Identifying the causal mechanisms of the quiet eye

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Short title: functional mechanisms of the quiet eye

Identifying the causal mechanisms of the quiet eye

Abstract

Investigations into the gaze strategies employed by athletes have determined that longer quiet eye (QE) durations (QED) are characteristic of skilled compared to less-skilled performers. However, the cognitive mechanisms of the QE and, specifically, how the QED affects performance, are not yet fully understood. In this review we integrate research that has examined the functional mechanism underlying QE and based on these observations, discuss the underlying neural networks that may be involved. We also highlight the limitations surrounding QE measurement and its definition and propose future research directions to address these shortcomings. Investigations into the behavioural and neural mechanisms of QE will aid understanding of the perceptual and cognitive processes underlying expert performance and the factors that change as expertise develops. This research has important implications for the development of expertise in sports as well as in other fields including medicine and amongst clinical populations to develop and enhance goal-directed action.

Key words: gaze, programming, attention, expertise

The Quiet Eye

In recent years, attention has been devoted to the investigation of gaze behaviour to identify the perceptual and cognitive factors involved in expert performance across different sports, as well as in other domains. Vickers (Vickers, 1992) highlighted distinct gaze patterns that differentiate expert and novice golfers while performing putts and identified that experts kept a steady fixation at a specific location before ball contact. This steady fixation just before movement initiation was later identified in basketball players and termed "quiet eye" (QE; Vickers, 1996).

The QE corresponds to the final fixation within 1–3 degrees of visual angle and a duration of at least 100 ms prior to a movement. Longer quiet eye durations (QED) are exhibited by experts compared to non-experts, while within-participant analyses also show that they are characteristic of successful compared to unsuccessful attempts, (Vickers & Williams, 2007; Vickers, 1996). In addition, with the use of video-based mobile eye tracking systems, these findings have been replicated across various types of aiming and interceptive sports including shooting (Causer, Bennett, Holmes, Janelle, & Williams, 2010), darts (Rienhoff et al., 2013), billiards (Williams, Singer, & Frehlich, 2002), table tennis (Rodrigues, Vickers, & Williams, 2002), and football (Piras & Vickers, 2011).

A number of researchers have successfully used the QE as a training tool to improve performance in different targeting sports (Causer et al., 2011; Moore, Vine, Cooke, Ring, & Wilson, 2012; Vine & Wilson, 2011) and recently, outside of the sporting area such as when training surgical skills (Causer, Harvey, Snelgrove, Arsenault, & Vickers, 2014). In these studies, QE training aimed at increasing QED (where to look and for how long), results in enhanced performance linked to relative increases in QED (for a detailed review, see Vine,

Moore, & Wilson, 2014). However, whether or not the duration of the QE *per se* causes these improvements in performance and how these benefits come into place are still subjects of interest. This research has highlighted the need to better understand the underlying mechanisms of QE and, in particular, investigate the beneficial effects of the QE on performance to implement effective training protocols (Behan & Wilson, 2008).

Much of the research on QE has focused on identifying distinct QED effects amongst expert and novice performers and in evaluating the training of QE as a performance-enhancing technique. A review that focuses on the latter and on learning under anxiety can be found in Vine et al. (2014). Vine et al. propose three potential explanations (attention control, focus of attention and response planning) of how QE may benefit performance and expedite learning. However, they only present one study in which the QE was directly manipulated and questions about the causality of the QED on performance still remain. In addition, limitations in the QE methodology have not yet been adequately addressed. Thus, in this paper, we review current research aimed at investigating the underlying mechanisms of the QE and the effects of directly manipulating it. Moreover, based on this current research, we propose potential neural networks that may be involved in QE. These notions may provide further insight into the facilitatory effects of longer QED on performance. In addition, we aim to highlight limitations surrounding the QE definition and measurement techniques, as well as the potential impact this may have on the interpretation of current literature. Finally, we propose future research directions to better understand the critical processes involved in QE.

The programming hypothesis

The QE is suggested to facilitate information processing and its duration reflects the time needed to program and fine-tune a response (Vickers, 2009). Long QEDs are suggested to extend the critical motor preparation period that consists of response selection and the fine tuning of movement parameters for motor programming (Moore et al., 2012). Williams et al. (2002) manipulated the complexity of a billiards shot (near versus far) as well as the time needed to complete a specific shot and demonstrated that QEDs were longer in skilled performers and in successful compared with unsuccessful shots. These authors further demonstrated longer QED with increasing levels of task complexity and when increasing the time needed for motor programming, in skilled and less-skilled billiard players. This evidence supports the programming hypothesis, as longer QEDs were observed in more complex tasks that required more information processing and longer programming times (Vickers, 2011).

Horn, Okumura, Alexander, Gardin, and Sylvester (2012) investigated QED and the effects of variable versus blocked practice in a dart-throwing task. They hypothesized that random target changes (to different targets at similar distances) would produce longer QED due to the increased programming demands of having to parameterize the response from one trial to the next, compared to the consistency of the blocked target presentation (same target and distance). Although performance (accuracy) differences between the practice groups were not apparent, longer QEDs were indeed observed during random compared to blocked practice and likely reflected the heightened cognitive effort during random practice to compensate for the additional task demands (increased on-line movement parameterization) (Figure 1). Horn et al. (2012) concluded that the longer QED was a functional element of programming demand rather than a by-product of successful aiming.

-Insert Figure1-

As with previous research, however, the QED effects on performance found in Williams et al.'s (2002) and Horn et al.'s (2012) studies were shown as a correlation of performance and did not reveal a causal relationship. In a recent study, Klostermann, Kredel and Hossner (2013) investigated the performance-enhancing effects of experimentally manipulated QED by varying response selection and stimulus identification demands. In their experiments, participants took part in an externally paced throwing task in which the onset of the last fixation and the amount of information to be processed were manipulated by presenting the target at different timings (short and long presentations) and locations (random and predictive) during movement unfolding. They showed that the facilitatory effects of longer QED on performance were apparent under a high information-processing load; however, QED effects seemed to disappear with increased predictability of the target's location and decreased task demands (Figure 2). Klostermann et al. (2013) argued that the predictability of the target might have facilitated relevant information processing that was not required during the QE period; consequently, QED effects were "dispensable" with high predictability and low task demands. This finding suggests that on-line control may have an important role for QE during aiming tasks (cf., Horn et al., 2012), highlighting the need to investigate these mechanisms while maintaining information load constant, as proposed by Klostermann et al. (2013). These data, together with Williams et al.'s (2002) and Horn et al.'s (Horn et al., 2012) findings, provide evidence for functional links between information processing and the effects of prolonged QED on performance. However, the precise

information that is important remains unclear; furthermore, additional mechanisms could

be involved, including the effective allocation of attention for information extraction.

-Insert Figure2-

QED and attentional focus

The allocation of visual attention is influenced by two control processes which include a

volitional (top-down) and a stimulus-driven (bottom-up) network (Corbetta & Shulman,

2002). Explanations of the QE have integrated these processes and the QE has been

suggested to aid the allocation of attention to relevant cues, while suppressing responses

from other stimuli (top-down control) (Vickers, 1996). It has also been suggested that, in

particular, external allocation of attention is responsible for the beneficial effects of the QED

on performance, as shown in QE training studies. Moore et al. (2012) showed that a QE

trained group developed longer QED and better performance compared to a technical

trained group during a golf putting task. The authors suggested that the benefits of the QED

derive from better response programming, yet the role of attentional focus (external focus)

was also highlighted, which possibly promotes longer QED, or is enhanced by the longer

QED (Moore et al., 2012; Vine & Wilson, 2011).

The facilitatory effects of an external focus of attention on motor performance and skill

acquisition have been previously described (for a review, see Wulf, 2007). It has been

suggested that an internal or an external focus of attention disrupts or facilitates automatic

control mechanisms respectively, and that the utilisation of these automatic processes results in decreased attentional demands, smaller movement adjustments and faster learning (Wulf, Shea, & Lewthwaite, 2010). Klostermann et al. (2014) also examined the links between QED and focus of attention. Their results replicated previous findings, in that instructed external focus resulted in better performance and experts exhibited longer QEDs. However, their correlation-based findings did not provide support for a performance-enhancing effect of the longer QED with an external focus of attention. It is worth noting that their instructions varied from previous research in order to exclude the impact of directing the participant's gaze behaviour, and the authors themselves expressed caution when interpreting these results. Klostermann et al. (2014) suggested an alternate explanation for their findings related to an inhibition hypothesis. It follows that the positive effects of longer QED are explained by the need to inhibit alternate movement variables to allow for the effective parameterisation of a single movement. Further research is needed to replicate these findings to provide support for this hypothesis.

It is possible that some aspects of external attention allocation are important for QED; however, to date the potential explanations with respect to attention allocation (i.e., movement automaticity or "constrained control theory" and a working memory load hypothesis) have not been experimentally related to QE, and more research is needed to probe both phenomena. In addition, given that gaze is typically directed in most QE training protocols, the effects of focus of attention may be influenced by these instructions as suggested by Klostermann et al. (2014). Moore et al. (2012) conducted a QE training study in golf and only included instructions related to gaze control for the QE training group compared to a technical trained group. They found that the QE trained group exhibited more expert-like putting kinematics indirectly associated with an external focus of attention (also see Causer et al. 2011). Moore et al. (2012) suggested that future research should

implement more than one group to manipulate focus of attention and further understand the benefits of QE training.

The current QE research is mainly focused on identifying the functional links that explain the effects of performance-enhancing QEDs. To date, the hypothesis based on the information processing load of motor programming (Williams et al., 2002) seems to be a suitable explanation for the QE phenomenon. Given that the QED effects have been successfully observed under experimentally controlled conditions (Klostermann et al., 2013; Williams et al., 2002) and during virtual tasks (see Behan & Wilson, 2008), it seems promising that the mechanisms explaining the benefits of the QE can be further explored in a controlled environment. From the studies included in this review, the QED effects on performance are not clear-cut, in that longer QEDs do not always correlate with better performance, as in Horn et al. (2012). The relative contribution of the QED on performance may be addressed through these controlled QED manipulations to identify why, how and when the QED effects manifest during targeting tasks. We further propose the investigation of the neural mechanisms that are involved in QE using these controlled manipulations that replicate the QE effects obtained in previous field research.

Functional mechanisms of QE: psychophysiological evidence

Visually-guided tasks such as targeting tasks require the accurate visual acquisition of a target, the integration of visual and proprioceptive (afferent) signals for motor programming and response selection to generate a motor response (Balslev, Miall, & Cole,

2007; Emma Gowen & Miall, 2006). The frontoparietal networks, particularly the posterior parietal cortex (PPC), are suggested to be involved in the integration of signals related to eye and limb movements (van Donkelaar & Staub, 2000). During these processes, internal representations of eyes, limbs, and the target are formulated together with predictions of the sensory consequences of the motor response (Wolpert, Ghahramani, & Jordan, 1995), and may also engage the cerebellum in this predictive process (Miall & King, 2008). Similarly, the allocation of visuospatial attention includes areas within the frontal and parietal lobes (Corbetta et al., 1998). It is evident that a tight coupling between visual attention orientation and the processing of the motor components of the task at hand is important for performance (Behan & Wilson, 2008).

Attention, eye movements and QE

 The networks activated during the allocation of spatial attention include the frontal eye fields (FEF), dorsolateral prefrontal cortex (DLPC) and PPC; areas that have also been individually associated with the control of eye movements. There is evidence supporting the strong links between attention and eye movements (Moore & Fallah, 2001, 2004; Rizzolatti, Riggio, Dascola, & Umiltá, 1987). Furthermore, it has been shown that attention allocated to a fixation point results in a "suppression" (reduced saccade amplitude and velocity) of the oculomotor system (Goldberg, Bushnell, & Bruce, 1986), suggesting that actively fixating on a location results in attention allocated to that point and not to a peripheral location. Thus, there seems to be extensive overlap between programming and attention networks as well as with areas involved in oculomotor control.

The definition of the QE implies the suppression of large eye movements between 1—3 degrees of visual angle and an enhanced ability to fixate on relevant cues and supress responses to irrelevant stimuli for a more efficient extraction of information. However, given the definition, a fixation of 100 ms may not be long enough to allow the shift of conscious attention, for example, saccade reaction times take about 200 to 250 ms (Saslow, 1967) after a stimulus is perceived and also, studies involving neuroimaging have shown perceptual processing of visual stimuli occurring > 100 ms (Pins & Ffytche, 2003). It is also important to note that the term "fixation" at 1-3 degrees of visual angle is determined by the technological limitations of current gaze trackers and may encompass other types of small eye movements within this definition. These eye movements may be used as a favourable strategy of a given task; for example smooth pursuit in golf putting, saccades during basketball throwing. FEF involvement is likely candidate given the close integration between the frontoparietal network and eye movement (fixation, saccade and pursuit) networks (Corbetta et al., 1998).

With respect to the "quiet eye" terminology, it is worth noting that the eyes are seldom "quiet" in that small eye movements occur during visual fixation. Fixational eye movements are essential for natural vision (McCamy et al., 2012) and include small (low velocity) drifts as well as (high velocity) microsaccades (< 1 degree occurring 1-2 per second) that contribute to fixation stability and prevent perceptual fading of a stationary object; however the precise role of microsaccades in long fixations remains controversial (for review see Collewijn & Kowler, 2008). A recent study investigating fixational eye movements (drifts and microsaccades) during distinct fading conditions, supports previous notions that microsaccades prevent and correct visual fading during prolonged fixation (McCamy et al., 2012). Furthermore, the size and frequency of the microsaccades determined the effectiveness of counteracting foveal and peripheral fading (McCamy et al., 2012).

Microsaccades can be suppressed during fine visual tasks, suggesting they may be modulated by attention, similar to larger saccades. For example, a higher rate of microsaccades to one side may indicate parafoveal information processing during visual fixation, as indicated by (Engbert & Kliegl, 2003), who investigated microsaccades during covert attention. Microsaccades during fixation appear functionally related to saccadic intrusions, which are also influenced by the shift of attention (Gowen, Abadi, Poliakoff, Hansen, & Miall, 2007). Thus, the amplitude and frequency of eye movements may provide important insights into the links between oculomotor control, visual perception and the allocation of attention in expert performance, which may be explored within the QE. Very small amplitude oculomotor noise is unlikely to disrupt vision; however, even moderate head motion requires the involvement of oculomotor compensatory mechanisms, such as the vestibulo-ocular response, optokinetic reflexes, smooth pursuit or saccades. This again suggests that other gaze behaviours may be occurring in the measured QE.

Motor programming, response selection and inhibition networks

It is suggested that the ability to maintain attention and ignore/suppress external stimuli, also found to be frontally controlled (FEF and DLPFC, DeSouza, Menon, & Everling, 2003) and a characteristic observed in expert performers, aids the programming and execution of a motor response. This selective process is therefore important during the aiming period in a targeting task. Vickers (1992, 1996) supported this suppression hypothesis (also see Klostermann et al., 2014) after observations of a QE offset during movement initiation, that is, eye movements outside of the QE threshold. Vickers (1996) suggested that this suppression behaviour prevents the interference of the movement plan from online visual

feedback. Given that QED effects have been recently associated with more complex tasks that require on-line control (such as during variable practice and the presentation of random targets), it may be that feedback and continuous monitoring (afferent) signals, including visual and proprioceptive information, are integrated during the QED. This finding suggests interactions between top-down and bottom-up control networks (or dorsal and ventral; Corbetta & Shulman, 2002) during target selection and computations for movement parameterization during the QE in goal-directed actions.

The relative contributions of inhibition and on-line feedback integration may be addressed by investigating the QE's temporal components (its onset and offset) during tasks with distinct requirements for these processes. For example, in Klosterman et al.'s (2013) experiments it was early QE onset that seemed to be important for accurate throwing, while findings from Vine et al.'s (2013) experiment using golf putting, suggested it was the late components (offset) of the QE that seem to affect performance, possibly due to higher demands of on-line control functions throughout the movement. In addition, examining these temporal components in QE may indicate a more efficient allocation of the timings that correspond to information extraction, motor programming and movement execution. These studies suggest that an important aspect of QE measurement is not only the duration but also the actual timing relative to the movement.

Finding the optimal balance between the timings when information extraction, motor programming and movement execution is particularly important for time-constrained motor actions, which are encountered in many sporting contexts. The time spent preparing a movement will facilitate the development of appropriate actions and will often help to minimize errors (Battaglia & Schrater, 2007). Expert performers have earlier QE onsets which result in longer QED, suggesting that they are able to find the relevant visual

information earlier and program the movement for longer irrespective of task constraints (Vickers, 2009). The first neurophysiological evidence of the QE's role in motor planning is reported by Mann et al. (2011), who investigated the Bereitschaftspotential (BP) during the QE period of expert and near-expert golfers. Their results showed increased cortical activation in right-central regions in experts compared to non-experts with an enhanced BP peak and greater negativity, which is suggested to be indicative of movement preparation.

The intraparietal sulcus and the premotor cortex (within frontoparietal networks) have been systematically shown to be involved in the programming of actions (Rushworth, Johansen-Berg, Göbel, & Devlin, 2003) and in particular, the pre-supplementary motor are (pre-SMA) has been associated with action selection (Mars, Piekema, Coles, Hulstijn, & Toni, 2007). The anterior cingulate cortex (ACC) receives input from the prefrontal cortex, also playing a role in action selection (Halsband & Lange, 2006). The cingulate cortex has also been associated with emotion regulation during goal-directed actions by manipulating goal outcomes in various tasks (Rolls, 2014). Emotion-related decision-making has been suggested to be an important aspect of the QE mechanisms. More specifically, a longer QED aids emotional control by enabling the individual to get into a suitable level of arousal to complete the task. This seems important in aiming tasks where a low arousal level is related to better performance and a longer QE may enable the individual to 'quieten' the body. For example, Vickers and Williams (2007) tested gaze control of biathletes under low and high anxiety conditions and found that longer QEDs were indirectly related to better performance under pressure situations and coincided with a reduced heart rate and reduced physiological arousal. Furthermore, the QE trained group in Moore et al.'s (2012) study, mentioned above, also showed a deceleration of heart rate prior to the golf putt combined with longer QED and improved putt-kinematics, compared to the technical trained group. However, phasic heart rate did not change during elevated anxiety

conditions in either training group, suggesting that this "quieting" of the body may explain

some of the benefits of QE training, but do not explain its effects during heightened anxiety

situations.

The involvement of these networks reflects higher order cognitive processing presumably

occurring during the QED. Studying the neural networks of a phenomenon observed in the

sporting field is no easy task. However, researchers have reported promising results, such

as the study by Wright et al. (2011), in which fMRI was used to investigate the neural

mechanisms associated with anticipation in badminton players of varying skill levels. The

authors were able to identify distinct levels of activation in task-relevant areas in experts

compared to novices and were able to correlate the activation of specific areas to show their

influence on performance (also see Heinen, Rowland, Lee, & Wade, 2006).

In summary, the neural networks and mechanisms responsible for the QE effects are not yet

fully   understood.   Skilled   movements   have   been   suggested   to   involve   the

dorsofrontoparietal networks, associated with the allocation of attention to relevant stimuli

and the suppression of distractors in the environment (Corbetta & Shulman, 2002;

Mevorach, Hodsoll, Allen, Shalev, & Humphreys, 2010; Mevorach, Humphreys, & Shalev,

2006); however, the extent to which these networks are involved in QE needs to be

investigated. Current research shows that QED is a function of task complexity, a finding

that agrees with the current proposed response programming theory of QE. It is further

suggested that the QE aids the maintenance of goal-directed (dorsal or top-down attention

system) attention control, perhaps via superior gaze control and the effective allocation of

visuospatial attention, while "suppressing" a stimulus-driven attentional system (ventral or

bottom-up system) (Vickers, 2009). These processes then allow for the motor programming

to take place during the QED. Thus, the programming hypothesis may be simplifying a more complex sequence of events that occur during the QE of a targeting task. Understanding the mechanisms of QE will aid the formulation of training programmes, which are often based on accepted practice rather than on procedures that try to optimise the critical processes involved (Causer et al., 2011).

Future directions and recommendations

There is still much to be addressed when attempting to explain the links between gaze and performance and the beneficial effects of a prolonged QED. The formulation of controlled manipulations of QE and the investigation of QE neural networks using neuroimaging and event related potentials (ERP) may shed some light on these links (e.g., Mann et al., 2011). Furthermore, with current neurophysiological techniques such as transcranial magnetic stimulation (TMS), causal relationships between anatomical regions and behaviour can be established, in addition to determining the extent and timing of their involvement. Neuroimaging reveals activation of specific neural networks during a performed task but does not determine the functional role of these regions in the observed behaviour. TMS is often used in conjunction with fMRI to determine the links between brain and behaviour by altering the activity of a specific region and examining the affects on behaviour. For example, Mevorach et al. (2010) combined fMRI and TMS techniques to investigate the role of different brain regions in attention control during a task that required the suppression of a response to stimuli. They found that TMS applied to the early visual areas led to reduced responses to distractors, which provided evidence for the functional role of these regions in attending or suppressing responses to salient stimuli. Similarly, the effects of QED may be

modulated by attention control regions, which may be determined by implementing these techniques. The combination of TMS and fMRI techniques has been proven to be robust in examining functional mechanisms and neural networks involved in behaviour compared to the less robust ERP measures obtained by electroencephalography (EEG). As such, caution needs to be taken when inferring brain activation of specific areas using EEG methods given the poor spatial resolution; however, EEG is well suited to test the timing of neural activity in a given task. With new technology emerging, it is now possible to measure electrophysiological responses during a golf-putting task, for example (see Mann et al., 2011), although regional information may not be robust using this method. Thus, combining these techniques (e.g., fMRI with EEG and/or TMS) may be of great benefit when trying to explain spatially and timing dependant networks involved in QE.

The relative contributions of the neural networks for attention control, programming and on-line control (functions presumably involved in QE) may depend on specific task-goal demands. For example, golf putting requires more dynamic on-line control functions compared to shooting a target, or shooting a moving target may require a balance between anticipation (pre-planning) and inhibition mechanisms afforded by increased attention control. Thus, generalisations of the functional mechanisms involved during the QE and how they influence performance should be characterised based on task demands.

A key issue is that the definition of the QE period is restricted by the sensitivity of the measurement systems that have been employed, which in turn impacts the interpretation of the results. Future research should address the arbitrarily defined threshold for determining QED and systematically evaluate whether performance and skill differences still hold at varying thresholds (e.g., 1 vs. 2 or 2 vs. 3 degrees of visual angle), thus examining the importance of the amplitude of eye movement during the QE. Research must

determine whether these eye movement differences are task or skill-related (i.e., experts may have better oculomotor control) and whether alternate gaze strategies other than fixations may come into play. Thus, caution should be taken when relying on fixation-attention mechanisms to explain the QE phenomenon, since other gaze strategies may be taking place within the QE, and distinct cognitive processes may be encompassed by a single QE definition or threshold. High-resolution eye trackers (under 0.1 degrees spatial resolution and sampling > 500 Hz) have limited use in real world sport settings, but may be used in laboratory-based tasks in which QED effects on performance are obtained during an aiming or interceptive task to better identify differences in oculomotor control and the amount and/or type (pursuit, saccades, microsaccades) of eye movement related to attention/inhibition mechanisms. For example: observed high frequency of microsaccades versus a higher rate of larger saccades would indicate an enhanced fixation ability of the former compared to the latter, which reveals disruptions in visuospatial attention. The use of these high-resolution eye trackers may also address discrepancies between different gaze measuring and analyses techniques for QE. QEDs have been reported using mobile video-based gaze trackers of different resolutions (e.g., 30 – 60 Hz), or using video cameras only, and one paper reported QED using electro-oculography (EOG; see Mann et al., 2011). The sensitivity of one technique over another may indicate that some aspects of QE are overlooked; for instance high variability between participants may hinder the effects of QED on hit or miss trials or QED differences between expert and novice groups. Different techniques may also underestimate or overestimate the duration of the QE, which has implications when attempting to examine the mechanisms involved, particularly when breaking the QED down into its temporal components (onset and offset).

In this review we also highlight the need to further examine the links between QE and attention and address whether it is simply gaze control or gaze control and the specific

allocation of attention that matters in QE. Experiments similar to Klostermann et al. (2014), in which gaze is not influenced by instructions but QE is manipulated may probe into these attention allocation mechanisms. We also suggest that training protocols need to implement approaches that go beyond the comparisons between elite and sub-elite individuals, and assess whether experts differ a priori from novices. These experimental approaches may include perceptual and cognitive manipulations to examine the ability to control gaze and inhibit intrusive responses when aiming in a crowded environment or during high anxiety situations. The response to these manipulations may change pre- to post-QE training within, and between skill groups, demonstrating not only that these mechanisms are important for QE but that they can be learned and adapted.

Conclusions

The QE appears to be an important measure of perceptual-cognitive expertise. In this review we have highlighted current research that has focused on the functional mechanisms of QE, involving direct manipulations and probes of the information programming theory. However, there are strong links between eye movement, attention and action programming networks, which may prove to be important during QE and thus, the relative contributions of these still need to be addressed. The importance of understanding the mechanisms of the QE will provide further knowledge of the behavioural and neural mechanisms of performance-enhancing strategies used by expert performers, used to improve goal-directed movements not only in sports but in other fields, such as surgery and amongst clinical populations such as children with developmental coordination disorders (DCD) and stroke survivors.

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Figure Captions

Figure1. The graph displays the mean QED and standard deviations (SD) of random and blocked practice (RP and BP, respectively) groups in targets aimed in the horizontal and vertical axes (HA and VA, respectively) during a dart-throwing task from Horn, Okumura, Alexander, Gardin, and Sylvester (2012). The random practice group exhibited longer QED compared to participants trained under blocked practice conditions. Despite this QED differences, the authors reported no significant correlations between accuracy of the throw and QED.

Figure2. The figure displays the externally-paced throwing task (A) implemented by Klostermann et al., (2013). Figure (B) shows the mean and SD radial error (measure of performance) and (C) displays the mean and SD QE onset and offset during the low task demands and high task demands conditions (LTD and HTD, respectively) in short and long target presentations (SP and LP, respectively). Statistically significant findings are highlighted ($p < 0.05$ * and **). Complexity was manipulated by implementing a random and a predictive target presentation during movement unfolding. Their results showed earlier QE onsets, which resulted in longer QED, during more complex tasks and during longer compared to short target presentations. A significant interaction was found between task demands and target duration presentation which revealed that participants threw more accurately only in high task demands conditions. Adapted from Klostermann, Kredel, and Hossner (2013).

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