Current Issues in Sport Science 1 (2016)

The Quiet Eye: Reply to sixteen commentaries

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TA RESPONSE

Article History:
Received 1st September 2016
Accepted 7th September 2016
Published 13th October 2016

Handling Editor:
Ernst-Joachim Hossner
University of Bern, Switzerland

Editor-in-Chief:
Martin Kopp
University of Innsbruck, Austria

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

Citation:
Vickers, J. N. (2016). The Quiet Eye: Reply to sixteen commentaries. *Current Issues in Sport Science, 1:118*. doi: 10.15203/CISS_2016.118
This is a response to commentaries on a CISS target article authored by Joan N. Vickers. For retrieving the whole target article including index of contents, editorial, main article, all peer commentaries and author's response:
Hossner, E.-J. (2016). Quiet Eye research – Joan Vickers on target. *Current Issues in Sport Science, 1:100*. doi: 10.15203/CISS_2016.100

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 (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

2016 | *innsbruck* university press, Innsbruck
Current Issues in Sport Science | ISSN 2414-6641 | http://www.ciss-journal.org/
Vol. 1 | DOI 10.15203/CISS_2016.118

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 underling 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). ***Causer*** 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 (Causer, Bennett, Holmes, Janelle, & Willams, 2010; Causer, 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, Ranvaud, & 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 (shot gun 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 ***Causer***, 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 moreso 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, orienteering, 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 ***Davids 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 Szulweski*** (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 motor 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 uncertainly 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 tension 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***; ***Causer***; ***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.

Funding

The author has no funding or support to report.

Competing Interests

The author has declared that no competing interests exist.

Data Availability Statement

All relevant data are within the paper.

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