An Ecological Approach to Gaze Behaviour in Sport

MILLER-DICKS, Matt, DAVIDS, Keith <http://orcid.org/0000-0003-1398-6123> and ARAÚJO, Duarte

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Abstract

The primary function of visual search in team sport contexts is to gather information for guiding actions relative to teammates, opponents, interpersonal spaces and distances, and objects in the environment. For instance, during search by elite performers, a goalkeeper gathers information from a penalty taker's body (i.e., the eyes, torso, and legs) and the ball location when coordinating the timing of when and where to move in the penalty kick situation. Similarly, in other team sports, point guards in basketball, quarterbacks in American football, and midfielders in football (soccer), are situated in dynamic performance contexts that require these athletes to actively search for information to act adaptively. When considered from an ecological perspective, gaze behaviour reflects one means of gathering optic information, and as such, active search also relies heavily on head and body movements. Thus, an ecological approach emphasises the study of gaze behaviour in sport to capture how athletes realise active exploratory actions to perform in sport performance. The current chapter will outline an active search account of sport expertise, firstly providing an overview of an ecological approach before reflecting on findings from experiments, which have aimed to understand differences in gaze behaviour between video-based and performance (*in situ*) settings. We conclude by focusing on implications of evidence which points to the functional role of variability in gaze behaviour between elite athletes, considered alongside avenues for future research.

In research on expertise in sport, an extensive body of literature exists on understanding the perceptual-motor processes that underpin elite performance (Seifert et al., 2013; Araújo et al., 2019). One facet of this research has been dedicated to the examination of gaze behaviour. To identify the important locations of information attended to by athletes during the visual control of sport actions, researchers have utilized eye-tracking systems to record foveal (central) vision (Dicks et al., 2009). Several measures have been studied with the aim of enhancing understanding of how expertise may shape gaze behaviour (cf. Williams & Ericsson, 2005), commonly focussing on variations around the location, duration, and number of fixations (McGuckian et al., 2018; Dicks et al., 2010b).

A notable feature of early gaze behaviour research in sport, specific to the study of anticipation and decision-making, was reflected in the use of video- or film-based paradigms to study expertise in laboratory contexts (for a review, see Dicks et al., 2009). During video tasks, participants are asked to watch a screen to respond to footage of a simulated sport performance situation before being required to predict an event outcome (Abernethy & Russell, 1987) or select and verbally report an action that they would perform if they were the player being observed (Vaeyens et al., 2007). Specific concerns over the disparity between video simulations and on-field performance settings have been conveyed for over 30 years (see Abernethy et al., 1993). The use of video technology limits, not only the information sources to be viewed, but also the actions that participants can make (see Dicks et al., 2009). Thus, a central concern has been that the processes underlying expertise may function differently depending on the action that a performer can realise within an experimental setting (Mann, et al., 2013).

In response to concerns regarding the suitability of video-based methods for the study of gaze behaviour in sport, contemporary perspectives (e.g., Araújo et al., 2017; Dicks et al., 2019; van der Kamp et al., 2008), motivated by James Gibson's (1979) ecological approach to visual perception have aimed to develop new *in situ* methods to study this facet of expertise. Indeed, Gibson's (1979) ecological theory of direct perception has long been emphasised as a starting point for the study of gaze behaviour in sport, given that the core theme of Gibson's theory is that the pick-up of information in the environment directly entails the detection of sources that are relevant for regulating one's actions (Beek et al., 2003; Savelsbergh et al., 2004).

The aim of this chapter is to provide an overview of the ecological perspective on how information regulates action, focusing on how associated research has examined gaze behaviour in sport. We begin by providing an overview of key tenets of the ecological approach, emphasising some theoretical considerations for gaze behaviour research in the sport sciences literature. We then provide an overview of key findings from experiments, which have highlighted differences in gaze behaviour between video and natural (*in situ*) settings. Finally, we consider contemporary evidence, which points to the functional role of variability in gaze behaviour between elite athletes, considered alongside requirements for future research.

An Ecological Perspective on Visual Perception and Action

Gibson's (1979) ecological approach to visual perception emphasises that adaptive human movement is underpinned by a synergetic relationship between an individual and the environment. When coordinating their movements with respect to their environment, humans use information to locate objects, obstacles, or surfaces in space *(where* information) at a specific moment in time *(when* information) (Araújo & Davids, 2009; Fajen et al., 2009). With experience, athletes can learn to exploit a range of surrounding patterned energy flows that informs how to act more effectively and efficiently (Warren, 2006). Performers are proposed to exploit surrounding spatiotemporal energy patterns that are specific to the 'to-beperceived' or 'to-be-acted-upon' properties of the environment. Therefore, inferential processes are dispensable and direct perceptual contact is possible. Gibson (1979) emphasised that animals with compound eyes, as well as animals with chambered eyes, show visually guided behaviour (such as catching in the presence of an expanding shadow specifying an approaching ball). These data have been construed as evidence that these animals have evolved to detect optical information in the array; thus, retinal images are not necessary for vision, but information is needed to regulate action (Mace, 1986).

Gibson proposed that the structure of information in the surrounding optical energy arrays (in the case of vision) are used by movers to control their movements relative to the environment (J.J. Gibson & E.J. Gibson, 1955). From this perspective, optical variables are features of the environment that specify the guidance of action, such as time-to-collision information that a goalkeeper might exploit when timing their diving action, relative to the moment that a penalty taker contacts the ball (Navia et al., 2017). By contrast, in the case of the penalty kick, there is also information that unfolds earlier in the penalty taker's run-up that does not specify the time-to-collision between the penalty taker and the ball (Dicks et al., 2010a). As such, individuals can learn to improve the accuracy of their behaviour if they detect the time-to-collision information that specifies action in the environment. Therefore, from this point of view, the development of perceptual skill entails a learning process whereby the performer begins to explore and later to exploit the specifying information available in the environment to couple to their movements (Jacobs & Michaels, 2007).

From an ecological view, the process of perceptual learning is referred to as the education of attention or attunement (E.J. Gibson & Pick, 2000; J.J. Gibson, 1966). For example, in racket sports such as tennis and badminton, if a highly-skilled player were consistently moving in the correct direction when anticipating the shots of an opponent, this would likely imply that they were attending to biological motion information that specifies the correct shot direction (Huys et al., 2009). By contrast, a lesser-skilled or novice player may attend to biological motion information that has a moderate or high correlation with shot direction, therefore supporting the adaptive control of movement. Huys et al. (2009) demonstrated that skilled tennis players' ability to anticipate opponent shot directions were dependent on the pick-up of global relative motion information distributed across arm and racket, trunk, and leg locations. In contrast, less-skilled players were less sensitive to these sources of biological motion information (Smeeton et al., 2013).

An example of how these proposals translate to the gaze behaviour and expertise is demonstrated through an oft-cited example of work conducted by Savelsbergh et al. (2002) who compared the gaze behaviour of near-expert and novice goalkeepers when watching video footage of penalty kicks. First, in order to set the scene, detailed kinematic analyses of penalty taker actions have revealed that information, such as the approach angle of the kicker to the ball, is largely incongruent with kick direction (Dicks et al., 2010a). In contrast, information that unfolds, following initiation of the kicking action, is more adaptive or useful; including the placement of the non-kicking foot and the orientation of the kicking foot at the moment of foot-ball contact (Lopes et al., 2014). Thus, gaze behaviour oriented to non-kicking and kicking foot locations, towards the end of the penalty taker action, is likely to support more accurate anticipation.

In support of such a suggestion, Savelsbergh et al. (2002) demonstrated that, as kick movement time elapsed, novice goalkeepers fixated on the trunk, arm, and hip regions of the penalty taker. In contrast, semi-professionals spent longer time fixating upon the kicking leg, non-kicking leg, and ball regions. Thus, the results indicated that the semi-professional goalkeepers had learnt to attend to fewer, more informative kinematic regions, such as the kicking leg, in comparison with the novice participants. A further study by Savelsbergh et al. (2005) indicated that near-expert goalkeepers with particularly high levels of success for predicting penalty kick direction fixated for longer on the non-kicking leg region of the penalty taker, in comparison to less successful near-expert goalkeepers who fixated for longer on the head region.

Further to providing a theoretical framework to examine the information exploited during sport tasks, an important contribution of Gibson's work is the proposal that perceptual attunement is an active process (Gibson, 1966). Gibson stressed the importance of the performer's movement in detecting and discovering specifying information. In Gibson's view, perceivers are rarely passive: to detect information, perceptual systems scan the ambient arrays to actively detect information. Furthermore, by moving, performers can create spatiotemporal energy patterns that are specific to environmental properties. Thus, as a performer moves, prospective information is generated, which informs on the difference between a current and required behaviour, modifying the relationship between athlete and the environment, and linking information and movement in a continual cycle (Dicks et al., 2019).

The emphasis on movement in perception implies that body, head, and eye movements co-structure information for guiding the athlete's interaction with the environment (van der Kamp & Dicks, 2017). Consequently, there is a requirement for empirical approaches to examine perception-action as a reciprocal system in sport expertise (Araújo et al., 2019). Indeed, it is this active perception account that has been increasingly instrumental in the motivation to study gaze behaviour when it is contextualized by actions, a perspective that we will consider further in the next section.

Differences between Video and In Situ Methodologies: The Importance of Context

A contemporary formulation that has been influential in the literature of gaze behaviour in sport is the perspective of van der Kamp et al. (2008) who integrated Gibson's (1979) theory of direct perception with the neuro-anatomical perspective of Milner and Goodale (1995). Milner and Goodale drew together neuroscientific evidence that two neuroanatomically separate, but interconnected, anatomical streams exist within the visual cortex: dorsal 'vision-for-action' and a ventral 'vision-for-perception'. The dorsal system is proposed to specialise in the use of visual information for the control of movements (i.e., action), whereas the ventral system is concerned with the use of visual information to obtain knowledge about objects, people, events, and places (i.e., perception).

Specific to sport performance, van der Kamp and colleagues (2008) proposed that vision for action entails the online pick-up of information to instantaneously control on-going movement, while vision for perception does not involve such a strict time constraint, with different sources of information exploited over long-time intervals (see also, Ramsey et al., 2022). Critically, van der Kamp and colleagues emphasised that perception and action (the ventral and dorsal systems) are complementary, the implication being that, in order to fully understand gaze behaviour in sport, it is essential for researchers to study the control of movements in real-time (Dicks et al., 2019; Navia et al., 2022).

The perspective of van der Kamp et al. (2008) is consistent with the long-held view that both the display characteristics and response modes used in the study of expertise (e.g., asking sportspeople to watch video simulations) are clearly different from those encountered during sport performance (e.g., Abernethy et al., 1993; Dicks et al., 2009). Indeed, it is important to acknowledge that some of the formative, seminal investigations of gaze behaviour in sport have been motivated by cognitive accounts of expertise (for a review, see Vickers, 2007). As such, the emphasis on *in situ* settings would appear to be of central importance to the development of understanding across gaze behaviour research (for a detailed discussion about how *in situ* relates to the ecological notion of representative task design, see Araújo & Davids, 2015). For instance, Abernethy (1990) compared the pattern of gaze and verbal response accuracy of expert and novice squash players under a video and on-court simulation of squash match-play. The trend of results revealed similar fixation patterns for both conditions, although there was a substantial increase in gaze locations on pre-contact ball-flight information for the on-court simulation. However, the on-court task was limited somewhat due to the non-portability of the eye-tracker system used, meaning that participants viewed the opponent's action from a seated on-court position, not whilst in motion on court.

Technological advances meant that Singer et al. (1998) were able to study the *in situ* pattern of gaze and service return behaviours of expert tennis players. Results indicated individual differences in gaze patterns used by expert players, with the two most skilled players in their study using pursuit tracking of the tennis ball throughout the ball-toss phase and during the initial and final portions of ball-flight. In comparison, less-skilled players used a considerably more scattered and variable scan-path comprising largely of anticipatory saccades (see also, Land & McLeod, 2000). The *in situ* findings of Singer et al. (1998) have been supported with comparable results highlighting the importance of gaze patterns specific to ball-flight information prior to successful interceptive actions (e.g., McPherson & Vickers, 2004; Rodrigues et al., 2002). Skilled athletes were shown to direct their gaze towards the kinematic actions of an opponent for a portion of the pre-ball contact time implying a possibly comparable pattern of gaze to video simulation tasks. However, the importance of this information appears only secondary to the information obtained from ball-flight (see also Panchuk & Vickers, 2006).

Relatedly, gaze-behaviour studies motivated by the perspective of van der Kamp et al. (2008), have demonstrated that sport performers utilize different information between visual judgement and visual perception-action tasks. Reminiscent of the earlier work of Abernethy (1990), Dicks and colleagues (Dicks et al., 2010b) reported distinct differences in the timing and location of eye movements of goalkeepers, contextualized in video and in situ settings. Moreover, and in support of proposals from Gibson's approach, even when in situ, different response requirements when facing penalty kicks result in different patterns of gaze (see

Figure 1). Specifically, goalkeepers were found to fixate the ball earlier and for a longer duration when attempting to save kicks in comparison with judgement-oriented response conditions.

INSERT FIGURE 1 ABOUT HERE

More recently, van Maarseveen et al. (2016) examined the performance of skilled football players on different video tests of decision-making and anticipation and compared these performances to on-field performance during small-sided games. Results revealed no correlations between the level of performance among the video-based tests. The on-field performance of the players was also not predicted by any of the video-based tests, suggesting that current laboratory (judgement-oriented) and field-based (action-oriented) measures of anticipation and decision-making capture different elements of these respective skills (McGuckian et al., 2018).

Variability and Individual Differences

The general trend in the literature on gaze behaviour in sport, as described in this chapter, has seen an increase in studies examining real-time sport performance settings, commonly referred to as *in situ* (Dicks et al., 2010a; Vickers, 2007). Whilst there appears to be a general consensus on the importance of such a methodological shift, arguably, debate still remains on how best to analyze gaze-behaviour data (Hunt et al., 2022). For example, a noticeable feature of the gaze-behaviour findings described in this chapter is that data are almost exclusively reported as a mean representation of group-level performance, averaged across participants (e.g., Dicks et al., 2010b). Thus, it has been interpreted that researchers have implicitly emphasised that gaze patterns may be relatively invariant within individuals of respective skill-levels (e.g., experts and novices) behaving similarly (Ramsey et al., 2020). The indirect implication of this view is that, to perform successfully, participants must converge upon a common (i.e., standardized) optimal gaze behaviour pattern to achieve successful performance outcomes in a given task (Vickers, 2007).

Dicks et al. (2017) recently highlighted an apparent contradiction in the domain of perceptual-motor control, with coordination studies largely taking an alternative approach to the gaze-behaviour literature described above. Movement coordination research has increasingly emphasized the role of coordination variability in adapting to task constraints (Davids et al., 2003). Specifically, studies have demonstrated that there are different coordination solutions that can be utilized by performers in order to achieve success within the same performance context (e.g., Chow et al., 2008). That is, researchers have aimed to capture differences within and between skill-levels during movement organization, with evidence pointing to the fact that variability in action appears to facilitate skilful action during both learning and performance (Araújo, Dicks, et al., 2019).

Based on coordination theory and data, Dicks et al. (2017) argued that calculation of the group average may misrepresent individual participant data, limiting understanding of learning and performance. For instance, recent research that has been motivated by an ecological dynamics perspective has demonstrated that skilled coordination behaviour is largely individualized and contextualized (e.g., Andrews et al., 2024). In the sport expertise literature, a central consideration that needs addressing, therefore, is whether variation in organization of gaze patterns may be indicative of an important aspect of adaptive performance. It follows that an over-reliance on average gaze data may mask understanding of the individual adaptations present in learning and development (Hacques et al., 2021).

Dicks et al. (2017) subsequently proposed new lines of investigation to better understand the role of variability in adapting gaze behaviour. In particular, it was proposed that a primary requirement for future research was whether the same level of success can be achieved after exploiting different patterns of gaze. For example, earlier research (e.g., Croft et al., 2010) had reported interindividual differences in the gaze behaviour – ranging from pursuit tracking patterns to rare foveation of the ball location – utilized by skilled youth cricket batsmen when successfully executing cricket strokes. Indeed, research that has subsequently presented individual participant variations in fixation durations during ten-pin bowling (Chia et al., 2017) and football goalkeeping (Ramsey et al., 2020) lend further support to such a suggestion.

Dicks and colleagues (2017) drew upon proposals from literature investigating the control of coordination (Müller & Sternad, 2004), to propose that a bandwidth (solution manifold) of variability in gaze would increase or decrease depending on the number of gaze patterns that can be used to achieve outcomes in a given task (Savelsbergh et al., 2004). Such a suggestion was supported by observations from basketball jump-shot and free-throw analyses. During the execution of jump-shots, only a small bandwidth of gaze patterns has been shown to support successful performance, whereas a number of gaze patterns appear possible prior to successful free-throw performance (de Oliveira et al., 2008).

Indeed, inter-individual analysis of the shooting actions of different skilled basketball players (Button et al., 2003) have revealed that coordination of elbow and wrist actions differ from throw to throw, allowing each player to co-adapt to subtle differences in ball-release parameters, arising from context, to maintain desired performance outcomes. Together, these results point to the existence of a bandwidth of gaze-coordination variability—standard deviation of joint variables and gaze durations—that allows a combination of joints (e.g., elbow and wrist) to act in synergy to achieve successful performance outcomes during skilled action (see also, Słowiński et al., 2019).

Returning to the penalty kick literature described earlier in the chapter (e.g., Savelsbergh et al., 2002), the implication of the view of Dicks et al. (2017) is that more than one gaze pattern could be used to successfully anticipate an opponent's action. Indeed, growing evidence supports this suggestion, with results from a study of expert futsal goalkeepers conducted by Navia et al. (2017), when facing penalty kicks. They found that gaze behaviour in the first phase of the run-up differed markedly between participants in the location and timing of fixations, whereas the gaze variation decreased in the second phase, interpreted as perceptual attunement to more reliable visual information as the kickers' actions unfolded (Dicks et al., 2010a). These findings suggest that looking at the right place at the right time may, in fact, be particularly critical for successful performance in interceptive actions (e.g., Land & McLeod, 2000). The search pattern used to arrive at a particular gaze location in a controlled experimental setting may not be a necessary prerequisite for successful performance in competitive contexts (Dicks et al., 2009).

The findings of Navia and colleagues (2017) may be indicative of a quiet eye (QE) gaze pattern. QE, which is the final fixation prior to final movement onset (Vickers, 1996; Vickers, 2007), has been proposed to reflect the parameterization of the necessary movement without the pick-up of further visual information during the control of action (Panchuk & Vickers, 2009). For example, Panchuk and Vickers (2006) reported that skilled ice hockey goaltenders utilized significantly longer QE durations for saved shots in comparison with trials in which goals were conceded (for a contrasting finding, see Piras & Vickers, 2011).

In order to further understand such contradictory findings, Ramsey et al. (2020) examined individual differences in gaze behaviour of five experienced goalkeepers with results revealing discrepancies in QE duration between and within participants (see Figure 2). For example, the QE of Participant 4 during one successful trial was 1,960 ms, while a QE duration of 160 ms was recorded on a separate successful trial for the same participant. Similarly, Participant 2 revealed QE durations ranging between 0 ms and 1,520 ms. Thus, comparable to the basketball shooting data described above (e.g., de Oliveira et al., 2008), findings indicated that variations in gaze behaviours can emerge without negative performance consequences. This finding implies that particular gaze dependent variables such as QE may be better understood if integrated into a broader understanding of information-movement coupling that emphasizes how context and individual differences may shape QE (see also, Harris et al., 2023).

INSERT FIGURE 2 ABOUT HERE

Conclusion and Future Directions

The literature described in the final section of this chapter has highlighted that multiple information-movement couplings can be used by different performers when achieving successful performance outcomes in sport (Dicks et al., 2017). However, it is important to note that further studies are required to better understand whether variation in gaze patterns may provide performers with a mechanism to adapt to dynamic sport settings (see Ramsey et al., 2020). Combining motion capture and eye tracking has begun to offer the opportunity to measure gaze and movement coordination simultaneously in order to determine a comprehensive understanding of perceptual-motor performance (Hunt et al., 2022). Such advances promise to bring implications for the understanding and development of sporting expertise. Whilst an in-depth study of the relationship between gaze behaviour and movement variability will further current empirical understanding, such an empirical endeavour would also require the development of novel measures (for examples in over-ground walking, see Hunt et al., 2023; Matthis et al., 2018).

Further understanding of the processes that underpin perception and action of elite performers, also has implications for training and development of such skills (Araújo et al., 2020; Dicks et al., 2017). In extant literature, gaze behaviour has often been used as the basis for learning studies, within which novices are trained to replicate the gaze patterns of experts. This approach has provided evidence of performance improvements after gaze training (e.g., Vine et al., 2011), although such findings have not been replicated across all studies

(Klostermann et al., 2015). Thus, future work would benefit from gaining a more comprehensive understanding of changes in gaze patterns during learning (Hacques et al., 2022) in order to better inform future training interventions that seek to expedite this facet of elite sport performance (Dicks et al., 2015).

References

Abernethy, B. (1990). Expertise, visual search, and information pick-up in squash. *Perception*, *19*(1), 63-77.

Abernethy, B., & Russell, D. G. (1987). The relationship between expertise and visual search strategy in a racquet sport. *Human Movement Science*, *6*, 283-319. Doi:10.1016/0167-9457(87)90001-7

Abernethy, B., Thomas, K. T., & Thomas, J. T. (1993). Strategies for improving understanding of motor expertise (or mistakes we have made and things we have learned!). In J. L. Starkes & F. Allard (Eds.), *Cognitive Issues in Motor Expertise* (pp. 317-356). Elsevier.

Andrews, M., Gorman, A. & Crowther, R. (2024). Functional movement variability to maintain delivery speed in cricket fast bowling. *European Journal of Sport Science*, doi:10.1002/ejsc.12045.

Araújo, D., & Davids, K. (2015). Towards a theoretically-driven model of correspondence between behaviours in one context to another: Implications for studying sport performance. *International Journal of Sport Psychology, 46*(6), 745-757.

Araújo, D., Dicks, M., & Davids, K. (2019). Selecting among affordances: a basis for channeling expertise in sport. In M. L. Cappuccio (Ed.). *The MIT Press Handbook of Embodied Cognition and Sport Psychology*. (pp.557-580). The MIT Press

Araújo, D., Hristovski, R., Seifert, L., Carvalho, J., & Davids, K. (2019). Ecological cognition: expert decision-making behaviour in sport. *International Review of Sport and Exercise Psychology*, *12*(1), 1–25. doi: 10.1080/1750984X.2017.1349826

Beek, P. J., Jacobs, D. M., Daffertshofer, A., & Huys, R. (2003). Expert performance in sport: views from joint perspectives of ecological psychology and dynamical systems theory. In J. L. Starkes & K. A. Ericsson (Eds.), *Expert Performance in Sport: Advances in Research on Sport Expertise* (pp. 321-344). Human Kinetics.

Button, C., Macleod, M., Sanders, R., & Coleman, S. (2003). Examining movement variability in the basketball free-throw action at different skill levels. *Research Quarterly for Exercise and Sport, 74*(3), 257-269.

Chia, S., Chow. J. Y., Dicks, M., & Lee, M. (2017). An exploratory analysis of variations in quiet eye duration within and between levels of expertise. *International Journal of Sport and Exercise Psychology*, *15*(3), 221-235 doi:10.1080/1612197X.2015.1114503

Chow, J. Y., Davids, K., Button, C., & Rein, R. (2008). Dynamics of movement patterning in learning a discrete multiarticular action. *Motor Control, 12*(3), 219-240.

Croft, J. L., Button, C., & Dicks, M. (2010). Visual strategies of sub-elite cricket batsmen in response to different ball velocities. *Human Movement Science*, *29*(5), 751-763.

Davids, K., Glazier, P., Araújo, D. & Bartlett, R.M. (2003). Movement systems as dynamical systems: The role of functional variability and its implications for sports medicine. *Sports Medicine 33,* 245-260.

de Oliveira, R. F., Oudejans, R. R., & Beek, P. J. (2008). Gaze behavior in basketball shooting: Further evidence for online visual control. *Research Quarterly for Exercise and Sport*, *79*(3), 399-404.

Dicks, M., Araújo, D., & van der Kamp, J. (2019). Perception-action for the study of anticipation and decision-making. In A. M. Williams & R. C. Jackson (Eds.). *Anticipation and Decision Making in Sport*. (pp.181-199). Routledge.

Dicks, M., Button, C., & Davids, K. (2010a). Availability of advance visual information constrains association-football goalkeeping performance during penalty kicks. *Perception, 39*, 1111-1124.

Dicks, M., Button, C., & Davids, K. (2010b). Examination of gaze behaviors under in situ and video simulation task constraints reveals differences in information pickup for perception and action. *Attention, Perception, & Psychophysics, 72*(3), 706-720. doi: 10.3758/APP.72.3.706

Dicks, M., Button, C., Davids, K., Chow, J. Y., & van der Kamp, J. (2017). Keeping an eye on noisy movements: on different approaches to perceptual-motor skill research and training. *Sports Medicine, 47*(4), 575 - 581. doi:10.1007/s40279-016-0600-3

Dicks, M., Davids, K., & Button, C. (2009). Representative task designs for the study of perception and action in sport. *International Journal of Sport Psychology, 40*(4), 506-524.

Dicks, M., van der Kamp, J., Withagen, R., & Koedijker, J. (2015). “Can we hasten expertise by video simulations?” Considerations from an ecological psychology perspective. *International Journal of Sport Psychology, 46*, 109-129. doi: 10.7352/IJSP2015.46.

Fajen, B. R., Riley, M. A., & Turvey, M. T. (2009). Information, affordances and the control of action in sport. *International Journal of Sport Psychology, 40*, 79-107.

Gibson, J. J. (1966). *The Senses Considered as Perceptual Systems*. Houghton Mifflin.

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. Houghton Mifflin.

Gibson, J. J., & Gibson, E. J. (1955). Perceptual learning: Differentiation or enrichment? *Psychological Review, 62*(1), 32-41. Doi: 10.1037/h0048826

Hacques, G., Komar, J., Dicks, M., & Seifert, L. (2021). Exploring to learn and learning to explore. *Psychological Research, 85*, 1367-1379, doi:10.1007/s00426-020-01352-x

Hacques, G., Dicks, M., Komar, J., & Seifert, L. (2022). Visual control during climbing: variability in practice fosters a proactive gaze pattern. *PloS One*, 17(6): e0269794. doi:10.1371/journal.pone.0269794

Harris, D.J., Wilson, M.R., & Vine, S.J. (2023). The functional role of visual information and fixation stillness in the quiet eye. *PLoS ONE*, *18*(11): e0293955. doi:10.1371/journal.pone.0293955

Hunt, R., Blackmore, T., Frost, G., Mills, C., & Miller-Dicks, M. (2023). The visual control of locomotion when stepping onto moving surfaces: a comparison of younger and older adults, *Experimental Gerontology*, 174, 112117, doi: 10.1016/j.exger.2023.112117

Hunt, R., Mills, C., Blackmore, T., & Dicks, M. (2022). Evaluating the integration of eye-tracking and motion capture technologies: quantifying the accuracy and precision of gaze measures. *I-Perception*, 13(0), 1-25. doi: 10.1177/20416695221116652

Huys, R., Cañal-Bruland, R., Hagemann, N., Beek, P. J., Smeeton, N. J., & Williams, A. M. (2009). Global information pickup underpins anticipation of tennis shot direction. *Journal of Motor Behavior*, *41*(2), 158-170. Doi: 10.3200/JMBR.41.2.158-171

Klostermann, A., Vater, C., Kredel, R., & Hossner, E. J. (2015). Perceptual training in beach volleyball defence: different effects of gaze-path cueing on gaze and decision-making. *Frontiers in Psychology, 6*, 1834.

Land, M. F., & McLeod, P. (2000). From eye movements to actions: how batsmen hit the ball. *Nature Neuroscience, 3*(12), 1340-1345.

Lopes, J. E., Jacobs, D. M., Travieso, D., & Araújo, D. (2014). Predicting the lateral direction of deceptive and non-deceptive penalty kicks in football from the kinematics of the kicker. *Human Movement Science, 36,* 199-216. Doi:10.1016/j.humov.2014.04.004

Mace, W. (1986). J. J. Gibson's ecological theory of information pickup: cognition from the ground up. In T. J. Knapp & L. C. Robertson (Eds.). *Approaches to Cognition: Contrasts and Controversies* (pp.137-157). LEA

Mann, D. L., Dicks, M., Cañal-Bruland, R., & van der Kamp, J. (2013). Neurophysiological studies may provide a misleading picture of how perceptual-motor interactions are coordinated. *i-Perception, 4,* 78-80. doi: 10.1068/i0569ic

Matthis, J. S., Yates, J. L., & Hayhoe, M. M. (2018). Gaze and the control of foot placement when walking in natural terrain. *Current Biology*, *28*(8), 1224-1233.

McGuckian, T. B., Cole, M. H., & Pepping, G. J. (2018). A systematic review of the technology-based assessment of visual perception and exploration behaviour in association football. *Journal of Sports Sciences*, *36,* 861-880. doi: 10.1080/02640414.2017.1344780

McPherson, S. L., & Vickers, J. N. (2004). Cognitive control in motor expertise. *International Journal of Sport and Exercise Psychology, 2*(3), 274-300.

Milner, A. D., & Goodale, M. A. (1995). *The Visual Brain in Action*. Oxford: Oxford University Press.

Müller, H., & Sternad, D. (2004). Decomposition of variability in the execution of goal-oriented tasks: three components of skill improvement. *Journal of Experimental psychology*. *Human Perception and Performance, 30*(1), 212-233.

Navia, J. A., Dicks, M., van der Kamp, J., & Ruiz, L. M. (2017). Gaze control during interceptive actions with different spatiotemporal demands. *Journal of Experimental*

Psychology: Human Perception and Performance, 43(4), 783-793. Doi: 10.1037/xhp0000347

Navia, J. A., Avilés, C., Dicks, M., & Ruiz-Pérez, M. (2022). The spatiotemporal control of expert tennis players when returning fast serves: a perception-action perspective. *Journal of Sports Science*, *40*(1), 16-23. doi: 10.1080/02640414.2021.1976484

Panchuk, D., & Vickers, J. N. (2006). Gaze behaviors of goaltenders under spatial–temporal constraints. *Human Movement Science, 25*(6), 733-752.

Panchuk, D., & Vickers, J. N. (2009). Using spatial occlusion to explore the control strategies used in rapid interceptive actions: Predictive or prospective control?. *Journal of Sports Sciences, 27*(12), 1249-1260.

Piras, A., & Vickers, J. N. (2011). The effect of fixation transitions on quiet eye duration and performance in the soccer penalty kick: Instep versus inside kicks. *Cognitive Processing*, *12*(3), 245-255.

Ramsey. H, Hacques, G., Seifert, L., Button, C., Davids, K., & Dicks, M. (2020). Considerations for the study of individual difference in gaze control during expert visual anticipation: an exploratory study. *Movement and Sport Science*, 110, 39 – 47, doi:10.1051/sm/2020006

Ramsey, H., Dicks, M., Hope, L., & Reddy, V. (2022). Expert sports performance during interaction: gaining maximum grip on deception and disguise. *Sports Medicine-Open*, *8*(47), doi:10.1186/s40798-022-00441-y

Rodrigues, S. T., Vickers, J. N., & Williams, A. M. (2002). Head, eye and arm coordination in table tennis. *Journal of Sports Sciences, 20*(3), 187-200.

Savelsbergh, G. J., Williams, A. M., van der Kamp, J., & Ward, P. (2002). Visual search, anticipation and expertise in soccer goalkeepers. *Journal of Sports Sciences*, *20*(3), 279-287. Doi: 10.1080/026404102317284826

Savelsbergh, G. J., Van der Kamp, J., Williams, A. M., & Ward, P. (2005). Anticipation and visual search behaviour in expert soccer goalkeepers. *Ergonomics, 48*(11-14), 1686-1697.

Seifert, L., Button, C., & Davids, K. (2013). Key properties of expert movement systems in sport: an ecological dynamics perspective. *Sports Medicine, 43*, 167-178.

Singer, R. N., Williams, A. M., Frehlich, S. G., Janelle, C. M., Radlo, S. J., Barba, D. A., & Bouchard, L. J. (1998). New frontiers in visual search: An exploratory study in live tennis situations. *Research Quarterly for Exercise and Sport, 69*(3), 290-296.

Słowiński, P., Baldemir, H., Wood, G., Alizadehkhaiyat, O., Coyles, G., Vine, S., Williams, G., Tsaneva-Atanasova, K., & Wilson, M. (2019). Gaze training supports self-organization of movement coordination in children with developmental coordination disorder. *Scientific Reports, 9*, 1712. https://doi.org/10.1038/s41598-018-38204-z

Smeeton, N. J., Huys, R., & Jacobs, D. M. (2013). When less is more: Reduced usefulness training for the learning of anticipation skill in tennis. *PLoS One, 8*(11), e79811.

Vaeyens, R., Lenoir, M., Williams, A. M., Mazyn, L., & Philippaerts, R. M. (2007). The effects of task constraints on visual search behavior and decision-making skill in youth soccer. *Journal of Sport and Exercise Psychology, 29*, 147-169. Doi:10.1123/jsep.29.2.147

van der Kamp, J., & Dicks, M. (2017). Looking further! The importance of embedding visual search in action. *Behavioral and Brain Sciences, e158*, 45-46. Doi: 10.1017/S0140525X16000273

van der Kamp, J., Rivas, F., van Doorn, H., & Savelsbergh, G. (2008). Ventral and dorsal contributions in visual anticipation in fast ball sports. *International Journal of Sport Psychology, 39*(2), 100-130.

Vickers, J. N. (1996). Visual control when aiming at a far target. *Journal of Experimental Psychology: Human Perception and Performance, 22*(2), 342-354.

Vickers, J. N. (2007). *Perception, Cognition, and Decision Training: The Quiet Eye in Action*. Human Kinetics.

van Maarseveen, M. J., Oudejans, R. R., Mann, D. L., & Savelsbergh, G. J. P. (2016). Perceptual-cognitive skill and the in situ performance of soccer players. *Quarterly Journal of Experimental Psychology*, 1-17. doi: 10.1080/17470218.2016.1255236

Vine, S. J., Moore, L. J., & Wilson, M. R. (2011). Quiet eye training facilitates competitive putting performance in elite golfers. *Frontiers in Psychology, 2,* 1-9.

Williams, A. M., & Ericsson, K. A. (2005). Perceptual-cognitive expertise in sport: Some considerations when applying the expert performance approach. *Human Movement Science, 24*(3), 283-307.

Figure 1

Cumulative mean (SE) percentage time spent viewing anatomical locations in comparison with the ball across experimental conditions (VSV = video simulation verbal; VSM = video simulation movement; ISV = in situ verbal; ISM = in situ movement; ISI = in situ interception) (Figure adapted from Dicks et al., 2010b).

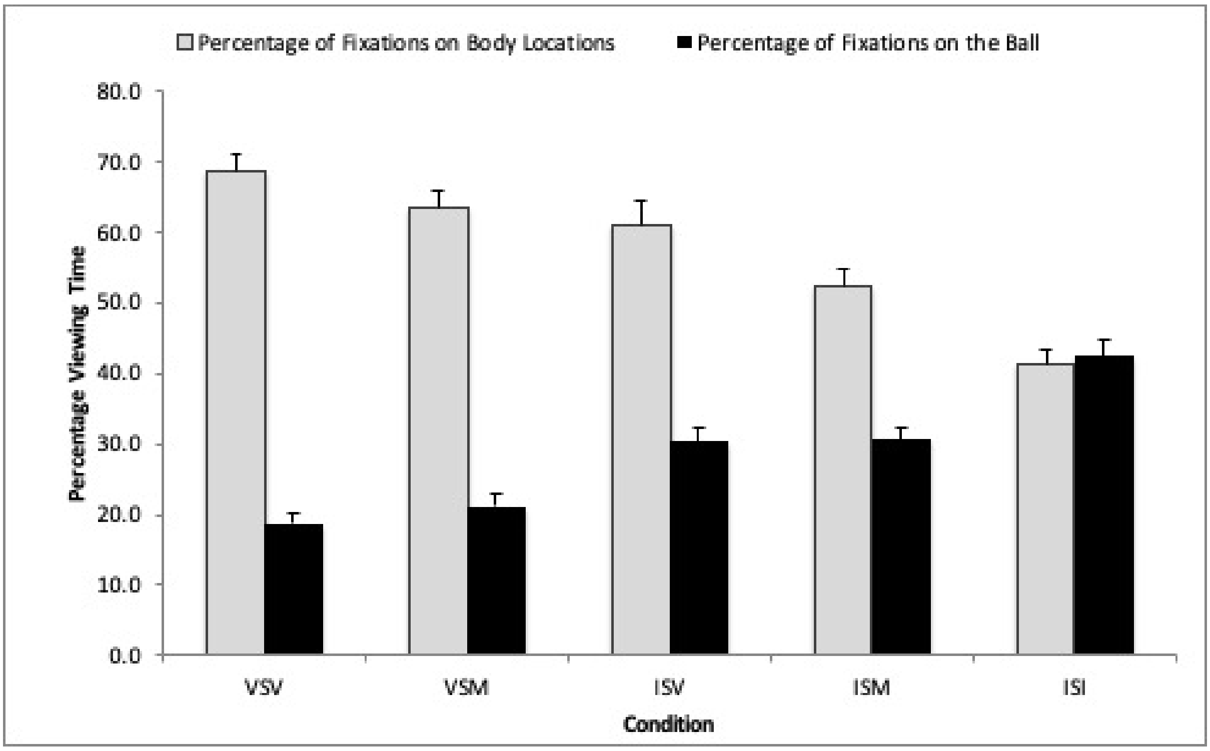

Figure 2

Quiet eye duration and location for each successful penalty kick save by the goalkeeper. Each circle data point represents an individual trial, the horizontal bars represent the mean duration for each respective goalkeeper, and the grey bars represent the standard deviation from the mean (Figure adapted from Ramsey et al., 2020)