time and indicate a slower, keeper-dependent strategy was used that is less effective.

Sergio Rodrigues was the first to couple a mobile eye tracker, with a six-camera motion analysis system, a Flock of Birds, the vision-in-action system and eye-head integration software. He measured the gaze and arm movements in real time in 3-D space of elite and novice athletes and children with ADHD (Rodrigues, Vickers, & Williams, 2002; Vickers, Rodrigues, & Brown,

2002). Participants tracked a rapidly moving table tennis ball and returned it to slow and fast cued targets across the table. To my knowledge no-one has completed a similar QE study in any motor task since. **Rodrigues and Navarro** suggest that the QE may be central to maintaining good posture and balance control, which depends on "translational components of head movements in space and eye movements ... [during optic] flow" (p. 2). They provide evidence that a long duration QE causes a "minimization of rotational consequences to the flow created by gaze stabilization [on a location in space]" (p. 2). They draw on dorsal and ventral models of visual attention control as posed by Milner and Goodale (1995) and refined later by Corbetta et al. (2008) to argue for a different function of the ventral attention system (VAN) and dorsal attention system (DAN). As described previously in this paper, the dorsal-parietal-frontal system may be central to maintaining a long duration QE, while the ventral system is responsible for re-orienting attention during moments that may indicate distraction resulting in loss of focus. The hypothesis brought forward by **Rodrigues and Navarro** (p. 2) is that postural regulation

is dependent upon a high degree of cooperation between the two pathways. ... A first prerequisite of an action is selecting a goal object to be addressed, when the object is "flagged" due to enhanced attention, during processing by the ventral stream ... [where the] QE period would be under control of the ventral vision-for-perception system, mentally representing environmental information, and the motor action would be regulated by the dorsal vision-for-action system, within the three-dimensional space.

Rodrigues and Navarro do not mention how the primacy of the QE in one system or the other can be established experimentally, but given the on-going and continuous nature of posture and locomotion and the critical need to acquire specific information underlying safe navigation, their suggestion is that the QE is set up by the top-down ventral system which is running the show, while the dorsal parietal system provides moment to moment bottom-up motor control. More research is needed to determine if this is the case.

Klostermann, Vater, and Kredel feel that a more productive approach is to center QE research on gaining a better understanding of the motor control system. In reference to Klostermann, Kredel and Hossner (2013), they propose an "inhibition hypothesis" in which the QE "shield[s] the parameterisation of the ... optimal task solution against alternative movement variants" (p. 1). **Klostermann et al.** feel that the QE is limited as currently investigated in the literature, and it might be "more fruitful to elaborate theoretical frameworks on the behavioural level that allow to experimentally test specific predictions in order to extend our understanding of the mechanisms underlying the QE" (p. 1). This is an important goal, as at the end of the day, it is very important we understand how changes in one or more of the five QE characteristics affect motor behavior. At the outset of this paper a number of key perceptual and cognitive

characteristics central to the QE were described that accompany successful motor performance. Each of QE location (spatial awareness), QE onset (anticipation and selective attention), QE motor phase (perceptual motor-coordination), QE offset (use of feedback), and QE duration (focus and concentration) can be manipulated and the effect measured in terms of changes on motor control. It would be a welcome addition if the experimental manipulation of these QE characteristics were also linked to related theories, such as efference copy/corollary discharge as discussed by *Helsen et al.*, the “efficiency paradox” as outlined by *Mann et al.*, the location-suppression hypothesis of Vickers (1996b), and other forms of perceptual and motor inhibition observed by previous authors.

A bridge with ecological psychology

Davids and Araujo seek to bridge the gap between the theoretical underpinnings of neuro-cognitive psychology and that of ecological psychology. They do not dispute that the five characteristics of the QE emerge in elite performers, but in one of those insights that jump off the page, they ask: “How to decide what is the critical spatial location that QE needs to target in each task? ... How can relevant spatial information be distinguished from non-relevant information, before the information extracted by the QE is transmitted to the brain?” (p. 2). *Davids and Araujo* rightly ask what causes elite performers to eventually select one location, out of the number of different locations that they could fixate. And why does this emerge as a characteristic of expertise? We don’t know why this occurs.

QE studies show that elite performers, when highly successful, select one QE location, while non-experts and near-elite performers often fixate multiple locations in a single trial. In a study in which novices learned to tie surgical knots, 43.7 % of their fixations were within one degree of the knot, compared to 77.9 % for elite thyroid surgeons (Vickers et al., 2015). Similar results have been found in golf, basketball, law enforcement, and shooting. In some tasks, such as a live simulation of an officer involved shooting, the use of additional eye movements at critical times can prove to be detrimental, even fatal to life itself. We carried out a study of elite and rookie police officers in which an assailant did a fast reverse pivot and shot a plastic bullet at an officer who was wearing an eye tracker (Vickers & Lewinski, 2012). The elite officers kept their QE on the moving assailant and fired with 75 % accuracy. In contrast, during the final half second, the rookie officers made a rapid saccade back to the sights on their gun in order to create a “sight picture”, leading to significantly lower accuracy of 62 %. More importantly, in catch trials, where the assailant drew a cell phone instead of a gun, 65 % of the rookies made the wrong decision and shot the assailant, compared to 18 % of the elite officers.

We don’t know why the road to expertise causes a change in the primary location or object fixated, but two ideas may serve as a beginning, the first being a trial and error approach which occurs when athletes train on their own without the advantage

of an elite coach, or other trainer who can provide insight into the optimal focus and concentration required, while the second builds on the work of Ericsson et al (1993) and the deliberate practice approach (Ericsson & Pool, 2016), as well as that of QE training. Accelerated progress has been documented using both the latter approaches, revealing the critical role of expert coaches and trainers. In terms of future research we need to determine why elite performers select a single high percentage QE location that is not identified by those with lower skills levels, even though they may train for similar periods of time, with a similar caliber of coaches and play in the same league. Is it because of superior insight and awareness and motor control achieved through: (a) a process of trial and error, (b) a process of deliberate practice, (c) QE training, or (d) another approach?

QE training is effective but we don’t know why

QE training involves teaching novices how to adopt the five QE characteristics of elite performers. Joe Causer, along with Mark Williams and colleagues, were among the first to design a triad of studies that provides guidance in how the QE should be isolated and trained in any motor task. They first isolated the QE in a specific sports task (shotgun shooting), then in a second study trained the QE using an elite prototype derived from this first study; and third, they carried out a study in which pressure was manipulated and the effect of anxiety on motor performance assessed (Causer et al., 2010; Causer, Holmes, & Williams, 2011; Causer, Holmes, Smith, et al., 2011). In addition to shotgun shooting, Joe Causer and colleagues carried out the first QE studies in surgical knot tying following the same design (Causer, Harvey, Snelgrove, Arsenault, & Vickers, 2014; Causer, Vickers, Snelgrove, Arsenault, & Harvey, 2014), and recently completed an ice hockey look-up-line study, to our knowledge the first study to couple the eye movements of both an offensive and defensive ice hockey player in a realistic 1 vs. 1 play (Vickers et al., 2016).

Causer cites a number of limitations in how QE training studies have been carried out, including “multiple training interventions (instructions, gold-standard eye movement, feedback of self), which makes it difficult to ascertain which manipulations are most effective (Causer, Janelle, Vickers, & Williams, 2012)” (p. 2). In my opinion this is due to changing how we define expertise in motor tasks from the original QE paradigm to the use of motor error scores that are not related to standards of excellence in the sport. This is why it is my recommendation that all QE research programs in a motor task begin with gaining an understanding of the five QE characteristics of elite performers, and that this information should be the only QE training intervention used (unless new additional QE characteristics are discovered). Overall, I agree with *Causer* who states a “more systematic and strategic approach to future research is needed to delineate the different theories and develop a stronger, more concrete understanding” (p. 1), a theme addressed in this timely review of the QE by many others, hopefully providing

insight to some of the points he raises. But if the history of science is any indicator, a true discovery has limitless potential and is used in ways that the originator and pioneers of first QE studies can never fully imagine.

Farrow and Panchuk both work extensively with elite athletes at the Olympic level, therefore they have a wealth of day to day experience about what it is like to use the QE in this environment. They state that “there is no question that QE training can be an effective method of eliciting behavioral change and improving performance in athletes” (p. 1), a position also held by **Causser**, and **Wilson, Wood and Vine**. Knowledge of what the optimal QE location is comes from studying elite athletes when they are successful. QE training studies show that when lower skilled performers are taught to adopt the QE location of elite athletes, their performance in the task improves more so than control groups who are trained using traditional training that stress proper technique and physiological function and emotional regulation to the exclusion of all else. It appears that learning to adopt the five QE characteristics of elite performers directs attention away from the body and negative emotions, and inadvertently promotes the development of an ability to ignore the momentary but necessary functions of the body.

Farrow and Panchuk state that QE training is a form of implicit training, which in my opinion is only partially correct. This is because in all motor tasks, there are two different locations where athletes can direct their attention, the first being the target or object in space that is their primary target in the task, and second a location within the body related to achieving and maintaining proper technique, efficient physiological arousal and/or emotional control. An optimal QE occurs during successful trials when the athlete’s explicit QE fixation and focus of visual attention is directed toward a specific target or object location within the external task environment. Note the QE location must be that identified previously by elite performers in the task. At the same time, their implicit attention during successful trials is on the automated technical, physiological and emotional requirements of the task.

Another important question raised by **Farrow and Panchuk** is what do you do when QE training is requested in a task where the QE of elite performers has not yet been isolated? While it is tempting to recommend that QE training *not* be carried out in motor tasks where the elite QE has yet to be defined, teachers and coaches do not have the luxury of restricting their training to sports where QE research exists. There is some evidence that the QE in one sport may transfer to another, especially when they are in the same category, i.e., within targeting, interceptive timing, or tactical. For example, Rienhoff et al. (2013) showed an association between the QE used in the basketball free throw and the dart throw. Vickers (2007) in Chapter 4 of her textbook places different motor tasks into three categories based on the similar type of gaze control needed to perform well in targeting, interceptive timing and tactical tasks. Above all we need the QE to be isolated in new tasks, such as baseball hitting, baseball pitching, football quarterback, football receiver, golf drive, golf chip, golf irons, downhill skiing, kicking field goals,

orienting, squash, or kayak racing (to name a few). Isolating the QE in a new task is a process that takes considerable effort (and one where it is very easy to incorrectly measure the QE), as *all* the fixations in order have to be tested relative to *each* phase of the movement, before one can conclusively be identified as the QE of elite performers when successful.

Frank and Schack lament the lack of “perceptual-cognitive approaches and their potential explanatory value with respect to the QE” (p. 1), and state that “perceptual-cognitive approaches discuss motor control in the light of action-based cognition. Specifically, the goal-directedness of actions, the anticipation of perceptual effects, and effect representations are of particular importance for action control according to this class of approaches” (p. 2). As evidence they cite (Frank, Land, & Schack, 2015) which determined changes in golf putting performance using three training groups: physical practice, combined physical and mental practice, and no practice. What makes this study unique is that the golfers wore a mobile eye tracker throughout but they did not receive any QE training. Instead, during the mental training portion of combined training they stressed an array of BACS, or “basic action concepts”. At no time were the participants taught the five QE characteristics of elite golfers, but instead they were engaged in exercises designed to develop a more refined mental representation of the golf putt in long-term memory from pre- to post- and retention test. The QE was defined as the final fixation prior to the onset of the backstroke, which is just partly consistent with most QE studies in golf. It is regrettable it was not measured to extend through the backstroke, forestroke and after contact, as normally occurs in QE golf studies (Vickers, 1992, 2007; Vine et al., 2011, Vine, Lee, Moore & Wilson, 2013). QE duration increased for the combined group from a low of around 1000 ms during the pretest to a high of 2300 ms during retention. Unfortunately, it was not clear if the QE was located on the ball or elsewhere, as QE location was not identified, thus preventing discussion relative to **David’s and Araújo’s** question about why an athlete’s perception of objects changes with the development of expertise. The results are intriguing, as it suggests that a long QE duration similar to experts can be developed without using overt QE training. One caveat mentioned by the authors is that the combined group was given twice the amount of putting practice as the physical group; therefore these results await more study.

Schorer, Tirp, and Rienhoff make a number of suggestions for future research and QE directions, including an improved explanation of the mechanisms and theoretical models behind the QE, which have been discussed previously in this paper. An additional, and very important suggestion they make, is that QE training programs need to have greater diversity in order to accommodate the needs of different learner groups. I agree, as the vast majority of QE training studies have followed a blocked training approach, in which the five characteristics of elite performers are taught, followed by blocked, repetitive practice and retention and transfer tests given within the span of a few days (an exception is Miles, Wood, Vine, Vickers, & Wilson, 2015a, 2015b). In agreement with **Williams**, the QE training approach

does recommend that a “decision training” approach is used, as used in the field and described in a number of publications related to teaching sports skills and tactics (Vickers, 2003, 2007; Vickers, Reeves, Chambers, & Martell, 2004). However, there has been limited application or research into the effectiveness of the decision training “tools” in QE training, which include the use of variable and random practice, bandwidth feedback, and questioning. Instead, blocked training is usually used to promote the desired QE elite focus during repetitive trials with little variation.

Causer mentions a limitation of current QE studies, which can have a limited number of acquisition trials and short retention periods. An exception is a series of QE training studies with typical children, aged 9-10, and those of a similar age with developmental co-ordination disability (DCD). Over a series of studies (Miles et al., 2015a, 2015b; Wilson, Miles, Vine, & Vickers, 2013), the five QE characteristics of elite children were taught in a throw and catch task using a part to whole approach with favorable results. Long-term retention was assessed after a two-month period with positive results in favor of QE training. QE training has also been carried out comparing the effectiveness of blocked and variable practice drills in the dart throw (Horn, Okumura, Alexander, Gardin, & Sylvester, 2012). QE duration did improve, but there was no difference in performance accuracy, which may have been due to using radial error as the sole measure of accuracy. The extent to which the participants improved in their ability to hit the target center (bull’s-eye) was not reported.

In terms of future QE training studies, it may be interesting to determine whether learners improve more as a result of knowing about their motor error scores (i.e., knowing what they did wrong), or knowing what they have done right in terms of elite performers’ QE characteristics (i.e., knowing about what is known to work). This question arises from two fundamental approaches to motor skill acquisition, the first based on the assumption that motor learning occurs best when participants receive knowledge of their motor errors, and the second approach based on the assumption they would progress faster when only receiving information about the elite QE characteristics known to lead to success.

The Quiet Eye facilitates emotional control and motor success

Wilson et al. (p.1) state there are few research groups that have

invested more time than most on testing the efficacy of QE training in populations as varied as children with developmental disorder (Miles, Wood, Vine, Vickers, & Wilson, 2015) to experienced sporting performers (Vine, 2011; Wood & Wilson, 2011); in tasks as varied as laparoscopic surgery (Vine, Masters, McGrath, Bright, & Wilson, 2012; Wilson et al., 2011) to machine gun shooting (Moore, Vine, Smith, Smith, & Wilson, 2014)

– a statement I wholeheartedly agree with. Their contribution to the field has been immense, not only in the quantity, but also the quality of their QE studies. There is no question we would not have many insights we have into the QE without the many innovative contributions of this group.

Wilson et al. raise three points in their commentary, first, QE training is effective but we don’t know why (similar to **Causer** and **Farrow and Panchuk**), second, neuroscience studies devoted to identifying the neural characteristics have questionable value (discussed later), and third, there is no real need to identify the QE in other tasks; the more important journey is toward QE theory development, a topic many commenters also agree is important and has been dealt quite extensively thus far.

Wilson et al. do not mention their extensive research into the effects of the emotion and pressure on the QE and motor performance, as in my experience the QE topic that gets the most attention from the public, coaches, athletes, parents, university students and others is why an optimal QE helps individuals perform better under high levels of pressure. Mark Wilson, Sam Vine and Greg Wood have specialized in this topic (Behan & Wilson, 2008; Harvey, Nathens, Bandiera, & Leblanc, 2010; Moore, Vine, Wilson, et al., 2012; Vine, Lee, Moore, & Wilson, 2013; Vine, Moore, & Wilson, 2014; Vine & Wilson, 2010, 2011; Wilson, Vine, & Wood, 2009; Wood & Wilson, 2012). They have brought a depth of understanding in terms of exploring beyond the five QE visuomotor characteristics, encompassing the complex interactions and interplay between state anxiety, visual attention, implicit versus explicit control, challenge versus threat states, perceived control and performance states, choking in motor performance, to name a few topics. Evidence shows the maintenance of an optimal QE helps athletes and others perform better under high levels of pressure. But we don’t know why. Nor do we know what happens within the brain when QE emotional characteristics are non-optimal.

Studies that have determined the QE under conditions of pressure and anxiety are affected by the social context, which most often includes momentary task demands. For example, Vine et al. (2013) had elite golfers perform under the pressure of sinking as many putts as possible out of six attempts. They compared the golfer’s QE on the first and last consecutive hit, and on the first missed shot. QE location on the ball remained similar, as did QE onset before the backswing. QE duration did not differ except for the portion on the green, which is called the QE dwell time – it occurs after the ball is hit and the QE remains rock steady on the green (Vickers, 2007). On hits the elite QE dwell time declined on the missed put from an average of 300-500 ms to less than a 100 ms on the misses, a result also detected earlier by Vickers (1992), although the term “QE dwell time” was not used back then. Why did the short duration of the QE dwell time contribute to the miss? Vine et al. (2013) suggest an error in feed-forward control, which I agree with. One characteristic that I have noticed in testing a number of golfers who have difficulty putting is their use of a rapid saccade just prior to ball contact, caused by their haste in wanting to

see where the ball goes relative to the hole. It takes about 200-300 ms to plan and initiate a saccade (Liversedge, 2011). The golf putt backstroke and forestroke is typically around 800 ms (combined) (Vine et al., 2013). This means that on putts with very short or non-existing QE dwell times the player has initiated an early offset of the QE. Since it takes between 200-300 ms to program a saccade, this means the player had to have initiated the saccade at the end of backstroke, or beginning of the forestroke, which resulted in a shorter QE dwell time and a saccade that negatively affected the alignment of the club head when it made contact with the ball. The motor consequences of this type of QE instability is provided by a number of studies that have found a shorter QE duration during unsuccessful putts accompanied by a change in the lateral direction of the final portion of the foreswing, as well as a tendency of the golfer to lift the club head in the vertical direction as the ball was struck (Moore, Wilson, Vine, Coussens, & Freeman, 2013; Moore, Vine, Cooke, et al., 2012; Moore, Vine, Wilson, et al., 2012).

Gegenfurtner & Szulewski present a compelling argument that everything an expert athlete does is impacted by the social context within which he or she exists. They present a "situated interpretation of expertise" in which "professional vision is conceptualized as a relational phenomenon, accomplished through interactions with other people and with environmental affordances" (p. 2). They propose that "visual expertise is contingent on the social dynamics of the game; [it] is reflexively aligned to the social group; and changes as the social context changes" (p. 2). Referring to Gegenfurtner, Lehtinen, and Säljö (2011), **Gegenfurtner and Szulewski** (p. 1) state they have

tested the predictive validity of expertise theories, QE is missing as a conceptual framework – a mistake perhaps. Our study demonstrated meta-analytically that expertise changes the amount, the speed, and the visual span of information processing in domains such as sports, medicine, and transportation. Experts compared to novices had more fixations of longer duration on task-relevant areas; fewer fixations of shorter duration on task-redundant areas; shorter times to first fixate task-relevant areas; and a longer saccadic length (Gegenfurtner et al., 2011). QE complements and extends these expertise differences with a particular focus on the temporality of attentional resource allocation in visuo-motor coordination; it highlights how significant a few milliseconds of gaze can be before an action is executed.

Furthermore, **Gegenfurtner and Szulewski** provide insightful analyses of expertise in basketball in terms of the performance of Steve Nash, Magic Johnson, and Shaquille O'Neal. They ask why is O'Neal a poor free throw shooter but an excellent shooter from the field. I have a theory about this, having carried out a fair amount of QE training with poor free throw shooters. First, they have been coached by dozens of well-intentioned coaches, and most of them tell shooters like Shaq to keep his fixation on the hoop during the total time he is shooting. I wish I could have gotten an eye tracker on Shaq as he shot free throws, as I

think I would have found the following gaze and motor control characteristics in his free throw but not his field shooting: (a) He does keep his fixation on the hoop throughout the shot, something elite shooters do not do; they cease fixations as soon as the ball passes through their visual field, which is a few centimeters in front of their eyes. (b) In order to accomplish fixating the hoop through the whole shot, he raises the ball above his head and looks under it as this is the only way he can do what his coaches have taught him; other shooters move the ball to the side – and in the process destroy their mechanics. (c) As he shoots in high pressure games this means he has to control his gaze, his hands, his body and his emotions – so he slows the shot down placing it under closed loop control, instead of using open loop control as used by Nash, and now by the current super star shooter Stephen Curry who appears to use the same style for both shots. They shoot rapidly and let the program that set up during the QE run off automatically without interference from their emotions, the crowd or other distractions.

As I read the commentary of **Gegenfurtner and Szulewski**, I was intrigued by their explanation of Messi and his different level of play in Spain and in Argentina, and the importance of "support staff who are exceptionally good themselves in their supporting roles. These networks of athletes and support teams form a rich social platform for professional excellence" (p. 2). This is precisely the point of Ericsson (Ericsson et al., 1993; Ericsson & Pool, 2016) and the need to create deliberate practice and decision training environments. Finally I wondered what would be needed to design an *in situ* study that would determine of a change in the QE due to social context would lead to poor performance. I tentatively defined a change in social context as the change in one or more of the five QE characteristics due to the effect on the performer of an opponent, teammate, coach, game official or a member of the crowd. A humorous real life example comes to mind from the NCAA in which "Speedo Guy" strips off and emerges like a "blooming flower" from the crowd sitting behind the basket (see <https://www.youtube.com/watch?v=8PEXG0mZKcw>). Speedo Guy's victim is the star of the team, an elite shooter who misses both of his free throws. When interviewed later, he states he missed his shots as he was distracted by Speedo Guy and lost his focus. All free throws must be performed within a set time period (usually between 5-10 s depending on the league) and there is pressure to get off the shot in a timely manner. If our elite shooter had been wearing an eye tracker I expect we would have seen a saccade to Speedo Guy behind the basket, and a fixation on him as he emerged like a blooming flower, resulting in less time to stabilize his normal QE fixation on the front of the hoop and perform the shot as he normally does. A QE study could easily be carried out to confirm if this change in "social context" precipitated a decline in shooting accuracy.

Some important methodological issues

Isolation of the QE has always made huge demands on complex eye tracking technology, motion analysis equipment that can range from 1 to 12 cameras, sophisticated eye-head integration and imaging software, and powerful statistical tools that are needed to analyze the data. So it is no surprise that a number of commentaries raise questions about the QE methodologies used. Mark Williams was the first to replicate a QE study after the first studies began to emerge in the late 1990 (Williams, Singer, & Frehlich, 2002). He has been a tireless advocate of the QE, carrying out many studies in both the laboratory and *in situ* environments. I have collaborated with Mark in past studies in table tennis and biathlon shooting (Rodrigues et al., 2002; Vickers & Williams, 2007; Williams, Vickers, & Rodrigues, 2002). He is a close friend, so close indeed, that we often argue and spar over the methods used in QE studies and approaches taken, as he prefers lab based approaches and I prefer the *in situ* environment. **Williams** has four main comments: (a) he laments the paucity of work that has attempted to better identify the causal mechanisms; (b) he feels the three degrees of visual angle used in the QE definition is arbitrary and not based on science; (c) he challenges the use of seven steps in the QE training system; and (d) although *in situ* studies are important, the better and stronger test is to confirm the QE characteristics within the more controlled laboratory setting.

First, **Williams** laments the lack of better explanatory mechanisms underlying the QE, and he has lots of company given many of the commentaries on the target paper, so I will not go into the topic further, except to agree that we need a theoretical rationale for the QE based in the expertise paradigm. Williams and his team will probably be the first to image the QE using MRI in a large project that he is currently leading (c.f., Gonzales et al., 2015). He is going to provide us with the first look at the neural structures of elite and novice archers, during simulated accurate and inaccurate shots in archery, a critical foundation for any QE theory.

Second, **Williams** (p. 2) questions why three degrees of visual angle is central to the QE definition. He states that

the definition of QE has emerged from the operational capacities of the main measurement system used to quantify the phenomenon (i.e., the ASL mobile eye system). Consequently, the definition is somewhat arbitrary rather than being linked to any underlying mechanism (see Gonzalez, Causer, Miall, Grey, Humphreys, & Williams, 2015a). The mobile eye system has a measurement error of ± 1 degree and a sampling rate of 50 or 60 Hz. The operational definition of QE is that the gaze remains within a visual angle of 3 degrees from the target for a minimum period of 100 ms.

The three degrees of visual angle (or less) of the QE has not been arbitrarily chosen, nor does it come from the operation of the ASL Mobile Eye, or any other eye tracker, but instead is derived from the neuro-physiology of the human eye and the

fact there is a very small region located at the back of the retina that is entirely responsible for converting light into information that can be perceived with high acuity by the brain. In order for a person to see with full acuity, light has to pass through the pupil, lens and other parts of the eye and land on the most light sensitive area at the back of the eye called the macula, within which is an even smaller area called the fovea.

Here, in this small area, spanning less than 2 degrees of the visual field, cones are extremely over-represented, while they are very sparsely distributed in the periphery of the retina. This has the result that we have full acuity only in this small area, roughly the size of your thumb nail at arm's distance. (Holmqvist et al., 2011, p. 21)

Consequently, most eye tracking companies have set their default visual angle to 3° for the same reason. All eye tracking companies also let you choose the actual visual angle you want to use, which in QE studies has varied based on task constraints from 1-3° of visual angle. In my first studies (e.g., Vickers, 1992), I used 3° of visual angle due to the inherent neurophysiology of the human eye and found rather robust QE results related to skill level, but less so for accuracy, or the interaction of skill level by accuracy. Once I began using 1° of visual angle, meaning the athlete fixated high acuity information sensed by the very center of the fovea, the skill by accuracy interaction occurred more often. I believe this is due to the more precise gaze control of elite athletes and the superior QE focus they are able to maintain within 1° of visual angle on a critical location and/or object within the task environment (for example, Harle & Vickers, 2001).

Third, **Williams** feels there is no need for the seven QE training steps (which were outlined in the target paper) to carry out a QE training. I disagree. Specifically, he feels that steps 1, 2 and 7 are not part of the training program, and that steps 3 and 4 are simply variants on a decision-training program I developed and have used for many years (Vickers, 2003, 2007; Vickers et al., 2004). Step 1 is the foundation of the QE and QE training, and for this reason the second sections in this response paper has been entitled: *The foundation of the QE lies in the expertise paradigm*. Without knowing what the five QE characteristics of elite performers are, QE training cannot be carried out correctly. Step 2 uses an eye tracker to record the QE of trainees in the same task as was performed by the elite athletes. It is critical they are able to see and compare their own QE to that of the expert prototype, frame by frame. They need to understand how their gaze control and focus of attention differs relative to the best in the world. Having used this process many times it is a powerful training process; athletes rarely argue about making critical changes in their focus and motor control when they see the difference between their QE and that of the best in the world. Steps 3, 4, 5 and 6 are grounded in the decision training approach, which is based on well-regarded and long established motor learning research in practice design, feedback, questioning and other areas central to applied mo-

tor learning. Finally, step 7 reflects testing the effectiveness of the QE in competitive environments, as the strength of any training system can only be assessed by the athlete's ability to withstand uncertainty and pressure. Only a few QE training studies have included Step 7 (Vine et al., 2011). The seven steps are ideal steps, and may be used in whole or part by researchers and practitioners, given the needs and resources they have. I see no problem with this, as a rich training model offers a lot of choice for researchers, coaches, teachers and instructors to select from, as people learn in many different ways.

Finally, **Williams** agrees the QE characteristics should be confirmed in the laboratory setting, as well as *in situ*, a point I agree with. I have just preferred to start with the real world setting, as I know a true discovery must be established within ecologically relevant environments eventually. I am very appreciative when QE results are replicated in the laboratory as additional insights are gained that may not be possible to achieve *in situ*. One has to be careful though how QE studies are carried out in the laboratory, as the use of traditional methods, such as the use of motor error scores as the sole measure of accuracy may be why some QE results that have emerged lately that have been difficult to interpret. This is a critically important topic I deal with in the latter part of this paper.

Another methodological issue of great importance is whether results are similar when the same athletes are tested using a video based (or similar) paradigm, compared to the *in situ* setting. **Foulsham** cites a meta-analysis by Gegenfurtner et al. (2011) in which shorter fixation durations were usually associated with higher levels of performance. Table 9 of this paper lists more than 70 studies in support of this result. However, the studies selected do not include any information where the participants physically performed, *in situ*, under conditions similar to those found in training or competition, but instead in all cases they responded to slides, video films, digital concept maps, static sequences of slides, photographs, and other stimuli that required limited movement. In Vickers (2007, pp. 35-41) I deal with the discrepancy in results found using "visual search" methods, and "vision-in-action" methods in which athletes physically perform during trials similar to those that occur in the real world. In vision-in-action studies, participants use fewer fixations of longer duration on a specific location. Only a few studies have tested athletes in both environments, one by Dicks, Button, and Davids (2010) who tested the same elite soccer goaltenders in five conditions. Three conditions required they respond in a visual search laboratory setting where they viewed videos showing an elite player performing penalty kicks on the goal, and two conditions occurred on the field where the same goaltenders had to stop penalty kicks made by the same kicker from the same angle as appeared in the videos. When the athletes responded to videos, the number of fixations was significantly higher on more locations and their duration was shorter than when they performed in the real world setting. On the field against a real penalty taker, their fixations were fewer and of longer duration to fewer locations.

QE studies have consistently shown an optimally long duration QE is a characteristic of elite athletes, even when the movements made by the athlete are fast and dynamic (see **Mann et al.**'s discussion of the "efficiency hypothesis" above). Elite athletes take longer to process information from fewer locations, while near-elite or lesser skilled athletes use more fixations of shorter duration during successful versus unsuccessful trials. For example, in Panchuk and Vickers (2006, 2009; Panchuk et al., 2016), eight elite ice hockey goaltenders attempted to stop shots taken by an elite shooter from distances of 5 m and 10 m. During saves their QE duration on the puck as it was released from the stick was significantly earlier and longer than when goals were scored. It appears that when you ask an elite athlete to respond to videos where there is less urgency involved, they take their time to look around, resulting in a greater number of fixations of shorter duration to more locations. In contrast, when you place them in a real-world situation where they have to stop a puck or ball coming at them at over 120-150 km/h, they exhibit an earlier QE onset and an extended focus using a longer QE duration before the final saving action is made with the hand, stick, foot or body.

Additional insight to why differences in these results have been found is provided by Foulsham et al. (2011), who examined differences when being immersed and moving in the world compared to when viewing video clips taken from the perspective of a walker. In both conditions, the participant tended to centralize their gaze in front, rarely looking to the edges of the scene. Centralizing the gaze on a "visual pivot" involves centering the gaze in a display and the use of peripheral vision to monitor the action. Visual pivot locations have been identified in gaze and QE studies in soccer (Piras & Vickers, 2011; Williams & Davids, 1998), and ice hockey (Panchuk & Vickers, 2006, 2009; Panchuk et al., 2016). Foulsham et al. (2012) found that when participants walk in the real world, their gaze is located down onto the pathway directly in front of them, in a manner similar to that reported in previous locomotion studies (Hollands, Patla, & Vickers, 2002; Patla & Vickers, 1997, 2003). When the participants watched themselves and others walking along the same parts of the pathway, they tended to look further ahead into space when watching a video, but they looked at more immediate locations in the real world, a difference Foulsham et al. (2012) attributed to the greater need to be sure the feet moved effectively and safely when actively walking versus watching. Differences also emerged in how the participants fixated persons walking toward them. In both conditions participants looked at people in the distance for equal amounts of time, but when they came close, and in particular crossed their pathway in front within a time window of 3 s, the active walker rarely looked at them, which occurred more often in the lab. Two reasons are given for the difference, the first being related to time needed to program the gait to avoid a collision, and the second due to the "authentic social context" afforded by the real world and the fact an approaching person can look back at you. People avoided eye contact in the live setting, as opposed to watching a video of the same individual (Laidlaw, Foulsham,

Kuhn, & Kingstone, 2011). In gaze/QE studies in ice hockey (Panchuk & Vickers, 2006, 2009; Panchuk et al., 2016), and soccer (Piras & Vickers, 2011) it is rare to find a high percentage of fixations located on the head of the opponent. This is because it is too easy to be deceived by a head fake, so athletes learn to avoid looking at an opponent's eyes or head and instead center their gaze on the middle of the chest, or on the torso, which are more reliable cues of the opponent's impending actions. In terms of future studies it is recommended that more studies be carried out in which the same participants interact with a video, slide or simulation of a movement, compared to when they are performing the task *in situ*.

A number of authors also mentioned that what we know about the QE is limited by eye tracking technology that can only collect eye data at 30 and 60 Hz, or at the rate every 33.33 ms (video frame rate) and 16.66 ms (video field rate), respectively, and additionally may not be as accurate in the field setting as found in the laboratory (**Causer; Foulsham; Klostermann et al.; Williams**). Helsen, Starkes, Elliott, and Ricker (1998) explored whether a fast eye tracker (120 Hz) provided more information than one at a slower rate (60 Hz) during a fast aiming laboratory task in which participants moved the eyes and hand freely. They found limited differences in hand movements and gaze and concluded that "even for a simple manual aiming movement done as fast as possible, data at 120 Hz showed very little advantage over that at 60 Hz" (p. 623). In the same vein, Panchuk and Vickers determined the gaze and saving movements of elite goaltenders at 60 Hz (Panchuk & Vickers, 2006) and at 30 Hz (Panchuk & Vickers, 2009; Panchuk et al., 2016), respectively, and found no differences that could be related to the data collection rate.

Spering and Schütz state that "the functional significance of QE for performance in targeting and interception tasks has not yet been established" (p. 1). Specifically they ask: "Does QE boost performance by enhancing visual processing of target information? Or does it serve to ignore distracting context information? Or is QE simply a byproduct of improved prediction?" (p. 2). They provide "direct evidence for perceptual benefits of smooth pursuit, fixational and predictive eye movements and outline potential mechanisms underlying these benefits" (p. 1) in an "eye soccer" simulation of the soccer penalty kick. To this end, they refer to Spering, Schütz, Braun, and Gegenfurtner (2011) who recorded the fixation and smooth pursuit eye movements (at 100 Hz) of undergraduates as they viewed the ball moving at speeds of 100, 300 and 500 ms on a monitor. Undergraduate participants had to judge whether the ball hit or missed the goal. They found prediction was better when pursuit tracking was on the ball during flight, rather than when it was fixated prior to the kick, a result that differs from soccer studies carried out *in situ*. A longer trajectory did not affect performance. They suggested that "during pursuit, an efference copy signal might provide additional motion information, leading to the advantage in motion prediction" (Spering et al., 2011, p. 1756).

Piras and Vickers (2011) carried out a similar study, but had skilled goaltenders respond to penalty kicks delivered using the instep or inside of the foot of skilled players in a soccer field setting. Ball flight times for instep kicks averaged 397 ms, which was similar to that reported for elite world-class kickers, a time that was also midway between the 300 and 500 ms used by Spering et al. (2011). They found few tracking gaze on the ball during flight. Instead, the location of the QE was on a visual pivot location between the kicking leg and the ball prior to the foot contact, which occurred before the goaltender rapidly stepped left or right to save the ball. In order to stop a penalty kick traveling at top speed from a distance of 11 m, a soccer goaltender has to initiate the saving action before the penalty taker kicks the ball. It would therefore be good to see if the "eye soccer" simulator would provide similar data using a life size video simulation in which the participants have to make a decision in the direction of the kicks by stepping as rapidly as possible left or right (as in a game) simulating the movements made during attempted saves (see method in Savelsbergh, Williams, van der Kamp, & Ward, 2002). If they react as in games, once the ball is kicked the dynamic stepping actions left or right perturbs the gaze and prevents smooth tracking on the ball, unless the flight path is directly at the goaltender when a short period of early eye tracking has been found. Given that the eye tracker used by Spering et al. (2011) recorded at a faster rate (100 Hz), it would be interesting to see if they are able to record pursuit tracking data we missed at the slower rate (30 Hz).

Spering and Schütz also mention that the QE is never quiet – which is true. The retina needs to be constantly refreshed with a new image and this is achieved through microsaccades and other miniature eye movements (Liversedge, 2011). Recently, a study recorded microsaccades in table tennis (Piras, Raffi, Lanzoni, Persiani, & Squatrito, 2015). The authors report microsaccades are conditioned by objects that attract visual attention and not by the direction in which the action is expected to be performed. Since Piras previously carried out a QE study in soccer (Piras & Vickers, 2011, discussed above), he also provides an interesting discussion on the relationship between microsaccades and the QE relative to the visual pivot (Piras et al., 2015).

Wilson et al. question whether using advanced imaging techniques like magnetic resonance imaging (MRI) or functional MRI (fMRI) or diffusion tensor imaging (DTI) will ever provide valuable information about the QE; they doubt much can be learned from "pretty brain pictures while participants lie in scanners" (p. 2). I tend to disagree. We need to know how differences in the QE affect the timing of the various neural structures and the subsequent effect on motor performance, leading to what **Causer** aptly calls "the QE advantage" (p. 1) and a deeper understanding of the "neural correlates of QE, which may give researchers a better understanding of the link between performance and QE" (p. 2), a topic stressed by many of the commentators. For example, if the structures in the dorsal network are activated early (QE onset) and maintained for an optimal period of time (QE duration) without ventral route activation, then the prediction is that motor performance will be

better. On the other hand, if the dorsal network is activated first and then the temporal regions later then it is predicted performance will suffer due to the intrusion of distraction, fear, anxiety and a host of other causes. It is true that the technology needed to measure these events requires the person be an observer of the action with limited movements, but brain imaging technology is evolving at a fast pace and to the point where we know (or can come to understand) which parts of the brain are activated (MRI) and when areas are activated given different stimuli (fMRI). Knowledge increases weekly about how electrical impulses (EEG), water molecules (DTI) and a myriad of other signals travel through the brain, relative to certain types of tasks and motor stimulation (EMG), and the effect these have on motor outcomes. Just as eye trackers are now mobile, easy to use and resistant to loss of calibration, so too will brain-imaging devices one day become mobile, light, and useable within *in situ* environments. In time, we will know how changes in the QE translate into improvements in the brain as a result of QE training.

Just as my colleagues have a concern about some methods used in QE studies, I too have one concern, and that is the lack of explanation I have observed in some QE papers which fail to describe how the researcher isolated one or more of the five QE characteristics. Most egregious of all are studies that simply state they used the software that ships with the eye tracker. All eye trackers ship with on-board software that automatically provides the x- and y-coordinates of the gaze in space. These x/y digital files are produced automatically and are completely ignorant about the location of fixations in the task environment, nor are they capable of indicating when fixations occurred relative to specific phases of the movement. Procedures that accurately couple perception and action have to be developed by the researchers, who need to specify, first, how they identified the location, onset and offset of the QE (Was it coded manually frame by frame on video, or by using software programs that allow to identify critical areas of interest?). Second, they need to explain how they coupled the external cameras and/or motion devices with the participants' gaze across phases of the movement; and third, how they determined which phase of the movement was the most important in terms of overall accuracy. All of these procedures should be made clear by researchers, and closely scrutinized by journal editors and reviewers.

The QE at a crossroads: The QE paradigm is distinct from the ML&C paradigm

It is clear from the comments above that QE research has been very successful to date, but after 20 years of QE research some commentators mention that the QE is at a critical crossroads, a statement I tend to agree with (**Baker and Wattie; Casner; Williams; Wilson et al.**). In a paper cited often by some commentators authored by Gonzalez et al. (2015) they state that there are "limitations surrounding the QE definition and measurement techniques, as well as the potential impact these have on the

interpretation of current literature" (p. 2). As evidence this publication presents results from a number of papers in which the QE results did not "reveal the causal relationship between QE and performance they expected" (p. 3). In my opinion there are two causes for some of the concerns expressed. First, there has been gradual departure from the early methods used to detect the QE, and the adoption of more traditional ML&C methods and their reliance on motor error scores as the sole measures of performance accuracy, without recognition of the standards of excellence from the sport or profession being investigated. Closer inspection of Gonzalez et al. (2015) shows the majority of the studies cited as evidence used motor error scores as the main measure of accuracy, which differs from how accuracy is normally determined in QE studies. Second, there has been a failure to recognize that the QE's origin is in the expertise paradigm, and that all investigations in a motor task should begin by first determining what the five QE characteristics are of elite performers. A number of QE studies have used novel tasks, for which no standards of expertise have first been established. Indeed, in some QE studies it is hard to determine if anyone was accurate as this data is not reported.

In the original QE studies by myself and others (Behan & Wilson, 2008; Mann et al., 2011; Panchuk et al., 2016; Rodrigues et al., 2002; Vickers, 1992, 1996a; Vickers & Adolphe, 1997; Vickers et al., 2002; Vickers, Rodrigues, & Edworthy, 2000; Vine et al., 2011, 2013; Williams, Singer, et al., 2002; Wilson & Pearcy, 2009), elite and near-elite athletes were tested on repetitive trials until an equal number of hits and misses were achieved (usually 10 trials of each). All accurate trials were used, and matched with missed trials that occurred just before or after, in order to control for practice effects. The five characteristics of the QE were then determined based on trials when the participants achieved a state of 100 % pure success versus 100 % pure failure, with success and failure being defined by the sport or profession being investigated. The original thinking was that only on successful trials would athletes optimally organize the billions of neurons in the brain that are used to plan, initiate and control the movement, while during inaccurate trials deficiencies would occur in neural activation and timing leading to the athlete focusing on the wrong QE location, or being too early or too late picking up critical information (QE onset), relative to a specific phase of the movement (QE movement). They may not hold their gaze long enough or too long (QE offset) leading overall to a period of focus and attention (QE duration) that was non-optimal.

In contrast, when QE studies are carried out using the ML&C paradigm, a set number of trials are completed per condition (usually 10-20) and an error score calculated such as absolute error (AE), variable error (VE), radial error (RE), root mean square error (RMSE) or percent accuracy (%). Hits and misses are combined (and confounded) and no true measure of performance accuracy determined. The QE is then determined relative to the average error score. Rarely do these studies relate the average motor error score obtained to standards of excellence from the sport or profession being studied. This approach has direct

impact of reducing the chance of accurately detecting the QE associated with the highest level of accuracy, which in turn affects QE training, which is based on the QE of elite performers when completely accurate. More importantly, this means norms for elite performers can never be determined accurately for the five QE characteristics, thereby providing a stable foundation for QE training.

The study of pure motor accuracy: The neglected variable

In the short period of time available for this response, I carried out an informal review of books and papers that I have collected over 25 years of teaching ML&C at undergraduate and graduate levels. I looked for any study reporting motor errors scores during hits versus misses, success vs. failure, etc. Overall, I found some studies within the laboratory setting, for example, Elliott, Binsted, and Heath (1999), Heuer and Sulzenbruck (2013), Van Halewyck et al. (2014), but I found very few in the field setting. Instead, in most papers successful performance is defined simply when motor errors scores were low, and unsuccessful motor performance when they were significantly higher, with little regard for the standards of excellence that may exist in the task being investigated.

More importantly, when motor errors scores are computed for sports tasks, in particular, they are biased toward failure, due to the inherent nature of competitive sport. A sport task does not become a cultural and competitive success unless it is hard to perform and where only a few are able to achieve to the highest level. For example, in baseball hitting, the best batting averages are in the .350 range, which means 65 % of pitched balls are not hit or hit poorly. The hole in golf is only 10.8 cm in diameter and the chances of making a one-putt is reserved for the very best. If the originators of the sport had made the hole 30 cm wide I doubt anyone would bother to play the game as it lacks the challenge that humans perversely enjoy. Since most ML&C studies include only 10-20 trials per condition, the likelihood of actually accurate trials occurring is low, so low indeed, that it has been too difficult to analyze accuracy or the interaction of skill level by accuracy given the limited statistical tools available in the past.

Recommendations for future QE studies

The main strength of the QE paradigm is the isolation of true states of accuracy, as defined by the sport or profession. Its main weakness is the large number of trials that must be performed by some participants before they achieve 10 hits and 10 misses (or an acceptable number of each). For example, if testing a basketball player who is 90 % accurate in competition, it can take more than 100 trials before recording the 10th miss. Thankfully there are very few 90 % participants, so data collection in these situations is manageable. The greater problem is when testing novices who find it hard to complete a large number of trials due to their low skill level, level of fitness and/

or motivation. Performing many trials is also not advised when testing children and those with disabilities. The main weakness of the ML&C paradigm is its inability to analyze pure states of accuracy and failure, as described above; its main strength is the set number of trials performed per condition and its long history of scientific achievement.

Going forward, I would like to make a couple of recommendations in terms of how QE studies should be carried out in the future. First, in motor tasks where the researcher's goal is to determine the QE characteristics due to accuracy as defined by a sport or professional area, then participants should be allowed to perform until they achieve an equal number of successful and unsuccessful trials (the traditional QE paradigm). Second, if it is not possible or preferred to use this approach, then the number of trials should be increased to 30-50 per condition, thereby giving participants a greater chance to record hits and misses. Newer statistical tools are able to analyze data sets with unequal number of hits and misses, unequal numbers of participants and missing and partial data, something that was difficult to do in the past. One of the newer models that is growing in use is an advanced regression technique called graduated estimating equation (GEE), which accommodates predictors such as skill level (high or low), accuracy (e.g., hits versus misses), and repeated tests (pre-post-transfer) as occurs in QE training studies, along with a measure of motor error (AE, RE, etc.) which is entered as a co-variate (for an excellent overview of the newer models, see Fitzmaurice, Laird, & Ware, 2011, which provides a number of applied examples). Finally, and to conclude this section, it is clear that when one looks at the history of research in ML&C, there has been a lack of research that explains the underlying neural, perceptual and cognitive foundations of pure motor accuracy, especially in sport and the applied professions, making it a field that offers great opportunity for those willing to accept the challenge.

Conclusion

It has been a very stimulating journey the last few weeks reading and responding to the many excellent comments made by the reviewers. The future of the QE has never been brighter and hopefully the recommendations made by the commentators and myself within this paper will stimulate new and improved directions. **Baker and Wattie** provide a number of further recommendations in terms of future goals in QE research which I agree we should work towards: First, they state there needs to be *replication* of QE results, which can only be achieved through greater stabilization of the methods used to collect QE data, a topic that has been raised often in this response. Second, they state that we need to provide a solid *explanation* for the QE phenomenon. In particular, they stress a need to understand the underlying neural foundations, a topic treated extensively by a number of commentators, with some excellent suggestions. Third, they recommend an *extension* of QE to more sports, medical and other motor tasks, a suggestion I strongly

agree with. The QE has only been identified in 28 motor tasks to date, and QE training only in nine. We need to establish elite norms for the five QE characteristics in as many sports tasks as possible, as this is needed to establish the solid base for QE training. Fourth, they recommend QE results be extended to other *concepts*, such as the fields of vision and transfer of learning. A number of old and new concepts have been suggested by the commentators, in particular: efference copy/corollary discharge, the efficiency paradox, simultaneous spatial localization, rapid resumption of search, social dynamics, ecological dynamics of the QE, the inhibition hypothesis, passive and active search, to name a few. Fifth, they state that *application* is the greatest real world impact of the QE, as it is a variable that is easily understood by athletes, coaches, trainers and others and that can be rapidly put into action in sport and other motor areas through QE training.

Finally, it appears a specific area of sports science does not become an established discipline until new professionals are certified, as occurs in exercise physiology or sports medicine. It might therefore be time to talk about what is needed to certify individuals as QE professionals. A number of professionals come to mind: *QE trainers* would be neuro-motor acquisition specialist whose primary job is helping participants at all age and skill levels to master the five QE characteristics. There is also a need for *QE instructional designers* who know how to develop elite prototypical videos and web portals that deliver task-specific QE training and feedback. *QE engineers, technicians and programmers* could improve mobile eye trackers and develop software being adepts at coupling perception and action in specific motor tasks. Other careers would be in *QE rehabilitation*, working with children with disabilities, such as DCD, ADHD, autism and other areas, and with the elderly in terms of improving balance and locomotion. Beyond, there are tremendous opportunities in medicine, in particular, in surgery and emergency medicine, and military and police organizations are also interested in QE training to improve performance and decision making skills under the highest level of stress.

In conclusion, the journey the QE has taken the past 20 years has been exceptional and it is due to the tremendous dedication of many – including those who have provided commentaries on this target article. I enjoyed reviewing QE studies that have been done in the past, and reading for the first time the papers of many who are new to the area and contributed to this volume. I apologize for omitting some excellent suggestions, due to length considerations, for the current response, however, I want to thank all commentators – because of your efforts state the future of the QE is exciting and limited only by our imagination.

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Data Availability Statement

All relevant data are within the paper.

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