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Visual search behaviours in expert perceptual judgements

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Introduction

Expert athletes make use of their visual system in a more advantageous way when anticipating the actions of opponents and when making decisions. This claim is most often supported by studies of *visual search* or *gaze behaviour* that use eye tracking to examine *where* expert athletes direct their line of sight. Early attempts at eye tracking were necessarily performed in the laboratory with participants watching still images or video footage designed to be representative of sport scenarios. More recent advances in eye-tracking technology have allowed studies of gaze to be readily conducted in the field while taking part in *in situ* sporting tasks (Kredel, Vater, Klostermann, & Hossner, 2017; Mann & Savelsbergh, 2015). This ‘paradigm shift’ has led to an enhanced understanding of the types of strategies expert performers might rely on, and in particular how expert behaviour can change when the task demands more accurately reflect those experienced during competition (Dicks, Button, & Davids, 2010; Roca, Ford, McRobert, & Williams, 2011).

In this chapter, we examine the visual search behaviours of expert athletes and discuss whether it is possible to characterise their behaviour during anticipation and decision-making tasks. We start by providing an overview of some key research findings from the past 30 years. In the second part of the chapter, we consider some of the mediating factors that influence visual search behaviour, including anxiety, contextual information, and performing a motor action. Finally, we conclude by considering whether it is possible to characterise the search behaviours of experts and focus on requirements for future research.

Overview of key findings

When skilled athletes make perceptual judgements, an analysis of their eye movements helps to reveal the visual search strategies that they use to identify information and can be used to make inferences about the specific locations from which information pickup should occur. Scientists have, in most instances, uncovered unique gaze behaviours in skilled athletes that are qualitatively and quantitatively distinct from those of lesser-skilled performers. In order to pick up meaningful information from an array of visual information, skilled athletes typically use structured and systematic visual search patterns rather than merely random strategies.

Gaze during anticipation

Superior anticipation in skilled athletes is underpinned by the use of both contextual information and by information pickup from the bodily cues inherent in an opponent’s action sequences. Gaze studies have demonstrated that superior anticipation may be facilitated by skilled performers attending more so towards bodily movements that occur *earlier* in the action sequence. For example, when anticipating the direction of a tennis serve, skilled players spend a considerable amount of time directing their gaze towards the server’s shoulder, rather than towards only the server’s racquet (Goulet, Bard, & Fleury, 1989). Similarly, in one-on-one defensive scenarios in football (soccer), during the early movement phases, elite players fixate more frequently on the knee and hip regions of their opponent, whilst novices fixate more frequently on the ball (Nagano, Kato, & Fukuda, 2004; Williams & Davids, 1998). This gaze behaviour suggests that, when observing an action sequence, skilled athletes tend to start by directing their gaze towards the body segments that commence the movement at the start of the kinetic chain, and then progressively shift their gaze towards segments or implements that move later in the chain (Abernethy, Farrow, Gorman, & Mann, 2012; Abernethy & Russell, 1987; Singer, Cauraugh, Chen, Steinberg, & Frehlich, 1996). Most commonly, this means that gaze follows a sequence where it shifts from segments that are proximal to the body core, through to those that are more distal (Figure 4.1A).

In addition to the analysis of gaze location, scientists have examined the *rate* at which the fixations transition between different locations. The key finding is that, when compared with less-skilled performers, skilled athletes often make fewer fixations of longer duration (Mann, Williams, Ward, & Janelle, 2007). The visual system uses *saccadic eye movements* to change the line of sight between successive fixations. During saccades, visual information processing is suppressed, or at least reduced (Campbell & Wurtz, 1978), and therefore it is sometimes suggested that a reduction in the number of fixations would be effective for avoiding saccadic suppression, allowing skilled athletes to more effectively extract and process visual information when under severe time constraints (Cauraugh & Janelle, 2002; Williams, 2000). Furthermore, a strategy that relies on fewer fixations may be associated with reduced information processing demands (Abernethy, 1990) and/or more information extraction from the display, thereby permitting more detailed information processing (Mann et al., 2007).

Crucially, by using eye movement recordings in conjunction with spatial manipulations, researchers have found that skilled athletes do not rely solely on their central (foveal) vision for information pickup during anticipation tasks. Experts sometimes use their central vision as a ‘pivot’ or ‘anchor’ point whilst redirecting their attention towards important information sources within the *peripheral* visual field (i.e. visual pivot strategy; Ripoll, Kerlirzin, Stein, & Reine, 1995; Shank & Haywood, 1987). For example, Woolley, Crowther, Doma, and Connor (2015) reported that football goalkeepers who had significantly better predictions of the shot directions of penalty takers mostly fixated on the non-kicking leg of their opponent; however, spatial manipulation of that leg (i.e. replacing the leg of a kick to the right with the leg of a kick to the left and vice versa) did not affect the anticipation accuracy of observers. The authors concluded that skilled players could adopt a global perceptual approach by fixating on specific regions within the field while extracting information from other body segments. It is well known that the point of gaze and the locus of attention can be dissociated so that attention can be allocated towards the peripheral visual field (Ryu, Abernethy, Mann, & Poolton, 2015; Ryu, Mann, Abernethy, & Poolton, 2016). Furthermore, rather than using eye movements, it is significantly faster to covertly switch attention using peripheral vision from one area of the display to another (e.g. Nougier, Stein, & Bonnel, 1991). Thus, skilled players could covertly shift their attention towards different locations within the peripheral visual field by using a visual pivot, resulting in fewer fixations of longer duration. These visual pivots are directed not only towards specific body segments, but also towards spaces where key events will occur in the future (e.g. ball release from the pitcher’s hand; Figure 4.1A) (e.g. Kato & Fukuda, 2002; Shank & Haywood, 1987). This evidence highlights one of the key limitations of eye movement recordings; while effective in showing the direction towards which central vision is directed, they cannot tell us where *attention* is allocated at that moment in time.

In *interceptive actions* such as those performed when hitting in cricket and baseball, batters gather visual information for anticipation from their opponents’ movements as well as the approaching ball (Panchuk & Vickers, 2006). Previously, in studies in which athletes intercept a moving ball before it bounces (e.g. volleyball and baseball) researchers have demonstrated that skilled players use smooth pursuit eye movements to keep their eyes on the ball longer than less-skilled players do, although even skilled players do not track the ball throughout its entire trajectory (Figure 4.1B) (Bahill & LaRitz, 1984; Hubbard & Seng, 1954). Longer tracking using pursuit eye movements is thought on the basis of laboratory-based studies to facilitate anticipation of the location of the moving target in the future (Brenner & Smeets, 2011; Spering, Schutz, Braun, & Gegenfurtner, 2011), though it is questionable how relevant smooth pursuit movements are in hitting sports because skilled athletes may rely more on the movement of their *head* to track the ball rather than their eyes (Mann, Spratford, & Abernethy, 2013). Research on the quiet eye phenomenon (Vickers, 1996) suggests that maintaining fixation on the moving target for the period immediately prior to a critical movement may facilitate interceptive performance by guiding accurate pre-planning and online control (Causer, Hayes, Hooper, & Bennett, 2017).

Gaze research in interceptive tasks where the ball *bounces* before bat-ball contact (e.g. cricket and table tennis) has uncovered additional features of gaze relied on by skilled athletes. The key finding is that skilled players, when compared with others, may be more adept at producing ‘predictive’ saccades towards the anticipated location of ball bounce (Land & McLeod, 2000; Mann et al., 2013). In other words, batters do not direct their central vision towards the ball throughout its ball flight; rather, they actively take their eyes off the ball (Figure 4.1B). It has been suggested that skilled batters make earlier predictive saccades, implying a better capacity for prediction (Land & McLeod, 2000; though see Sarpeshkar, Abernethy, & Mann, 2017). The reason why players make predictive saccades towards the bounce may be to make use of information available from the location and timing of the bounce when formulating an action, with the latter part of the ball trajectory before bounce difficult to rely on to identify the post-bounce trajectory (Land, 2006). Mann et al. (2013) reported that some of the world’s best cricket batters produced predictive saccades not only towards the ball bounce but also often towards the location of bat-ball contact (see also Sarpeshkar et al., 2017). They speculated that the ability to direct gaze towards contact could allow batters to monitor the path of the ball with their peripheral vision to make adjustments to their bat swing as late as is permissible by the sensorimotor system. Gaze towards the contact location may also facilitate better feedback to improve the accuracy of subsequent actions.

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Gaze when making decisions

In dynamic situations that require tactical decisions, performers must identify and attend to the most information-rich areas from the extensively distributed visual scene and make effective use of these areas (Williams, Davids, & Williams, 1999). Skilled performers appear to make better use of both their central *and* peripheral vision to attend to this information when making decisions. Vaeyens et al. (2007) investigated gaze behaviour during decision-making scenarios in football and found that successful decision makers relied on central search strategies that featured a greater number of gaze transitions between the player in possession of the ball and other meaningful areas of the display, reflecting a more structured search pattern using the ball carrier as a constant frame of reference (Figure 4.2A) (see also Mann, Farrow, Shuttleworth, & Hopwood, 2009; Roca et al., 2011). In regard to peripheral vision, skilled players sometimes fixate between, rather than towards, individual players or objects. Afonso, Garganta, Mcrobert, Williams, and Mesquita (2012) reported that highly skilled volleyball players, when playing in 6 vs. 6 situations as a defender, spend more time fixating on the receiver and the space between the attacker and the blockers, while lesser-skilled players fixate more on the attacker themselves. Skilled athletes spend more time fixating on functional spaces, which are intermediate to a number of areas of interest. Afonso et al. (2012) stated that the more effective use of peripheral vision would allow for the simultaneous extraction of a greater amount of information.

Tenenbaum (2003) conceptualised the gaze differences between skilled (context-control strategy) and less-skilled players (target-control strategy) based on long-term working memory (LTWM) theory (Ericsson & Kintsch, 1995). According to this theory, visual context-control that consists of visual search carried out under the control of memory representations directs attention to cues within a larger area around the visual fixation point, thereby eliminating irrelevant information from being elaborated upon in long-term memory. This may allow for faster decision making (Figure 4.2B).

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Factors that influence gaze behaviour

Physical exertion

A large body of literature has investigated the effects of exercise on cognitive performance, with two recent meta-analyses reporting contrasting results about whether exercise increases or decreases cognitive function (Chang, Labban, Gapin, & Etnier, 2012; Lambourne & Tomporowski, 2010). Importantly, however, the largest positive effects of exercise on any information processing measures were on visual search behaviour.

Researchers have suggested that physical exertion can produce faster response times when identifying the presence of a feature in generic visual search tasks (Aks, 1998), and when viewing sport-specific stimuli such as the ball on a football field (McMorris & Graydon, 1997). However, the positive effects observed may be specific to automated perceptual processes and mediated by individual characteristics (Moore, Romine, O’connor, & Tomporowski, 2012). Bullock and Giesbrecht (2014) showed that individuals with higher aerobic capacity performed a visual search task faster than those who were less fit, but that these effects only emerged after exercise had begun. Research into sport performers has consistently demonstrated positive effects of physical exertion on the speed of performing visual search tasks, but this is moderated by factors including physical fitness and skill level. Surprisingly though, with some exceptions (e.g. Casanova et al., 2013; Vickers & Williams, 2007; Table 4.1), most of this research has not examined *measures of gaze behaviour* that would offer insights into how the search patterns change as a function of exercise.

Player numbers

When making tactical decisions in dynamic scenarios, the number of players or features within the scene can strongly alter the differences found in the gaze of skilled and lesser-skilled performers. A series of experiments in football have used screen-based stimuli to compare the gaze behaviour of skilled and less-skilled defenders under different situtational constraints (Williams & Davids, 1998; Williams, Davids, Burwitz, & Williams, 1994). In 11 vs. 11 situations, skilled players made *more* fixations of shorter duration, with the fixations generally directed towards more peripheral areas of the display, while less-skilled players tended to focus instead on the player in possession of the ball. In 3 vs. 3 situations, there was no difference in the search rates of the skilled and less-skilled players, with all players tending to fixate on the ball and the player in possession of the ball. Finally, when viewing 1 vs. 1 situations, skilled players again employed a higher search rate, with skilled players focussing more on the hip and foot of their opponent, and less-skilled participants retaining fixation towards the ball. These findings demonstrate that differences in the gaze behaviour of skilled and less-skilled athletes can change depending on the specific constraints of the task being performed (see also Vaeyens, Lenoir, Williams, Mazyn, & Philippaerts, 2007; Vaeyens, Lenoir, Williams, & Philippaerts, 2007).

Contextual information

Non-visual situational constraints such as the presence of contextual information can also alter gaze behaviour, though the literature in this area has delivered conflicting results about whether this additional information has a positive or negative effect on performance. McRobert, Ward, Eccles, and Williams (2011) and Runswick et al. (2018a) both used a video-based temporally occluded cricket-batting task to examine the influence of contextual information on anticipatory performance, with each showing that accuracy improves with the addition of contextual information that provides additional clues about the likely outcome of the next trial. In the case of McRobert et al. (2011), this was coupled with a reduction in the mean fixation duration of the skilled batters. In comparison, Sarpeshkar et al. (2017) manipulated the likelihood of changes in ball trajectory, and Runswick, Roca, Williams, Bezodis, and North (2018b) introduced simulated game situations, each while recording the gaze of cricket batters who attempted to intercept the ball *in situ*. Both studies found that the additional contextual information had a *negative* effect on interceptive performance. While Runswick et al. (2018b) found no effects of context on gaze behaviour, Sarpeshkar et al. (2017) showed that the decrease in batting performance was associated with a decrease in time spent using predictive gaze strategies. In reconciling the differences between these studies, it may be that contextual information that *narrows* the number of possible outcomes will induce more top-down control and facilitate predictive gaze strategies that are advantageous. However, context that *increases* the number of possible outcomes (e.g. Sarpeshkar et al., 2017) could generate greater uncertainty and *decrease* performance by reducing the skilled performer’s ability to rely on those predictive gaze strategies.

Anxiety

Anxiety appears to influence gaze behaviour in a negative way. Causer, Holmes, Smith, and Williams (2011) reported that high anxiety decreased the shooting performance of elite shotgun shooters, and resulted in final fixations of shorter duration (less quiet eye). In a more dynamic task involving anticipation and decision making, Vater, Roca, and Williams (2016) showed that anxiety slowed the anticipatory judgements of skilled football players, a change that was associated with increased mental effort, and a decreased number of fixation locations relied on. When inducing anxiety in an *in situ* cricket-batting task, Runswick et al. (2018b) found that batters used shorter fixations towards more locations, and ultimately decreased the quality of their bat-ball contact (also in karate, see Williams & Elliott, 1999). The findings suggest that it is important to include anxiety in practice environments so that performers can learn to adapt to changes in gaze behaviour that can occur in response to pressure.

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Display and response characteristics

So far, we have presented research findings that have used either laboratory-based or *in situ* experimental designs to investigate factors that affect gaze behaviour (Table 4.1). It is increasingly clear though that gaze behaviour can be influenced by the way in which the perceptual information has been provided, and the responses required from participants. Most researchers have used paradigms that simplify tasks in laboratory settings to allow for greater experimental control. For instance the use of video footage as stimuli provides control and reproducibility, with third-person video footage providing methodological convenience because it is simpler to record (Mann et al., 2009). Responses to these stimuli have often consisted of verbalised, pen-and-paper, or simplified movements that allow for the unambiguous recording of responses, but do not require execution of the actual movement. Traditional information processing approaches rely on the assumption that the size, shape, and speed of objects are perceived largely through bottom-up information incident at the eye (e.g. Marteniuk, 1976). In this case, video-based paradigms, and simple responses, can produce meaningful findings when investigating gaze behaviour in anticipation and decision-making performance.

Questions have been raised as to whether the simplified experimental tasks traditionally relied on would result in findings that replicate those that would be found in the performance environment (Dicks et al., 2010; Mann, Abernethy, & Farrow, 2010; Singer et al., 1998). For instance, embodied cognition theory hypothesises that processes such as perception cannot be separated from movements of the body, because images created from external information are scaled based on one’s ability to act upon them (Proffitt, 2006). This approach extends the idea of affordances proposed by Gibson (1979), and means that the ability to act could influence perceptual behaviour and performance in sport enviornments (see Gray, 2014 for an overview). In their meta-analysis of research into expert perceptual-cognitive skill, Mann et al. (2007) found that the magnitude of expert-novice differences in skill is larger for *in situ* designs that require participants to make movement responses. In support, Dicks et al. (2010) investigated the behaviour of football goalkeepers who attempted to save penalty kicks in three *in situ* and two video simulation conditions in which verbal, joystick, and interceptive responses were used. The goalkeepers’ visual search behaviour differed as a function of the experimental design, particularly when participants were required to perform the interceptive movement. The findings suggest that research that uses perceptual or simplified movement responses may not replicate the type of gaze behaviour that would be expected to occur in a performance environment. Given, though, the manner in which the response types differed between the video simulation and *in situ* tasks in the study by Dicks et al., it is less clear whether there were genuine differences in gaze behaviour as a result of the type of response. Further work is necessary to verify this claim.

Can we model ‘expert-like’ gaze?

There has been a growing desire to summarise exactly what it is that expert performers do differently with their gaze during perceptual-cognitive tasks. An ability to model expert gaze is desirable; it would not only help develop an understanding of the processes that underpin expert performance, but would also allow scientists to perform hypothesis-driven research to predict and test outcomes when examining gaze. It would also help facilitate the development of training interventions designed to improve sport performance through the facilitation of more ‘expert-like’ gaze. But while there is a clear desire to be able to model expert gaze, it remains a challenging task.

The most common conclusion from studies of visual search has been that expert performers are characterised by gaze that is more *refined* and *efficient* than that of lesser-skilled performers (e.g. Mann et al., 2007; Savelsbergh, Williams, van der Kamp, & Ward, 2002; Williams et al., 1999). In some senses this is true, particularly when considering the spatial dynamics of gaze, that is, considering the *direction* towards which skilled athletes allocate their central vision. Experts are indeed more structured in where they look, for instance, in employing the proximal-to-distal gaze strategy when anticipating the actions of others (Goulet et al., 1989) and when using referential fixations from and back to the ball carrier when making decisions (Vaeyens, Lenoir, Williams, & Philippaerts, 2007). But it is in the temporal dynamics where the difficulties emerge when attempting to characterise expert gaze. This is best exemplified by the examination of *search rate*, which remains the most commonly reported variable for gaze analysis. A large number of studies have found that experts, when compared to lesser-skilled performers, rely on a *lower* search rate during anticipatory and decision-making tasks (i.e. fewer fixations of longer duration). However, there are numerous other scenarios in which experts rely on a *higher* rather than lower search rate, and this questions what might be the most efficient temporal strategy for gaze, and whether it is possible to characterise expert-like gaze in the temporal domain.

Much of the early work in visual search in sport supported the idea that experts rely on a lower rate of visual search. In classic work, Helsen and Starkes (1999) investigated the visual search behaviour of expert and intermediate football players who were required to watch first-person video clips of football scenarios and decide the most appropriate course of action to take when the ball was kicked towards them. Not surprisingly, expert players made faster and better decisions, but crucially the experts had a *lower search rate* when performing the task. Similarly, when anticipating the direction of penalty kicks, Savelsbergh et al. (2002) showed that expert football goalkeepers used fewer fixations of longer duration than novices, largely directing their gaze towards the kicking leg, non-kicking leg, and ball, whereas novices fixated on other areas including the trunk, arms, and hips. This finding was interpreted to be evidence that the expert goalkeepers used a ‘more efficient search strategy’ than the novices.

The tendency for expert performers to rely on fewer fixations of longer duration is supported by the Mann et al. (2007) meta-analysis of 42 studies of perceptual-cognitive skill in sport. In that study it was concluded that, when aggregated across all studies, experts rely on fewer fixations, with those fixations lasting approximately 23% longer than those of lesser-skilled athletes. There were, though, two mediating variables that influenced the magnitude of the effect size. First, the magnitude was much larger in strategic sports such as football and basketball, where wider search is required when compared to interceptive sports such as tennis and baseball. Second, the magnitude of the effect was often larger in paradigms that tested decision making and task performance *in situ* than it was when testing anticipation. These results suggest that it *is* more common for expert performers to rely on a lower search rate, but that caution is required in generalising too widely because the likelihood of finding the effect will be biased by both the sport and the specific perceptual-cognitive skill being tested.

Recent work in interceptive tasks such as cricket batting exemplifies situations in which experts rely on a higher rather than lower rate of visual search. When investigating the ability of skilled and less-skilled cricket batters to anticipate the ball flight of deliveries bowled by an opponent, McRobert, Williams, Ward, and Eccles (2009) found that skilled batters searched more locations than less-skilled batters. This equated to a ‘more exhaustive’ search pattern that was used to “search and encode scenes at a richer and more sophisticated level than less-skilled players” (p. 474). McRobert et al. (2011) subsequently found that in a scenario more representative of actual competition where batters viewed the same opponent several times in a row, the skilled but not less-skilled batters *increased* their search rate. Similarly, when hitting the ball experts sometimes rely on gaze that exploits a higher search rate; even though laboratory studies suggest that smooth pursuit should provide the most effective strategy for intercepting a moving target (Brenner & Smeets, 2011; Spering et al., 2011), skilled batters produce more saccades and often spend less time with their gaze directed towards the ball (c.f., research on quiet eye) (Land & McLeod, 2000; Mann et al., 2013; Sarpeshkar et al., 2017).

Not only are experts found to rely on a higher search rate in interceptive sports, but they also in some situations rely on a higher search rate in strategic sports such as football. In particular, a faster search rate has been associated with *superior decision making*. Mann et al. (2009) investigated the gaze behaviour of skilled youth footballers when viewing video clips of the same scenario that were shown from either a first-person player perspective or a third-person aerial perspective. The results revealed that decision making was superior when viewing the aerial rather than player perspective, with the players relying on more fixations of shorter duration when viewing the aerial footage. Similarly, when examining the decision making of youth football players, Vaeyens et al. (2007) found no difference in the search rate of participants of different playing levels (elite, sub-elite, regional). However, when applying a within-task criterion to compare those who were successful and unsuccessful decision makers (Vaeyens, Lenoir, Williams, & Philippaerts, 2007), those who were successful used a higher search rate. Collectively, these studies provide examples of superior perceptual-cognitive performance being underpinned by a search strategy that employs *more* rather than fewer fixations.

Given the manner in which the rate of visual search varies across different tasks, it seems reasonable to question whether one of the two strategies would constitute a ‘more efficient’ or ‘effective’ approach. On the one hand, efficiency may improve when employing a *lower* rate of visual search due to the extra information processing that can be performed by reducing the number of saccadic eye movements (during which information processing is diminished) (Williams et al., 1999). Yet it seems reasonable to ask why experts would need *more time* to process the visual information available during a given fixation or tracking eye movement. A more ‘efficient’ approach might be one where the same information can be processed *more quickly*. Faster processing could provide the expert with more time to scan for additional information (using a *higher* rate of search), particularly in invasive sports where the athlete is surrounded by a wealth of potential information sources (Jordet, 2005). Similarly, in hitting tasks, faster processing could allow the performer to prepare for subsequent movements, as may be the case for earlier saccades in cricket batting (Land & McLeod, 2000).

The use of a ‘visual pivot’ is another strategy that would decrease the rate of visual search and could be interpreted to constitute a more efficient approach. When using a visual pivot, central vision is directed towards a single location while peripheral vision is used to covertly switch attention between other objects (Nougier et al., 1991; Williams, 2000). This approach could be more efficient because it avoids the need for unnecessary eye movements and helps to increase the speed at which attention can be redirected between objects of interest (Nougier et al., 1991). However, skilled athletes sometimes avoid this approach and instead prefer to rely on more shifts in the direction of gaze. The rapid reduction in the acuity of vision away from central vision means that there are significant limitations in the quality of the visual information possible using peripheral vision. Accordingly, skilled athletes in some situations rely on faster rates of visual search than others, as is demonstrated by their higher rate of referential fixations away from and back to the ball carrier (Mann et al., 2009; Vaeyens, Lenoir, Williams, & Philippaerts, 2007), and the incidence of skilled footballers who use a higher frequency of ‘exploratory head movements’ to search for the position of other teammates prior to receiving a pass from a teammate (Jordet, 2005). In these situations it appears as though skilled athletes optimise their performance by preferring to perform more fixations rather than less.

Early research examining eye movements was necessarily exploratory; it was very difficult for researchers to make *a priori* predictions about the strategies on which skilled performers might rely, meaning that some of the best insights emerged from studies that interpreted differences in the gaze of skilled and less-skilled performers in a post hoc manner (e.g. Abernethy & Russell, 1987; Williams et al., 1994). Using this approach, it has been quite reasonably assumed that the optimal gaze strategy for a given task must be that employed by the skilled athletes. Given the growing body of literature on skill-based differences in gaze, it is now imperative that researchers work towards the generation of *a priori* hypotheses about the expected gaze behaviour of skilled athletes. To do so, researchers need to develop a more nuanced model of expert gaze that takes into account the constraints of the task, rather than relying on an all-encompassing statement that experts rely on a more efficient strategy and/or a lower search rate. For instance, given the different ways in which the concept of ‘efficiency’ can be interpreted, it seems questionable whether the term sufficiently describes gaze behaviour in a way that would lead to falsifiable predictions of expert behaviour. It should only be used in an *a priori* manner if it is unambiguous what constitutes more efficient behaviour in the task. Given the very goal-oriented nature of the type of tasks performed in sport (Kurz, Hegele, & Munzert, 2018), a nuanced model of expert gaze behaviour is required that can better account for how gaze is influenced by different tasks (e.g. anticipation, interception, and decision-making tasks) and by different constraints during the task (e.g. manipulations in the number of players and the amount of anxiety).

Conclusions and future directions

The classic approach to studies of gaze has been to compare the gaze behaviour of groups of skilled and lesser-skilled athletes, typically by collapsing not only the data for all trials for each individual, and then subsequently by collapsing the data across all individuals within a group. This approach has provided critical insights into the behaviour of skilled athletes, but it has been criticised because it fails to address how intra- and inter-individual differences in gaze may help to explain variability in behaviour (Dicks, Button, Davids, Chow, & Van der Kamp, 2017). When comparing individual athletes, it remains unclear whether differences between the anticipatory and decision-making performance of skilled athletes within groups can be explained by differences in their gaze behaviour. Some insights have been provided by studies that perform a within-task split of skilled players to show that good decision makers exhibit different gaze behaviours to poorer decision makers (Vaeyens, Lenoir, Williams, & Philippaerts, 2007). This work needs to be extended to examine how well differences in gaze explain differences in the performance of individuals (e.g. van Maarseveen, Oudejans, Mann, & Savelsbergh, 2018), and whether an individual’s gains in performance following training interventions that alter gaze can be explained by changes in their own gaze behaviour. On an intra-individual level, little is known about whether the amount of variability in gaze behaviour recorded across an individual’s own trials would differ between skilled and less-skilled athletes (for an exception, see Figure 4.3), and whether any variability in an individual’s gaze behaviour can explain differences in performance on a trial-by-trial basis. It would be particularly interesting to establish whether errors in gaze behaviour could explain an individual’s own instances of skill failure (Button, Dicks, Haines, Barker, & Davids, 2011; Dicks et al., 2017).

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Another consequence of the tendency to collapse data across individuals is that little is known about the gaze behaviour of *truly elite* athletes. Given the nature of sport, truly elite individuals, by definition, are a very small sample of the population; therefore it is not always possible to recruit large numbers for a research study (Swann, Moran, & Piggo, 2015). This has led to researchers needing to include athletes of a lesser skill level in their samples in order to meet the requisite sample sizes for publication, and in many cases classing their entire group as ‘expert’ or ‘elite’. This leads to a discrepancy between the data published in research articles and what is representative of an expert in reality. In order to overcome this, there have been calls for a greater push for individual case studies of *truly elite* athletes (Sarpeshkar & Mann, 2011; Williams, Fawver, & Hodges, 2017). Despite the challenges, there have been some attempts in the literature to identify the visual search strategies of truly elite athletes. As shown in Figure 4.3, Mann et al. (2013) examined the gaze of two of the world’s best cricket batters when facing deliveries projected by a ProBatter ball machine. The researchers found that, contrary to previous studies in similar fast-ball sports (Land & McLeod, 2000), these truly expert batters used a search strategy that included two predictive saccades to anticipate the location of (1) where the ball would bounce, and (2) where the bat would intercept the ball. This ensured that the batters were able to maintain their gaze on the ball at contact. A previous study of a ‘professional’ batsman suggested that only one saccade was used to bounce, and that batters could not ‘see’ the ball at contact (Land & McLeod, 2000). These data are a good example of the differences in gaze strategy between highly skilled and *truly elite* individuals. Based on these data, it is imperative that researchers and practitioners aim to gain a more in-depth understanding of the truly elite individual.

Finally, there is a requirement for future work to enhance the level of complexity with which gaze behaviour is analysed and presented. Most work to date has focussed on examining differences in lower-level characteristics, such as search rate and fixation location, while much less is known about whether experts have an advantage in their higher-level behavioural strategies. For instance, expert gaze is often remarked to be more ‘structured’ and ‘sophisticated’ that that of others. Measurements are required to better explore and quantify these higher-order strategies, including measures of the degree of randomness or structure in visual search (e.g. *entropy*; Allsop & Gray, 2014; Ryu et al., 2016); the level of variability between and within participants across trials (e.g. Sarpeshkar et al., 2017); and measures that uncover the structure and/or patterns that skilled athletes rely on when sequencing their eye movements, using, for instance, Markov chain modelling (Button et al., 2011) or bioinformatics approaches typically used for exploring DNA sequencing (Cristino, Mathôt, Theeuwes, & Gilchrist, 2010).

In summary, in this chapter we have reviewed the current literature on how experts rely on their visual search behaviour in order to make fast and accurate perceptual judgements. With the advances in technology and knowledge about the behaviour of skilled athletes, scientists have been able to develop a detailed understanding of how visual information is exploited to make efficient and effective judgements in high-pressure environments. However, given the constraints and differences in methodologies employed across the domain, especially with display and response characteristics, it remains difficult to extrapolate these data to an applied setting for training and development. The impact of critical aspects of performance that are prevalent in competitive sport, including anxiety, physical exertion, and contextual information, further clouds the transferability of these data for practitioners. Therefore, despite the wealth of research in this area, and the descriptive data outlining the ‘typical’ expert characteristics, there is a lack of a nuanced theoretical model to make *a priori* predictions for the type of gaze behaviour that should be expected of an individual in a specific task. In future, researchers should look to develop such a model, taking into consideration inter- and intra-participant variability, as well as provide a more rigid framework for isolating ‘truly’ expert gaze characteristics and how these are developed.

Figure 4.1 A schematic representation of gaze behaviour when anticipating. Grey and white (open) circles, respectively, indicate the visual fixations made by skilled and less-skilled athletes.

Figure 4.2 A schematic representation of gaze behaviour during decision-making tasks. Panel A represents referential fixations made by skilled players from and back to the ball carrier. Panel B shows the gaze strategy proposed by Tenenbaum (2003), indicating the use of a visual pivot by skilled but not less-skilled athletes.

Figure 4.3 An example visualisation of intra- and inter-individual differences in variability of gaze. The figure displays a schematic demonstration of gaze behaviour across a series of trials, adapted from Mann et al. (2013). Each horizontal line represents the time course of an individual trial for the two elite (E1 and E2) and two club-level participants (C1 and C2) for three different bounce locations (full, good, and short length) when cricket batters hit a ball. Symbols demonstrate the presence and timing of saccades, and whether gaze coincided with the ball at the moment of bat-ball contact. The presentation of individual trials conveys information about intra- and inter-participant variability between trials and across conditions.

Table 4.1 Factors affecting gaze behaviour: examples of relevant research.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Influencing factor | Illustrative research | Task | Performance measure | Key gaze measures | Display/response | Conclusion |
| Physical exertion | Casanova et al. (2013) | Football defending | Anticipation | Visual Search | Screen/option selection | Exercise induced a decrease in anticipation accuracy and in the number of fixations. |
|  | Vickers and Williams (2007) | Biathlon | Shooting Accuracy | Quiet Eye | Simulated shooting system | Quiet eye duration and shooting accuracy decreased with higher power output. |
| Player numbers | Williams and Davids (1998) | Football defending | Anticipation | Visual Search | Screen/movement response | Skill-level differences in visual search behaviour were observed in 1 vs. 1 but not 3 vs. 3 conditions. |
|  | Williams et al. (1994) | Football defending | Anticpation/decision making | Visual Search | Screen/movement response | Using 11 vs. 11 film, skilled performers displayed more fixtions of shorter duration than less-skilled. |
| Contextual information | McRobert et al. (2011) | Cricket batting | Anticipation | Pre-release fixations | Screen/movement response | Anticipation accuracy increased and fixation duration decreased in context conditions. |
|  | Sarpeshkar et al. (2017) | Cricket batting | Bat-ball contact | Ball-flight saccades | Pro-batter/interception | Quality of bat-ball contact and time using predictive gaze decreased in context conditions. |
| Anxiety | Causer et al. (2011) | Shotgun shooting | Shooting accuracy | Quiet Eye | *In situ* | Shooting accuracy and quite eye duration decreased in anxiety conditons. |
|  | Runswick et al. (2017) | Cricket batting | Bat-ball contact | Pre-release fixations | *In situ* | Quality of bat-ball contact decreased and number of fixations increased in anxiety conditions. |

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