Review

# Exploring the cognitive mechanisms of expertise in sport: Progress and prospects

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ABSTRACT

*Objectives:* The present paper elucidates some cognitive mechanisms of expertise in sport that have emerged from recent studies of three topics in psychology: motor imagery; flow and "clutch" states; and the "quiet eye" phenomenon.
*Design:* A selective narrative review was conducted of research on the three preceding topics. Special consideration was given to recent studies by European researchers on these topics.
*Method:* Following a brief overview of theoretical approaches to sport expertise, the paper examines certain cognitive mechanisms of elite athletic performance that have emerged from recent studies of motor imagery; flow and "clutch" states; and the "quiet eye" phenomenon. In the final section, conclusions are drawn about theoretical progress in understanding the cognitive mechanisms of expertise in sport.
*Results:* The mechanisms underlying sport expertise reflect both task-specific and universal cognitive processes (e.g., mental representations).
*Conclusion:* Considerable progress has been made in identifying the cognitive mechanisms underlying expertise in sport but additional research is required to address certain unresolved issues in this field.

## 1. Introduction

We have long been fascinated by the achievements of "experts" - people who appear to transcend human information processing constraints by producing consistently outstanding performance in a specific field. Not surprisingly, research on expertise, or "the characteristics, skills, and knowledge that distinguish experts from novices and less experienced people" (Ericsson, 2018, pp. 3–4), has spawned a profusion of research including scholarly handbooks (e.g., Ericsson, Hoffman, Kozbelt, & Williams, 2018), a new journal (*Journal of Expertise*), special editions of other journals (e.g., Campitelli, Connors, Bilalic, & Hambrick, 2015) and popular science books (e.g., Syed, 2010).

Within this multidisciplinary field of inquiry, research on sport expertise (see history in Baker & Farrow, 2015) is important for both theoretical and practical reasons. Theoretically, the study of expert athletic performance provides an empirical window on how people's mental representations (i.e., their internal structures in long-term memory [(LTM]] that correspond to objects, ideas or anything that the brain is thinking about; Ericsson & Pool, 2016) guide skilled action. For example, consider the "mind sport" (de Groot, 1946) of chess. Briefly,

Chase and Simon (1973) discovered that top chess players were better than novices at encoding and recalling meaningful (but not random) patterns of play from actual game situations. To explain this cognitive advantage, Chase and Simon (1973) postulated that the experts' superior performance was facilitated by rapid and efficient retrieval from LTM of "chunks" of chess knowledge accumulated through experience. Technically, chunks may be defined as information-rich representations of collections of elements that have strong 'if-then' associations with each other (see also Poolton & Masters, 2014). Inspired by Chase and Simon's (1973) seminal discovery, Allard, Graham, and Paarsalu (1980) showed that expert basketball players enjoyed an analogous superiority over less skilled counterparts in recognizing and recalling patterns of play from dynamic game situations – thereby raising the possibility that *similar* mental representation mechanisms may underlie expertise in *different* domains (chess, basketball). At a practical level, research on expert-novice differences in sport is important because it offers the promise (or "Holy Grail"; see Williams, Ford, Hodges, & Ward, 2018) of early prediction of future athletic expertise as well as practical training interventions (e.g., Dicks, Pocock, Thelwell, & van der Kamp, 2017).

Unfortunately, research on expertise in sport has been hampered by

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a variety of (i) semantic, (ii) methodological and (iii) conceptual problems. Firstly, at the semantic level, the meaning of the terms "elite" and/or "expert" is unclear. For example, these terms have been applied to samples of athletes ranging from inter-varsity performers (e.g., Steiner, Denny, & Stemmle, 2010) to Olympic champions (e.g., Grant; Schempp, 2013). To resolve this confusion, Swann, Moran, and Piggott (2015a) devised a precise classification system for expert athletes which takes into account demographic factors such as their highest standard of performance, their success at that level, and the amount of experience that they have gained at that standard. Of course, the success of this system will depend greatly on the extent to which expertise researchers in sport report such demographic details in their studies. Secondly, at the methodological level, a major challenge facing cognitive researchers in sport is to develop rigorous ways of tracing the component processes of expertise in athletes. In this regard, Farrow, Reid, Buszard, and Kovalchik (2018) advocated the use of measures such as eye-tracking technology (see also Moran, Campbell, & Ranieri., 2018) and non-invasive three-dimensional motion capture systems to record athletes' action capabilities. The third problem afflicting expertise research in sport - and the one which we shall tackle in this paper - is conceptual and concerns the relative neglect of the *cognitive mechanisms* (i.e., "interaction between basic cognitive processes"; Bilalic, 2017, p. 5) underlying elite performance.

To illustrate this neglect, whereas a recent search of the PsycINFO database using "expertise in sport" yielded 1164 'hits', one for "mechanisms of expertise in sport" produced only 75 relevant studies. Surprisingly, the term "mechanisms" is absent from the index of the *Routledge Handbook of Sport Expertise* (Baker & Farrow, 2015) although it is included in the more recent *Cambridge Handbook of Expertise and Expert Performance* (Ericsson, , Hoffman, , Kozbelt, , & Williams, 2018). From such strands of evidence, we conclude that sport psychology researchers appear to be more concerned with the identification of expert-novice differences in athletes than with attempting to understand the psychological processes that underlie them. We acknowledge, however, that this latter quest is exceptionally difficult because as Gobet (2018) noted, "the mechanisms underpinning expertise include feedback loops, interact in nonlinear ways and often evolve as a function of time" (p. 50). In order to address this explanatory gap, the present paper elucidates some cognitive mechanisms of expertise that have emerged from recent studies of three topics in sport psychology: namely, motor imagery; flow and "clutch" states; and the "quiet eye" phenomenon (terms defined later). We chose these topics for three reasons. Firstly, although they have attracted a plethora of research in sport psychology, their underlying cognitive mechanisms remain largely unresolved. Secondly, research on these topics is important because it can serve as a bridge between sport psychology and related fields such as cognitive psychology (see review by Moran, Guillot, MacIntyre, & Collet, 2012) and cognitive neuroscience (Cheron, 2016; Spering & Schutz, 2016). Finally, in accordance with the theme of this special issue, several European research groups have played prominent roles in investigating the three topics under scrutiny.

The paper is organised as follows. To begin with, we provide a brief overview of theoretical approaches to sport expertise. Then, we address three specific questions concerning the cognitive mechanisms underlying athletic expertise. Firstly, what light can research on motor imagery shed on action representation in motor experts? Secondly, what does the study of flow and "clutch" states reveal about the mechanisms underlying expert performance? Thirdly, what cognitive mechanisms underlie expert-novice differences in the perceptual phenomenon of "quiet eye"? In the final section, we draw some conclusions about theoretical progress in understanding the cognitive mechanisms of expertise in sport.

## 2. Overview of theoretical approaches to research on expertise in sport

Research on expertise in sport is rooted in the cognitive paradigm in psychology. A key theoretical debate within this paradigm is whether human cognition is computational (i.e., our knowledge is stored in an abstract format that is independent of any particular sensory modality) or embodied (i.e., our knowledge is "grounded in, and simulated through, sensorimotor activity"; Slepian, Weisbuch, Rule, & Ambady, 2011, p. 26). In recent years, the latter position has gained influence with the discovery that many of the brain circuits that are responsible for abstract thinking are inextricably linked to those that process sensory experience. For example, the cognitive simulation process of mental imagery (defined in the next section) shares certain mental representations, neural structures, and theoretical mechanisms with like-modality perception and with motor preparation and execution (see review by Moran et al., 2012). More precisely, mentally simulated and executed actions activate many common brain areas such as the posterior parietal, premotor, and supplementary motor cortex which are all involved in the planning of movements (Munzert, Lorey, & Zentgraf, 2009). Theoretically, such evidence suggests that embodiment approaches are well-equipped to explain the mechanisms underlying mental simulation. However, a note of caution is necessary in this regard because despite its intuitive appeal, the embodied cognition paradigm (Wilson, 2002) has been criticised for its vagueness and logical weaknesses in explaining cognitive phenomena (see review by Goldinger, Papesh, Barnhart, Hansen, & Hout, 2016).

## 3. Motor imagery practice and expertise

Mental imagery is a multimodal (i.e., involving different sensory systems) cognitive simulation process that enables us to represent perceptual information in our minds in the absence of actual sensory input (Munzert et al., 2009). A key simulation process is "motor imagery" - a dynamic mental state during which the mental representation of a given motor movement is rehearsed in working memory without any overt sensory input or motor output (Collet & Guillot, 2010). Perhaps the most frequent application of this process in sport is "motor imagery practice" (MIP) or the systematic use of imagery to rehearse covertly a movement in one's imagination without actually executing it (Di Rienzo et al., 2016). This process has also been studied in psychology as "mental practice" (Vandell, David, & Clugston, 1943), "covert rehearsal" (Corbin, 1967), and "motor imagery training" (Mizuguchi et al., 2013).

Since the 1890s, hundreds of experimental studies have demonstrated the efficacy of MIP in improving skill-learning and skilled performance in sport and other domains (Driskell, Copper, & Moran, 1994). In order to understand the mechanisms underlying these effects - especially the discovery that expert performers tend to benefit more from MIP than do novices - Jeannerod's (1994, 2001, 2006) motor simulation theory (MST) and research by Schack and colleagues (e.g., Frank, Land, Popp, & Schack, 2014; Schack & Mechsner, 2006) deserve particular scrutiny.

Although space limitations preclude a detailed account of MST (but see O'Shea & Moran, 2017), its central tenets may be summarised as follows. Firstly, it postulates that motor imagery and action planning share a common mental representation. Next, it proposes that the motor system is part of a cognitive network that includes simulation processes like motor imagery and action observation (AO). Interestingly, functional magnetic resonance imaging (fMRI) research confirms that several areas that are known to be involved in motor planning and motor execution (e.g., supplementary motor cortex, premotor cortex) are activated by MIP and AO (Hardwick, Caspers, Eickhoff, & Swinnen, 2017). Thirdly, Jeannerod (2001) postulated that actions involve a *covert* stage during which they are prepared or simulated mentally. This covert stage involves "a representation of the future, which includes the

goal of the action, the means to reach it, and its consequences on the organism and the external world. Covert and overt stages thus represent a continuum, such that every overtly executed action implies the existence of a covert stage" (p. S103). Finally, MST argues that "motor imagery … should involve, in the subject's motor brain, neural mechanisms similar to those operating during the real action" (Jeannerod, 2001, pp. S103−S104) – the "functional equivalence" hypothesis (see review by Moran et al., 2012). Thus, overt and imagined actions share a motor representation of an intention to act. Whereas this intention is converted into an actual physical movement in the case of overt actions, it is not executed in the case of imagined actions. Explicitly endorsing a "functional equivalence approach", Holmes and Collins (2001) developed a theoretically based checklist (the PETTLEP approach; see critical review by Wakefield, Smith, Moran, & Holmes, 2013) for the effective implementation of motor imagery intervention in sport. The acronym PETTLEP encapsulated seven practical issues to be considered when designing MIP scripts and implementing imagery interventions for optimal efficacy in sport. To explain, "P" refers to the athlete's physical response to the sporting situation, "E" is the environment in which the imagery is performed. "T" is the imagined task, "T" refers to timing (or the pace at which the imagery is performed), "L" is a learning or memory component of imagery, "E" refers to the emotions elicited by the imagery and "P" designates the type of visual imagery perspective used by the practitioner (either first person or third person; see earlier in chapter). Overall, the PETTLEP model proposes that in order to produce optimal "behavioural matching between imagery and action" (Wakefield et al., 2013, p. 117), interventions should take into consideration each of the preceding aspects of imagery. In their review of this approach, these authors concluded that many "imagery interventions based on PETTLEP principles tend to produce significant improvements in skill and strength performance relative to traditional imagery interventions" (pp. 115–116).

### 3.1. Let us now consider how the study of mental representations and that of MI can shed light on athletic expertise

According to Schack and Mechsner (2006), athletes' mental representations of motor skills can be investigated fruitfully as LTM structures that involve hierarchically organised clusters of "basic action concepts" (BACs). These BACs resemble the cognitive chunking of body postures and movements as tools for realizing action goals (Schack, Essig, Frank, & Koester, 2014). Typically, they correspond to functionally meaningful elements of a given skill. For example, in the case of the tennis serve, they include "ball throw", "bending the knee" and "racket follow-through". Thus, Schack and Mechsner (2006) discovered that experts tennis players' mental representations of the serve were well matched with the functional demands of this skill. By contrast, the cognitive representations of the serve among tennis novices were more variable and less well matched with task demands. Subsequently, Schack and colleagues demonstrated that motor imagery practice modifies athletes' mental representations of actions. For example, Frank et al. (2014) required novices to practise a golf putt mentally, physically, or in a combination of both modes of training over three days, while a control group did not practise at all. Participants' putting performance and mental representation structures were tested before and after the intervention and after a three-day retention interval. Results showed that participants who had practiced mentally, either solely or in combination with physical practice, revealed mental representation structures that were more similar to those of experts than did participants who had not practised mentally. These findings confirm that MIP helps to refine and elaborate athletes' mental representations of action. According to Wright et al. (2018), MIP "involves the generation of visual and kinaesthetic aspects of a movement and so may enhance an individual's mental representation primarily by developing the sensory consequences associated with different basic action concepts" (p. 119). But how can we investigate athletes' mental representations

experimentally? In addressing this question, Calmels, Elipot, and Naccache (2018) used visual priming methodology to investigate possible differences in the mental representation of movements between expert and novice gymnasts. In experimental psychology, "priming" is the facilitation of the perception of a stimulus by previous experience with a similar stimulus. In their study, Calmels et al. (2018) used static visual stimuli that either implied (primed) or did not imply human whole-body movements (gymnastics movements and static positions). Specifically, they required participants to perform a response time task in which they had to decide as quickly as possible whether a given target image depicted either a gymnastics movement or a resting position. Results showed that priming facilitation effects were stronger in the expert gymnasts than in matched controls, suggesting that these experts "possess more refined representations than non-expert performers" (p. 1547) – an interpretation that is consistent with the findings of Schack and Mechsner (2006) discussed earlier.

What can the study of MI reveal about the brain mechanisms of motor expertise? Two findings are notable – the first reveals some general cortical activation differences between expert and novice performers when using imagery while the second concerns the role of individual differences in MI ability. To explain, Wei and Luo (2010) investigated expert-novice differences in patterns of cerebral activation during imagery of professional (a diving task) and simple (a basic gymnastics task) motor skills. They found that the expert performers displayed greater activation in the parahippocampal cortex (PHC; which is associated with visuospatial processing and episodic memory; Aminoff, Kveraga, & Bar, 2013) during imagery of professional skills and more focused activity in the prefrontal regions in both tasks. Building on this evidence, a review by Debarnot, Sperduti, Di Renzo, & Guillot (2014) concluded that the brain plasticity that occurs during MIP closely mimics that detected after physical practice of the same motor skills. But imagery ability appears to play a key role in modulation of brain activity. Therefore, extrapolating from such evidence, Debarnot, Sperduti, DiRienzo, and Guillot (2014) postulated that with appropriate mental training, the pattern of cerebral activation that occurs during imagery by "poor" (low-skilled) imagers and/or novice athletes should improve to a level that is close to that recorded in "good" (high-skilled) imagers. This intriguing hypothesis requires empirical validation by future researchers.

### 3.2. Cognitive mechanisms of flow and "clutch" performances in sport

The ability to 'make it happen', or to produce 'clutch' performances (any performance increment or superior performance that occurs under pressure circumstances; Otten, 2009, p. 584), is a hallmark of expertise in sport and one which distinguishes truly elite performers from their less skilled counterparts. In this section, we argue that the acquisition of metacognitive knowledge (i.e., insights into, and control over, one's own mental processes; Moran & Toner, 2017) allows experts to flexibly allocate their attentional resources in response to the wide range of challenges they face in performance environments. One psychological state underlying exceptional performance in sport is "flow" - an optimal experience which can be brought about by engaging in challenging activities that demand intense levels of concentration and which contains clear goals and provides immediate feedback (Swann, Crust, Keegan, Piggott, & Hemmings, 2015). As space limitations preclude a comprehensive review of this topic, the present paper is necessarily selective. Accordingly, it highlights a few recent studies by European investigators (e.g., Swann and colleagues; and Harris and colleagues) on the subjective experience of flow among athletes (e.g., see Swann, Crust, Keegan, Piggott, & Hemmings, 2015) and of the cognitive mechanisms underlying its occurrence (see Harris, Vine, & Wilson, 2017a). Thus, Harris, Vine, and Wilson (2017b) cited evidence demonstrating how supervisory attentional and cognitive control systems of the brain (including the fronto-parietal dorsal stream) are highly active during the flow state. Intriguingly, recent experiments show that flow states

require attentional effort and cannot be considered fully automatic. For example, using a simulated driving task, Harris et al. (2017b) found that the absorption that characteristically accompanies flow is based on an efficient but *effortful* form of attention (as measured by peak ratings of absorption, peak heart rate and reduced gaze variability). Harris et al. (2017b) used eye-tracking technology to explore the role of effective attention control in flow states. Mediation analysis revealed a small indirect effect of quiet eye (QE – see next section of paper) on basketball free throw performance through flow score. The authors argued that optimal QE may have enhanced flow thereby resulting in improved shooting performance. Furthermore, they suggest that quiet eye training that promotes goal-directed control may, in turn, "create an attentional state that is conducive to flow" (Harris et al., 2017b, p. 346).

Similarly, qualitative research has shown that optimal performance in sport is characterised by the flexible deployment of attentional resources. To illustrate, Swann, Keegan, Crust, and Piggott (2016) conducted interviews with professional golfers and discovered two different psychological states during excellent performance. One of these was a flow-like state which they termed "letting it happen" and the other was a state which they labelled "making it happen". This latter state was described as an intense state of optimal arousal during which participants experienced a sense of heightened and effortful concentration. For example, one golfer revealed: 'I made myself focus even more on that last hole … I was trying a little bit harder to be intense' (Swann et al., 2016, p. 108). The process of "making it happen" seems to overlap with the phenomenon of "clutch" performance in sport (Otten, 2009). This latter state is evident when an expert athlete succeeds at a point in competition where success or failure has a significant impact on the outcome of the contest (Hibbs, 2010). Interestingly, sport psychology researchers have only recently begun to explore the psychological states underlying this phenomenon. Thus, Otten (2009) used structural equation modelling to predict performance on a free throw task and found that perceived control was the best predictor of performance under pressure.

To gain a deeper understanding of the state of mind experienced by athletes while excelling under pressure, Swann, Crust, and Vella (2017a) interviewed participants from a range of sports about a recent excellent performance (i.e., one in which they had achieved a high place in competition). States of clutch and flow were reported and these occurred in specific contexts and through separate processes. *Flow* appeared to arise among athletes as a growth in confidence following a good start to a competition. In contrast, *clutch* performance arose in pressure contexts when athletes became aware that they had to raise their game in response to the challenge. When this happened, they used psychological strategies such as setting microgoals and using positive self-talk. Although flow and clutch states were found to share a number of characteristics (e.g., confidence, perception of control), clutch states were distinguished by certain unique characteristics such as an increase in maximal effort (rather than feelings of effortlessness) and the use of conscious processing (rather than performing on automatic pilot). Swann et al. (2017) argued that these findings challenge the traditional assumption that there is only *one* ideal or optimal performance state (e.g., Anderson, Hanrahan, & Mallet, 2014).

In a follow-up study, Swann et al. (2017b) interviewed athletes from different sports about their subjective experiences of clutch performances. Defining criteria of such performance included *complete and deliberate focus, intense effort, heightened awareness* (including awareness of self, self-monitoring), *heightened arousal, absence of negative thoughts,* and *automaticity of skills*. Interestingly, the data from this study indicate that both automatic and controlled processes may be involved in clutch states. In stark contrast to earlier accounts of flow/peak performance, Swann et al.'s findings (2017b) show that performing at one's best often requires *increased effort* rather than letting things happen; conscious control rather than automated processing (see also Toner & Moran, 2014); intensity; and effortful concentration. Thus, athletes who

experienced a clutch state appear to have drawn on self-regulatory processes in order to increase self-monitoring and to consciously invest intense effort in their performance.

Swann and colleagues' research has elucidated some of the cognitive mechanisms of *clutch* states supporting excellent performance in sport. In addition, their studies have identified various strategies which athletes employ to induce clutch performances. For example, Swann et al. (2017a) found that "open" goals (e.g., goals which are exploratory yet still challenging; 'See how well I can do') were reported during flow, whereas "fixed" goals (which include specific and challenging objectives) were reported during clutch states. While fixed goals might include a golfer setting a particular score that he/she needs to achieve, open goals are less structured and specific in nature ('seeing how well I can do'). In Swann et al.'s (2017a) study, fixed goals helped athletes to increase their effort, intensity and concentration thereby allowing them to maintain performance proficiency in a clutch situation. These qualitative findings have received support from a recent experimental study in which participants performed a letter and number identification task whilst either being prescribed "open" or specific goals (Schweickle, Groves, Vella, & Swann, 2017). In line with the researchers' predictions, those participants prescribed open goals reported higher levels of flow while those prescribed specific goals reported higher levels of clutch. The authors concluded that specific goals might be most appropriate when a competitor's primary objective is to win/perform better than one has before while open goals might serve a greater benefit during training when one is seeking to enhance confidence.

As Swann et al. (2017) acknowledged, flow occurs in contexts of exploration, discovery and experimentation but clutch states may be more influential during pressurized situations when a lot hinges on the outcome of performance. Given the received wisdom in the expertise literature that proceduralised action should be allowed to unfold without interference from explicit processes, how might we explain the finding that increasing the conscious resources one devotes to a task is an important mediator of clutch performance? We regard skilled performance as remaining open to strategic control and argue that experts are accustomed to alternating between reflective and pre-reflective modes of bodily awareness/processing in order to maintain or improve their performance proficiency (see Toner, 2017; Toner, Montero, & Moran, 2016). In fact, findings from a number of studies on the flow phenomenon have shown that experts retain a keen and lucid sense of the kinaesthetic sensations that accompany fluent and efficient movement execution. For example, Bernier, Thienot, Codron, and Fournier (2009) found that elite swimmers reported a *heightened* sense of *bodily awareness* (e.g., tingling sensation in their muscles) during flow. Similarly, Jackman, Fitzpatrick, Lane, and Swann (2017) reported that national hunt jockeys experienced altered physical perceptions during this state. One of the defining features of the clutch state is that athletes possess a heightened awareness of the situation and its demands (Swann et al., 2017). Here, they appear to use afferent information as a means of ensuring that performance is progressing according to plan or as a signal that they are facing a particularly difficult challenge and that they may need to switch from an automated to a controlled mode of processing.

The findings from Swann and colleagues' research suggest that optimal performance states are underpinned by the use of both automated procedures and metacognitive knowledge. Clearly, experts possess a wide breadth of declarative knowledge (contrary to claims that they are afflicted by impoverished episodic recollections or "expertise-induced amnesia"; Beilock & Carr, 2001) and "metacognitive" knowledge which allows them to direct lower-order motor control. Metacognitive processes enable experts to monitor, control and regulate strategies in order to meet contextually-contingent demands that they encounter during competitive performances (MacIntyre, Igou, Campbell, Moran, & Matthews, 2014). MacIntyre et al. (2014) argued that metacognitive control may be required when performers face difficult or previously

un-encountered situations, when automatic processes fail to solve the challenge, or when accessible information is considered inappropriate for the task at hand. Such attentional control is crucial if experts are to produce clutch performances. The capacity to flexibly allocate one's attentional resources is likely to distinguish those who excel from those who 'choke' or under-perform under pressurized conditions. How could we measure experts' capacity to exert effective attentional control? One possibility is to use electroencephalography (Cheron, 2016) and eye tracking technology (Harris et al., 2017b; Moran, Campbell, & Ranieri, 2018) to measure task-relevant indices of attentional control while experts perform complex tasks in pressure situations.

### 3.3. Cognitive mechanisms of quiet eye: the promise of electrooculography and pupillometry

It has long been known that efficient gaze behaviour facilitates anticipation and skilled behaviour in athletes (Winograd, 1942). For example, Mann, Spratford, and Abernethy (2013) found that world-class cricket batters use eye movement strategies to predict the location at which their bats would hit the ball. Since the mid 1970s, over 60 studies have used eye tracking technology to investigate various aspects of gaze behaviour in sport (Kredel, Vater, Klostermann, & Hossner, 2017). One such aspect is "quiet eye" (Vickers, 1996, 2016) - a distinctive pattern of gaze behaviour that is evident among expert performers prior to skill execution in aiming (target-based) sports. Briefly, Vickers (1996) reported that prior to free throw shooting, expert basketball players displayed significantly longer durations of final fixation on targets than did near-expert counterparts. This pattern of visual behaviour was named the "quiet eye" period (commonly abbreviated to "quiet eye"; QE) and designates "a final fixation or tracking gaze that is located on a specific location or object in the visuomotor workspace within 3° of visual angle (or less) for a minimum of 100 ms" (Vickers, 2007, p. 11) prior to the onset of a critical movement. QE can last between 300 and 2000 ms depending on the sport. QE effects have been reported in many sports such as basketball (Rienhoff, Fischer, Strauss, Baker, & Schorer, 2015) and golf (Klostermann, Kredel, & Hossner, 2014a). A frequent finding is that successful aiming is related to longer QE durations than is unsuccessful aiming (Klostermann, Kredel, & Hossner, 2018). Also, expert athletes show longer QE durations than do less skilled counterparts (Sáenz-Moncaleano, Basevitch, & Tenenbaum, 2018)). At first glance, this classical association of longer QE durations with increasing motor expertise is an "efficiency paradox" as it appears to contradict the speed and efficiency that typically defines expert performance. However, Vickers' (2011) pre-programming of action hypothesis postulates that the longer duration of QE among experts than novices reflects the extended time required to programme and fine-tune a response. This hypothesis seems circular, however, because it lacks an independent measure of the cognitive processing that it purports to explain. A more recent explanation comes from Klostermann and Hossner's (2018) "inhibition hypothesis". Briefly, this hypothesis proposes that as a result of extensive experience, expert athletes develop elaborate "task solution" mental workspaces. Consequently, they may require a relatively long QE period in order to shield the chosen (optimal) task solution from very similar, but less successful, variants of it.

What cognitive mechanisms underlie QE effects? Vickers (2009) speculated that attentional processes are crucial to it, when referring to "the time needed to process cognitively the information that is being fixated or tracked *and to focus attention on the demands of the task*" (p. 283, our italics). Subsequently, several groups of European researchers (e.g., Ducrocq, Wilson, Smith, & Derakshan, 2017; Ducrocq, Wilson, Vine, & Derakshan, 2016) have investigated the role of attention in QE. For example, Ducrocq et al. (2017) studied the effects of attentional control training on proficiency in tennis volleying. Results revealed significant benefits of such training in extending QE (i.e., inducing a later offset) and in improving tennis performance in high-pressure

conditions. In a similar vein, Walters-Symons, Wilson, and Vine (2017) identified "a link between QE and the allocation of attentional resources to the task (effort)" (p. 21). Interestingly, Harris, Vine, and Wilson (2017c) explored the link between QE and the occurrence of flow. Specifically, they provided preliminary evidence that "flow may be preceded by changes in visual attention, suggesting that further investigation of visual attention may elucidate the cognitive mechanisms behind flow experience' (p. 343).

In the past, an impediment to research on attentional processes underlying QE was the absence of an objective measure of mental resource allocation or cognitive effort (Gallicchio, Cooke, & Ring, 2018). However, two potential solutions to this problem have emerged from recent research on objective psychophysiological measures – especially, electrooculography (EOG; which measures time-varying changes in the electric dipoles of the eyes, Gallicchio et al., 2018) and pupillometry (or the objective measurement of continuous, task-evoked changes in the diameter of the pupil of the eye as a function of cognitive processing; Laeng, Sirois, & Gredebäck, 2012; Freeman and Mathôt, 2018). To illustrate the former, Gallicchio et al. (2018) demonstrated the utility of EOG in studying QE and expertise in golf putting. They found that visual information was actively processed only *after* movement initiation - raising some doubts on the long-standing hypothesis that QE is a correlate of motor programming (Vickers, 1996). This finding is in line with that of Klostermann, Kredel, and Hossner (2014b) who demonstrated a relationship between the performance enhancing effects of experimentally controlled long QE durations and visual information processing.

Turning to pupillometry, research suggests that pupil dilation responses can provide a valid and reliable index of the 'intensity' of mental activity or "attentional effort" (Moran et al., 2016). Typically, larger pupil diameters reflect increased attentional resource allocation on the part of the perceiver. When expressed relative to a baseline, these task-evoked changes serve as an objective index of cognitive activity. Indeed, task related fluctuations in pupil diameter are associated with activity in the dorsal attention network (DAN), dorsolateral prefrontal cortex (DLPFC), thalamus, and superior colliculus (SC) (Alnæs et al., 2014). Interestingly, Campbell, Toth, and Brady (2018a) used pupillometry measures to show that during mental rotation of abstract images, females display larger increases in pupil diameter, hence exerting significantly more cognitive resources than males in order to achieve a similar level of performance. In sport and performance psychology, European researchers have shown that pupillometry can elucidate expert-novice differences in attentional effort during QE (see Campbell et al., 2018b; Moran et al., 2016; O'Shea & Moran, 2016, O'Shea & Moran, 2018). These studies revealed that pupil dilation (an index of attentional effort) increases steeply during QE. This finding suggests that visual search involves little effort in the initial stages but increased effort as the task progresses towards an appropriate response decision. Clearly, it would be interesting to investigate this hypothesis using laboratory simulations of sport decision-making situations.

### 3.4. Conclusions about mechanisms of expertise: the importance of different levels of analysis

In this paper, we explored some insights into the cognitive mechanisms (especially mental representational and attentional processes) underlying expertise that have emerged from recent research (largely European) on motor imagery practice; flow and "clutch" states associated with exceptional athletic performance; and the visual attentional phenomenon of quiet eye. Although sport expertise may be regarded as "task and sport specific" (Farrow et al., 2018, p. 239), it is supported by certain universal cognitive mechanisms of memory. For example, as Bilalic (2017) argued, "all experts, without exception, employ their LTM to circumvent inherent cognitive and neural limitations" (p. 225). But how can we resolve this apparent contradiction between *mechanism specificity* and *mechanism universality* when attempting to explain the

cognitive processes that underlie athletic expertise? In attempting to answer this question, the 'levels of analysis' approach pioneered by Marr (1982), a seminal figure in computational neuroscience, may be helpful. We acknowledge, however, that some expertise researchers in sport psychology informally use similar approaches already. For example, in their analysis of the practice experiences that shape the development of expert performance in sport, Williams et al. (2018) distinguished between the "macro level" (practice history profiles) and the "mirco-level" (deliberate practice). So what does Marr's (1982) theoretical approach involve and why is it relevant to the present review? Briefly, in his posthumously published book, *Vision*, Marr (1982) distinguished between three different levels of analysis or explanation of complex information processing systems: the *what/why* level (which concerns the purpose of the computational processes under investigation), the *how* level (which concerns how information is represented), and the *physical realization* or *hardware* level (which concerns how computational processes are neurally implemented). In the case of sport expertise, the computational level of analysis is concerned with the question of how expert athletes produce consistently exceptional performance in a particular domain. Interestingly, a recent study by Kilteni, Anderson, Houbbrg, and Ehrsson (2018) investigated the "computational equivalence" between imagined (imagined self-touch) and real (actual tactile sensations) actions. The specific question examined was whether or not the brain's internal forward models predict the sensory consequences of imagined movements as they do for executed movements. Results showed that imagined self-touch is attenuated just as real self-touch is and that such MI-induced attenuation adheres to the same spatio-temporal principles as does the attenuation produced by executed movements. Kilteni et al. (2018) concluded that MI recruits forward models to predict the sensory consequences of imagined movements. Next, representational level analysis specifies the processes or mechanisms by which this performance is executed. In sport expertise, whereas some of these mechanisms may be task- or sport-specific (e.g., experts' declarative knowledge of their specialist domain), other mechanisms (e.g., the speed with which they can bypass working memory limitations in retrieving "condition-action" chunks from memory) may be universal. Finally, the neural implementational level of analysis refers to the way in which underlying mechanisms are instantiated by the brain. For example, consider the neurobiology of some of the adaptations induced by athletic expertise. Thus, Wei, Zhang, Jiang, and Luo (2011) used cortical thickness measurement to investigate the neuroanatomical changes that occur among expert divers as a result of their training experience. Results revealed three cortical regions with significantly increased cortical thickness in the expert divers. These regions included the left superior temporal sulcus, the right orbitofrontal cortex and the right parahippocampal gyrus. Based on such evidence, Wei et al. (2011) concluded that extensive training produces measurable structural changes in the brains of divers. More generally, we propose that the use of a formal "levels of analysis" approach may help expertise researchers to clarify the conceptual status of their empirical work. This approach seems particularly suitable for a multidisciplinary field like sport expertise where research is conduced on individual differences in psychological processes; cognitive representations and mechanisms; neurobiological adaptations; different types of practice regimes; and a mosaic of different socio-cultural factors and developmental pathways. To conclude, we recommend that a "levels of analysis" approach should be adopted more frequently by expertise researchers to disentangle different purported explanations of elite athletic performance.

## Conflicts of interest

The authors wish to report that they have no conflict of interest to declare for this manuscript.

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