Ecological cognition: Expert decision-making and action expression in sport

Abstract

Expert decision-making can be directly assessed, if sport action is understood as an expression of embedded and embodied cognition. Here, we discuss evidence for this claim, starting with a critical review of research literature on the perceptual-cognitive basis for expertise. In reviewing how performance and underlying processes are conceived and captured in extant sport psychology, we evaluate arguments in favour of a key role for actions in decision-making, situated in a performance environment. Key assumptions of an ecological dynamics perspective are also presented, highlighting how behaviours emerge from the continuous interactions in the performer-environment system. Perception is of affordances; and action, as an expression of cognition, is the realization of an affordance and emerges under constraints. We also discuss the role of knowledge and consciousness in decision-making behaviour. Finally, we elaborate on the specificities of investigating and understanding decision-making in sport from this perspective. Specifically, decision-making concerns the choice of action modes when perceiving an affordance during a course of action, as well as the selection of a particular affordance, amongst many that exist in a landscape in a sport performance environment. We conclude by pointing to some applications for the practice of sport psychology and coaching and identifying avenues for future research.

Keywords: Ecological cognition, action choices, expertise, affordance selection, constraints, information

Main text: 9305 words.

Introduction

How expert athletes decide to do what they do is a topic that has interested scientists for several decades (e.g., Beise & Peasley, 1937), and particularly sport psychologists(e.g., Straub & Williams, 1984). It has been argued that sport is a most appropriate context for studying expert decision-making (Gilovitch, 1984, Gilovitch et al, 1985). According to Gobet (2016), sport is a domain of expertise, where expertise relies on perception: "experts literally 'see' things differently compared to novices" and "these differences in perception and knowledge affect *problem solving* and *decision making*" (Gobet, 2016, p.7).

Predicated on these ideas, studies of decision-making in sport have intensively tested athletes'perception and anticipation, attention, memory, and decision-making. An important gap emerges immediately: decision-making in sport, by following trends in cognitive psychology, has neglected the important role of *action* and its constitutive role in cognition (Araújo, Ripoll & Raab, 2009; Prinz, Beisert & Herwig, 2013; Wolpert & Landy, 2012). In this article, we critically overview research on the perceptual-cognitive basis of decision-making, before we present an action-based alternative, from the ecological dynamics framework, clarifying repercussions for theory and research in sport psychology.

The perceptual-cognitive framework for the study of decision-making in sport

Currently, the perceptual-cognitive view of decision-making tends to focus on use of perception, memory and decision-making tasks to capture performance and to identify mediating mechanisms (Williams & Abernethy, 2012; for previous reviews see Bar-Eli, Plessner & Raab, 2011; Cotterill & Discombe, 2016; Hodges, Huys & Starkes, 2007; Raab & Helsen, 2015; Tenenbaum & Gershgoren, 2014; Williams & Ward, 2007).

Paradigms for capturing perceptual-cognitive performance

Research in sport has purported to reveal experts' ability to use "advance cues" for anticipatory responses, or to anticipate outcomes of an immediate opponent's action, often before an action is completed (e.g., Abernethy et al., 2001; Williams et al., 2002). Early research showed that expert players are better than novices at detecting deceptive moves by an opponent (e.g., Jackson et al., 2006). Also, in comparison with novices, experts display visual search strategies that tend to fixate on movements of an opponent's body segments that are more remote from an end effector when completing an action such as hitting a ball (e.g., Abernethy & Russell, 1987). Research methodologies employed allowed participants to observe, and respond to short 'sport-specific courses of action', captured in a series of video-clips (also in films, static images and point-light displays). The clips are edited to present an entire course of action, testing: (i) rapidity and accuracy in controlled response conditions (e.g., response time paradigm), or (ii), relative importance of spatial and temporal variables in decision-making by occluding specific information sources (spatial occlusion paradigm), or varying durations of each clip (temporal occlusion paradigm). Traditional explanations for these findings were similar to original proposals of de Groot (1965) studying chess players: perception in experts is better developed because they can access more refined internal representations as knowledge structures (e.g., Ericsson & Kintsch, 1995).

Recognition and recall have been associated with the study of memory, through identification of sequences of play. Several studies in sport have used brief presentations of domain-specific material, followed by a recall task (e.g., Allard & Starkes, 1980). In these tasks, a series of slides or video-clips are presented, and participants have to indicate verbally or on paper, as quickly as accurately as possible, which slides or clips were already presented, and which were new (recognition paradigm, e.g., Smeeton et al., 2004), or to recall players' positions in a display (recall paradigm, e.g., North et al., 2011). Results showed that experts attain better recall and recognition performance than non-experts, with *structured* performance situations, but not with unstructured situations. These results have been explained with reference to chunking theory (Chase & Simon, 1973), and this and other memory-based representations are assumed to underpin experts' performance superiority, particularly with respect to decision-making (Tenenbaum & Gershgoren, 2014, see Kording & Wolpert, 2006 for a Bayesian formalization).

The influence of the information-processing paradigm on the study of decision-making in sport has promoted what Simon (1956) called 'bounded rationality' (including related, more contemporary, approaches, e.g., fast and frugal heuristics, naturalistic decision making): humans are rational within the limits imposed by their cognitive systems (inferring the capacity to process information). The reasoning behind the claim that rationality is bounded suggests that understanding decision-making requires studying both the environment and the decision-maker. Even if a decision-maker meticulously follows normative steps of rationalization, there is still an influence of environmental constraints to consider.

The fast and frugal heuristics framework places greater significance on the role of the environment than the information-processing approach, and is aligned with the arguments of Simon (1956). It addresses environmental variables that are representative of those in socio-cultural settings, towards which an experiment is intended to generalise, as Brunswik (1944; 1956) originally proposed. Fast and frugal heuristics are strategies for decision-making that do not involve much searching for information or computation (Gigerenzer et al., 1999). This approach has some similarities with the naturalistic decision-making framework (Klein, 1998) that has investigated decision making of experts under time pressure in their domain of expertise. A significant conclusion of both frameworks is that experts tend not to deliberate between options but expediently implement the first *satisfactory* action. Raab and colleagues conducted research within the fast and frugal heuristics framework in sports contexts (see Raab, 2012 for a review). For example, they (Raab & Johnson 2007; Johnson & Raab, 2003) used video clips of team sports performance which were interrupted when a player with the ball faced several possible actions. Participants choosing better options generated fewer options. Expert players, performing under time constraints, use the 'take the first' heuristic, choosing the first alternative that emerged and better players tended to select the 'best' option. Option generation and selection were proposed to occur in an athlete's memory, from internalised knowledge representations of performance (Raab, 2012).

Similar knowledge structures are proposed as an explanation for how athletes generate different probabilistic expectations on how an event may evolve, such as the potential success associated with performing a certain action (e.g., a pass or dribble with a ball), or in predicting next movements of an adversary (e.g., Alain & Proteau, 1980; McRobert et al., 2011). It is assumed that the mind or the brain calculates the statistical distribution of likely event probabilities, and the level of uncertainty in sensory feedback (Kording & Wolpert, 2006; Williams & Abernethy, 2012), before making a decision.

Paradigms for measuring the mediating mechanisms of decision-making

The prevailing approach assumes that to understand mediating mechanisms employed by performers to make decisions, measures of behaviours like eye movements, verbal reports, as well as imaging of neurophysiological and neuroanatomical function, should be undertaken (Williams & Abernethy, 2012). Recently, neuroscientific evidence has been proposed to support theoretical arguments of cognitive sport psychologists (e.g., Tenenbaum, Hatfield et al., 2009), highlighting brain activity putatively “underlying" processes of perceptual-cognitive performance (e.g., Williams & Abernethy, 2012; Yarrow, Brown & Krakauer, 2009). Although using highly restricted micro-movements (e.g., button-pressing, blinking, pointing), research related to sport performance has postulated that experts tend to display more consistent brain behaviours during preparatory periods before initiating movement (Hatfield & Hillman, 2001). These include: (i)more efficient organization of brain regions (Milton et al., 2007), or (ii), specific brain areas displaying greater 'activation levels', (Aglioti et al., 2008; Wright et al., 2011), in experts compared to novices. These findings have been interpreted as support for a mirror neuron system (Rizzolatti & Sinigaglia, 2016), which is proposed to transform internal sensory representations of the behaviours of other performers into motor representations of an observed behaviour. Later in this chapter we argue that the prevalent idea of 'brain activity', as the underlying mechanism of perceptual-cognitive performance, is a fallacy. Brain activity does not constitute proof of the presence of representations, and it should not be misconstrued as action or cognition (e.g., as if activity level is indicative of the brain 'deciding for' an individual).

Eye movement recording has also been used to assess how performers visually search a displayed image or scene during decision-making (Ripoll et al., 1995; Vickers, 2016; Williams et al., 2004). Expert players tend to exhibit fewer fixations of longer durations and focus for a longer time on areas of free space that could be exploited or exposed (e.g., Vaeyens et al., 2007). Again, these findings are explained as revealing the underlying neural structure (Vickers, 2016), for example, as explained by mirror neuron theory (Rizzolatti & Sinigaglia, 2016). Additionally, verbal protocols, as described by Ericsson and Simon (1993), have also been used, either concurrently or retrospectively, as a way to evaluate thought processes that mediate action (e.g., McPherson & Kernodle, 2007; Kannekens et al. 2009). Regardless of the discrepancies between 'what we say, what we do' (Araújo et al., 2010), verbal reports are interpreted as responses to “situation prototypes”, represented in long-term memory (MacMahon & McPherson, 2009; Ericsson & Kintsch, 1995).

Criticisms of representational approaches to decision-making in sports

Previous research on perception, action and cognition has typically been grounded on theories of memory enrichment through representations (i.e., schemas, scripts, schematas, programs and the like), which consider stimuli in the environment to be impoverished for individuals. The role of internalised knowledge structures is to enhance meaning and richness of stimuli. Stimuli need encoding, and transformation by internal mechanisms that transform meaningless stimuli into meaningful representations, in order to interpret the environment and program the body to implement actions during performance (Kording & Wolpert, 2006).

Alternatively, non-representational approaches (e.g., ecological dynamics, Araújo et al., 2006; for a discussion among different approaches see Araújo & Bourbousson, 2016) are predicated on the idea that perception and cognition are embedded and embodied, emphasising the study of the performer-environment relationship as an appropriate scale of analysis. We elaborate some criticisms of the representational approach to cognition, where cognition is seen as information processing that results in representations in the mind or brain (Rowlands, 2009). In interpreting these criticisms, we discuss ecological dynamics as an important *action-based*, non-representational approach to cognition. From this perspective, cognition is the on-going, active maintenance of a robust performer–environment system, achieved by closely coordinated perception and action (Araújo et al., 2006; Stepp et al., 2011).

Theoretical criticisms: The world is its best model

The representational approach to human performance considers representations as containing meanings of symbols (i.e., perceptual encoding of stimuli in the brain, motor programs decoding intentions from brain, through the nervous system, to physical apparatus for coordinating actions, e.g., muscles, joints, limbs, bones)(see Araújo, 2007, Shaw, 2003). Representations are assumed to 'stand for' things in the world and things in the body. However, the mechanisms typically proposed for associative memory, or generally, knowledge structures are *epistemic mediators*. They provide contact with the world for an individual athlete. Computationally, this process of making contact requires conventional rules of reference that specify what symbols refer to, as well as rules of common usage that specify symbol meaning in actual contexts. The conventional connection of symbols to what they represent necessarily involves establishing common conventions through perceptual means (Shaw, 2003). Currently, little, if anything, is known about how the vital computational processes of symbolic encoding, decoding, and respective rules, are biologically implemented. In contrast, the ecological dynamics approach holds that ambient energy distributions are necessarily specific to the facts of the environment and of a performer's actions relative to the environment (Gibson, 1979; Turvey & Shaw, 1995). As Warren (2006, p.361) asked, if perceptual and cognitive states are representations, how is it possible for an agent to know what they stand for, without presuming some other direct access to the world?

In sport, the majority of decision-making studies follow the assumption that decision-making and perceptual judgements are predicated on internalised knowledge structures operating as inference engines to deliberate on 'the' best decision, or the decision that 'best fits' the task. In this process, the same assembly of stimuli is assumed to be perceived and commonly represented in the mind of every observer of a situation. These stimuli are viewed as always constraining similar decisions and actions (the “correct” decisions made by experts, for example). Thus, it is believed that some people decide well and other people decide poorly. The problem is that, in open, dynamic systems there is no “best decision”, since the most functional decision at any moment may compromise future decisions (Araújo et al., 2006; Davids & Araújo, 2010). During the act of perceiving, the limbs, ears or eyes of a performer explores available information in an environment. Complex, structured energy fields of ambient, patterned energy (i.e., information), such as light reflected from objects, are an environmental resource to be sought and exploited by individuals, whocontinuously modulate their interactions with the world, i.e., exerting their agency (Withagen et al., 2017). Information is the basis for maintaining contact with the environment because it is specific to its sources. Thus, various exploratory actions of perceptual systems are required for perception to occur. For the ecological dynamics approach, meaning in perception is not derived from any form of mental association, or labelling, but only from information detected by an observer. Therefore, perceptual learning, for example due to training and experience, is the process of becoming *attuned*, i.e., better able to differentiate more and more kinds of information, increasing the range and economy of the information detection process (Reed, 1993).

These arguments suggest that an individual's regulation of behaviour can be explained without the postulation of mental representations. Decisions are expressed by actions (Beer, 2003). Planning an action before acting (denoted as "strategical" in sports science) can influence the course of decisions (e.g., where to explore), but behaviour is always dependent on circumstances (action is not a mechanical outcome, but it is "tactical", i.e. an intentional exploration for an efficient solution). In this respect, decision-making is an *emergent* behaviour (Araújo et al., 2006). As the individual moves with respect to her/his surroundings, there are opportunities for action (affordances, Gibson, 1979) that persist, arise, and disappear, even though the surroundings remain the same. Changes of action can give rise to multiple variations in opportunities for subsequent actions. To exemplify, in team games, two defenders may face an attacker with the ball, but the gap between the defenders may vary momentarily, inviting different actions of the attacker, depending on his/her capacities (e.g., speed of movement), amongst other things. Perception of *affordances* (opportunities for action) is the basis for performers controlling her/his behaviours *prospectively*, i.e., regulating future behaviors (Gibson, 1979; Turvey, 1992). An important aspect of expert performance involves acting in a manner that is consistent with ways that are socio-culturally endorsed (Barab & Plucker, 2002, van Dijk & Rietveld, 2017), such as those valued in different sports. Experience in acting in a performance context attunes performers to perceptual variables that reliably specify the state of the environment relevant to performance in a specific task (Araújo & Davids, 2011). In this way, athletes can use the situation as its own best model, actively exploring and scanning it in detail at specific locations according to particular needs in the moment. This idea was elegantly described by Rodney Brooks, a prominent scientist in robotics as 'the world as its best model' (Brooks, 1991). Accordingly, robotics and other areas (e.g., computational neuroscience) are actively searching for embodied and embedded explanations for cognition (including perception and action) (see Clark, 2015) for a recent review). If social, historical, and possibly other external processes, are to be taken as integral constraints on skilled action, then traditional notions of expert performance (which relegate these processes to an individual's internal environment) should be re-examined: focusing on contexts and relations channelling expert performance

Methodological criticisms: Variables that are beyond immediate observation

How scientific findings from laboratory experiments can provide effective interventions in society (Ericsson & Williams, 2007) has become a major concern within sport psychology. A critical issue is that disregard for the need to study *functional* behaviours in traditional empirical designs has led to a decoupling of perceptual processes from actions on relevant external objects and events (Fajen, Riley, & Turvey, 2009; van der Kamp et al., 2008). Neisser (1976) recognised this weakness, in his seminal treatise on cognitive psychology, arguing that laboratory settings with contrived and trivial tasks, rather than everyday situations in life, can lead to the emergence of artificial decisions and behaviours. Examples abound in sport, perhaps best exemplified with reference to research methodologies in which film and video presentations have been used to simulate sport performance contexts. Discrepancies between these task constraints and performance in sport contexts have long been well-documented (Williams et al., 1999; Williams & Abernethy, 2012). These concerns were endorsed by a recent meta-analysis (Travassos e al., 2013) which clarified how expertise effects on decision-making in sport were moderated by ubiquitous response modes (verbal reports, button pressing, performance of micro-movements) and methods of stimuli presentation (slides, images, video presentations, *in situ*) in research. Moderating effects on decisions and actions were most obvious when participants were required to move in highly controlled laboratory conditions, rather than when actually performing sporting actions under *in situ* task constraints (Travassos et al., 2013).

For example, evidence has revealed that, when cricketers bat against a bowler, ball projection machine or a video simulation of a bowler with a projection machine, significant variations in timing of movement initiation and downswing initiation arise under the different task constraints (Pinder et al., 2011). Similar findings have emerged in studies of catching behaviours (Stone et al., 2015). Such findings indicate the relevance of *representing* in investigations, the key constraints of performance environments (see Brunswik, 1956). The *representativeness* of a particular situation helps participants to achieve performance goals cyclically, by acting to perceive information to guide further actions (Araújo & Davids, 2015). There needs to be a clear correspondence between behaviours in one context (an experiment or a training session) and behaviours in another context (a performance environment) (for detailed arguments see Araújo & Davids, 2015). The concept of correspondence is of great importance in decision-making, because, among other things, it is linked to our ability to perceive similarities between contexts. Recently, Seifert and colleagues (Seifert et al., 2013, 2016) showed how training on an indoor climbing wall might facilitate climbing on a frozen waterfall. Correspondence between behaviours in these contexts resulted in emergence of the use of quadrupedal locomotion, facilitating use of limb extremities and control of gravitational forces due to the vertical support needed for locomotion.

Performance in sport contexts involves actions, in which perceptual judgements and decisions are embodied(Araújo et al., 2006; Beer, 2003). Much previous research has linked perception to verbal responses, eye movements or neuroanatomical parts of the body supposed to express variables beyond immediate observation (i.e., decisions, judgments). However, actions by which cognition is expressed require that information be available in the patterned ambient energy for behaving with respect to environmental constraints. In this regard, actions, not their surrogates, are true cognitive behaviours.

Hidden reductionism: Expert decision-making is not that which happens in a body location

Gobet (2016) has proposed that 'the jury is out' with regard to whether neuroscience has "really taught us anything surprising and critical" (p.184) concerning expert anticipation and decision-making. Gobet (2016) also suggested that studying the nervous system at the level of brain regions is the wrong level of analysis for understanding such processes. To exemplify, the mirror neuron hypothesis (Rizzolatti & Sinigaglia, 2016) is a theory grounded on representations, located in the CNS, which are considered to have just the right type of organization needed to produce behaviours (Churchland & Sejnowski, 1989).

This type of reductionist explanation of decision-making, as an internalised neurophysiological process, seems to endorse psychological attributes as specific anatomical substrates, and not as emerging from interactions of the *individual-environment system*. This is an organism-centred view of behaviour which misses a central point: the reciprocity between an organism and environment (Davids & Araújo, 2010). Such a neurophysiological perspective is predicated on a conceptualisation of a CNS that perceives, executes, conceives and constructs an action forthe organism. For this reason some neuroscientists have argued that sport represents a valuable natural context which challenges the brain (Walsh, 2014). However, it is the performer, who actually perceives and acts during dynamical interactions with sport environments, not separate parts of his/her body (e.g., components of a nervous system), (Araújo & Kirlik, 2008). Athletes act to perceive and perceive to act (Gibson, 1979), with many more subsystems engaged in the emergence of behaviours than simply the CNS. Evidence for this view is abundant in the literature, traced back to Dewey (1896) (but see recent reviews of empirical evidence from Reed, 1982; 1996; Richardson et al., 2008; Seifert et al., 2016b; Teques et al, in press). Sport experts are active performers engaged in dynamical transactions with their functionally defined environments. Thus, expert performance is not possessed by the brain of a performer, but rather it is best captured as an ongoing, dynamically varying relationship that has emerged (and continues to emerge) between the constraints imposed by the environment and the capabilities of a performer (Araújo & Davids, 2011).

This conceptualisation does not mean that the role of neurophysiological systems in these continuous interactions should not be considered (Teques et al., in press). After studying the emergent interactions of environment-athlete systems under the specific constraints of sport tasks, researchers can investigate what affordances (opportunities for action) are relevant, how they channel action, what the structure of such actions are and how the entire process involves the contributions of many individual sub-systems such as the nervous or the cardiovascular sub-systems. In ecological analyses of neural processes underlying behavioural regulation (Järvilehto, 1998), a basic principle of nervous system functioning is the self-organisation *tendencies* of neuronal assemblies.Neuroanatomical organizations are temporary, only relatively stable and self-organizing to capture the embeddedness of individuals in their environments, dependent on what Gibson (1966a, 1966b) called the *resonance* of a perceptual system to ecological information. Gibson proposed that “The brain is a selftuning resonator" (Gibson, 1966b, p. 146) and achieving resonance implies that the perceiver learns to become 'tuned' to specific patterns of ambient energy (e.g., sound from the steps of an approaching opponent or vision of an approaching ball). Such structured information specifies features of a particular substance, surface, object, or event in relation to a particular individual. Resonance is not something that a brain achieves in isolation, but involves all the body (sub)systems involved in perceiving and acting in the environment (Gibson, 1966a). Resonance captures how the brain-body-environment system is embedded and embodied (Teques et al., in press).

Similar reasoning can be applied to use of eye movements or verbal protocols as explanatory mechanisms in expert decision-making. Like neurophysiological processes, eye movements and concurrent verbalizations may be related to performance. But they also may not, although performance may still be maintained (e.g., high levels of performance achieved by Paralympic athletes such as blind or deaf-mute performers). A key point is that partial (neural or eye activity) or surrogate processes (verbalizations) are not different aspects of decision making in sport (Cotterill & Discolmbe, 2019); more importantly they are not the phenomenon of interest. The embeddedness of a performer within the performance environment during action is the phenomenon of interest. Why study the behaviour of the eye if what one really wants to study is the exploratory behaviours of a player or of a team? Why not move directly to the study of actions, and how it reveals the performer's exploration, problem solving or reasoning in a performance task?

It is worth noting that researchers can actually test hypotheses about action and cognition directly. Different kinds of activities and different kinds of information produce various cognitive functions. All of them have their basis in perceptually-guided actions. Investigators can modify ambient information in addition to modifying task demands when they seek to study cognition. Since action is an expression of cognitive processes, it is possible to look at organizational and functional aspects of contextualized action in testing hypotheses about cognitions in behaviour (Araújo et al., 2006, Correia et al., 2013).

An ecological dynamics account of decision-making in sport

Ecological dynamics can be traced to areas of science tangential to sport performance. Two seminal researchers were instrumental in its origin: the ecological psychologist James J. Gibson (1966, 1979) and the physicist and biomechanist, Nikolai A. Bernstein (1967, 1996). Turvey (1977) first highlighted the relevance of their work for understanding of perception and action, further elaborated by Kugler, Kelso and Turvey (e.g., 1980) by introducing the language of complex systems from physicists such as Prigogine (Prigogine & Nicolis, 1971), Haken (1977), and Iberall (1977). A comprehensive exposition of these ideas, and their implications for sport scientists, was provided by Davids and colleagues (Davids et al., 1994; Williams et al., 1992). Importantly, Davids et al.'s (1994) paper was influential for indicating the interdisciplinary relevance of their insights for the sport sciences (especially motor learning, biomechanics, sport psychology, sport pedagogy, performance analysis). A further important impact in the sport sciences was made in developing an ecological dynamics rationale for decision-making byAraújo et al. (2006), where the link to Brunswik's (1944, 1956) concept of *representative design* was firmly established. There are three important assumptions of the ecological dynamics approach, which are worth emphasizing in discussions of decision-making: i) behaviour emerges from the performer-environment system; ii) perception is of affordances (opportunities for action); and iii), action, therefore cognition, emerges under interacting constraints.

Behaviour emerges from the performer-environment system

Behaviour is defined at the ecological level of analysis: the level of interactions between an organism and its environment, both continuously shaping each other (Gibson, 1979; Richardson et al., 2008). A consequence of this idea is that behaviour can only be understood, not simply according to the characteristics of a performer, but symmetrically according to the characteristics of a performance environment. If sport psychologists seek to generalize behaviours from one context (e.g., experimental laboratory, training session) to another context (competition, a performance environment), there should be clear theoretical guidance on establishing behavioural correspondence between contexts. This guidance is available in ecological psychology (e.g., Brunswik, 1956), where it has been demonstrated how athlete behavioural patterns are generated from the tight coordination emerging between a performer and a performance environment in the service of achieving specific performance goal (e.g., coupling limb movements when climbing a vertical surface, Seifert t al., 2014; for a review, see Araújo & Davids, 2015).

A tight performer-environment relationship seems to be a 'common-sense' view proposed in traditional sport psychology. However, a misconception is that the performer is typically regarded as *the* active agent, with the environment acting as a passive 'backdrop' that merely supports an individual's selection of actions, providing sources of stimuli to control behaviours (Araújo & Davids, 2011). The separation of organism and environment leads to theorising in which the most significant explanatory factors in behaviour are located *within* the organism. The upshot is that causes for behavioural disturbances are located in disturbances of brain function or in lack of sensitivity to 'cues to control' performance (e.g., O'Brien & Ahmed 2015; Wolpert & Landy, 2012; Yarrow et al., 2009). In ecological dynamics, there is no internal knowledge structure or central pattern generator inside the organism responsible for controlling action. Rather, all parts of the system (brain, body, environment) are dynamically integrated during action regulation, just as both hands in the air are needed for the task of clapping. Contemporary research has clarified this misconception through the identification and analysis of eco-biophysical variables that capture the embedded relations between a performer and his/her environment (Araújo et al., 2006, Correia et al., 2013).

Perception is of affordances

In ecological psychology, environmental properties can directly inform an individual performer about what he/she can and cannot do in a performance environment (Gibson, 1966a, 1979; Michaels, 2000). For example, the rate of dilation of an image of an approaching object on an individual's retina can provide time-to-collision information without mental computations of distance or speed of an object to intercept it (Lee, Young, Reddish, Lough, & Clayton, 1983; Craig & Watson, 2011). By calibrating information of their own action capabilities, individuals directly perceive *opportunities to act* in the environment (i.e., affordances) (Gibson, 1979). The concept of affordances captures the fit between the constraints on each performer and the properties of the environment. Cognition emerges during such continuous interactions at the ecological scale of analysis, i.e., the performer-environment system (Turvey, 1992), not from an internalised model of the world (the world is its own best model). Affordances, as possibilities for action in a particular performance setting, are what an arrangement of surfaces, texture and objects *offers* to a performer. Whether a gap between two defenders, for example, is passable or not is not determined by its absolute size (whether measured in cms, metres or feet and inches), but how it relates to particularities of an individual performer, including size, speed and agility. The concept of affordance presupposes that the environment is directly perceived in terms of what *actions* a performer can achieve within a performance environment (i.e., it is not dependent on a perceiver's expectations, Richardson et al., 2008). Affordances are dynamic, changing across continuous performer-environment interactions (Fajen et al., 2009) and are not representational properties of mind. Perceiving an affordance is to perceive how one can act in a particular set of performance conditions. Affordances capture the dynamics of the continuous interactions among individuals and their environment (Araújo & Davids, 2016).

Performers can anticipate or prospectively control their actions by producing movements guided by information about future states of affairs in a performance environment (Beek et al., 2003; Montagne, 2005; Turvey & Shaw, 1995). Gibson (1966a, 1979)termed this direct perception, or "knowledge of" the environment. This type of knowledge is not formulated in pictures, symbols or words, because it is the knowledge that makes the formulation of pictures and words possible. Knowledge of the environment obtained through direct perception is not subjective or private. Information is available in the environment, and many performers can detect it. On the other hand, Gibson conceived another type of knowledge: "images, pictures, and written-on surfaces afford a special kind of knowledge that I call mediated or indirect, knowledge at second hand" (Gibson, 1979, p. 42). This kind of knowledge, or indirect perception, is intrinsically shared, because it involves the displaying of information to others. In these cases the information on which direct perception can be based is selectively adapted and modified in a display, for example as a schematic presentation of the co-positioning of players in two handball teams. They consolidate gains of perception by mediating knowledge through communication. The role of indirect forms of knowledge is to make others aware and to articulate shared knowledge (Reed, 1991). Thus, contradicting some unfortunate misinterpretations in sport psychology (e.g., Ripoll, 2009; Sutton & McIlwain, 2015; Williams & Ward, 2007), the ecological dynamics approach is deeply concerned with knowledge and considers cognition to play an important role in theoretical explanations of human behaviour (Araújo et al., 2009a).

A recurrent question to ecological psychologists is "what about consciousness?". Scientists and philosophers have argued about the nature of consciousness, whether it exists or can be verified, without reaching a consensus about the involvement of mind–body dualism, physical reductionism, or epiphenomenalism (Shaw and Kinsella-Shaw, 2007).   Specifically in psychology, Wilhelm Wundt and William James conceived consciousness without separating inner and outer experiences. Chalmers (1996) identified the 'easy' and 'hard' problems in defining consciousness. The solution to the easy problem involves discovering the alignment between behaviours and their neurological correlates. The 'hard' problem implies moving beyond mere correlation to show how the nature of experience (behaviours) superimposes on the nature of physiological events. Merely correlating inner and outer events, avoids questions of how experience arises and where its content comes from (Shaw & Kinsella-Shaw, 2007). Correlation between two data series says nothing about the nature of the items correlated.

For Shaw and Kinsella-Shaw (2007) consciousness facilitates the detection and use of information. It can improve its integration, specification, interpretation, and generalization, as well as making movement control more flexible and coordinated over a wider range of tasks. Consciousness contributes to the adaptive value of being aware of one's needs, preferences, and intentions with respect to actual or potential performance situations. However, the greater the ecological significance of what one needs to be aware of, the more likely it will be attended to. As Gibson put it:

> "Perceiving is an achievement of the individual, not an appearance in the theater of his consciousness. It is a keeping-in-touch with the world, an experiencing of things rather than a having of experiences. It involves awareness-of instead of just awareness. It may be awareness of something in the environment or something in the observer or both at once, but there is no content of awareness independent of that of which one is aware (Gibson, 1979, p.239)."

With this understanding of perception, Gibson advanced the holistic view of consciousness of Wundt and James, by eliminating the need for solving the "easy-hard" problems of consciousness. Within this view these problems do not even arise: mental and material have equal status (Shaw & Kinsella-Shaw, 2007). Gibson followed James and Holt in rejecting the mind-matter dualism in that consciousness needs to be capable of physical characterization. For example, the experience of observing a goal scored when a football is curved through the air, implies a particular way of kicking the ball by a soccer player, in relation to a specific position related to the goal, and to the specific angle of the observer. These physical relations are needed for this experience to occur. Consciousness is a physical relation that only exists at the level of the individual-environment system. If one subtracts such relations, only matter exists. Individuals can directly perceive their situation and themselves in that situation without needing a 'consciousness copy' of it:

Grounded situational awareness emerges when the performer notices what surrounds her/him, what is changing, and what is emerging (Shaw, 2003). Importantly, to be aware of an affordance is not to have some kind of belief about the world (e.g., beliefs about cause and effect; Reed, 1996). Informed awareness is not just information about the environment, but of information about oneself in relation to that surrounding environment as well (Shaw & Kinsella-Shaw, 2007).

Recently, Seifert, Cordier and colleagues (2017), in a study about decision-making in climbing, showed that, during previewing, climbers do not necessarily make plans based on mental representations for programming their actions. Rather previews help them become aware of functional properties of the environment. They perceive opportunities for action rather than neutral physical properties (metrics such as distance (in cms or inches) to reach a hold). By capturing gaze behaviours during route previewing, and by relating those behaviours to actual climbing actions, Seifert and colleagues (2017) demonstrated that previewing allowed climbers to become perceptually attuned to affordances. Once acted upon they implied adjustments and revealed new information that, in turn, implied further adjustments and so on towards goal achievement (see Araújo, Dicks, & Davids. in press). Previewing (attuning to specific affordances) can be considered a strategical behaviour (changing at a slower timescalewithout relying on mental representations and motor programing). The explorations, adjustments and choices actually made during the implementation of this strategy in climbing (faster changing) tactical behaviours. These continuous interactions in person-environment relations during performance do not require a role for non-observable concepts such as mental representations and motor programs.

Action, therefore cognition, emerges under constraints

One consequence of the performer–environment system assumption is that behaviour can be understood as self-organized under constraints, in contrast to organization being imposed from inside (e.g., the mind) or outside (e.g., reinforcement contingencies, or the instructions of a coach). Performance is not prescribed by internal or external structures, yet within existing constraints, there are typically a limited number of stable solutions that can achieve specific desired outcomes (Araújo et al, 2006). An athlete's task is to exploit physical (e.g., rule-determined performance area characteristics) and informational (e.g., characteristics like surface features to be used in vertical ascent or distances to angles between co-positioning other players) constraints to stabilize performance behaviours. Constraints have the effect of reducing the number of configurations available to an athlete at any instance. In a performance environment, behaviour patterns emerge under constraints as less functional states of organization are dissipated. Athletes can exploit this tendency to enhance their adaptability and even to maintain performance stability under perturbations from the environment. Importantly, changes in performance constraints can lead a system towards bifurcation points where choices emerge as more specific information becomes available, constraining the environment-athlete system to switch to more functional paths of behaviour (such as performing a half volley on court in tennis, rather than a volley, as ball trajectory changes due to top spin on the ball). Measurement of the dynamics of eco-biophysical variables (e.g., the angle between an attacker-defender-goal) enables understanding of how the cognitive functioning might be predicated on emergent, on-going performer-environment interactions in sport (Araújo et al., 2006; Correia et al, 2013).

Choice of action modes while perceiving an affordance

When a performer changes from one action mode (walking towards a ball) to another (running after catching it), transitions among stable behavioural states (i.e., action modes) emerge from dynamic instabilities in the athlete-environment system. Transitioning provides a universal decision-making process for switching between distinct behavioural patterns (Kelso, 1995). Such stabilities and instabilities do not exist *a priori* in the (internalised) memorial structure of a performer, nor are pre-determined in the structure of the environment. Rather they are co-determined by the confluence of constraints and information, exemplifying how control lies in the emerging relations of the individual–environment system. This is a key point for sport psychologists to understand when they engage with athletes to help improve their decision-making behaviours. Emergent behavioural patterns have been formally modelled using differential equations and potential functions to describe the dynamical interactions of system components (e.g., Haken, Kelso, & Bunz, 1985; Scholz, Kelso, & Schöner, 1987). The landscape changes as attractors disappear or emerge. Athletes can exploit system multi-stability, transiting between different action modes.

Araújo and colleagues (e.g., Araújo et al., 2006; Davids & Araújo, 2010) have previously explained that decision-making behaviours during performance emerge in such a landscape of attractors (stable system states), as *potential* task solutions. In contrast to the traditional view of arriving at a putative 'single best solution', athletes modulate their interactions with the environment until the performer-environment system arrives at a stable, functional solution. A viable option selected is the *strongest* attractor for an individual-environment system at any given moment, with other options having less strength of attraction. Decision-making is explained through an integration of intentions, actions and perceptions, since selected behaviours are the realization of affordances. This selection only emerges from the continuous interactions of an individual and a performance environment. Ignoring other options is a consequence of the dynamical (athlete-environment) system relaxing to one stable state, concomitantly ignoring remaining options (attractors). The presence of a stronger attractor does not eliminate the influence of other attractors in the dynamic landscape of action possibilities (e.g., Araújo et al. 2014). Under dynamic performance conditions, other attractors (i.e., as options) may emerge and exert their attraction. Dynamical models can explain different decisions through the same underlying process of originating and decaying attractors. A model initially proposed by Tuller, and colleagues (Tuller et al., 1994), for judging between pronounced words accounted for decision-making behaviours in other tasks such as the walk-run transition (Diedrich & Warren, 1998), or the decision to start from right or left positions in a sailing regatta (Araújo et al., 2015). In the model of Tuller et al. (1994), it is assumed that the system's state changes over time influenced by the dynamics of the attractor landscape. In the study of Araújo et al. (2015), the system's state was the decision, expressed by ecological constraints such as the sailors' place on the starting line and the angle between the wind direction and the starting line. In agreement with predictions of Tuller et al.'s (1994) model, Araújo et al. (2006, 2015) observed properties such as qualitative changes, abrupt jumps, critical fluctuations and multi-stability. In the crucial pre-start period, there was no single "valid" course for each boat to follow, so the boats engaged in an intensive pre-start competition, with each continuously trying to gain a positional advantage over opponents. Analysis of the pre-start period revealed that, although decisions regarding the discrete 'most favourable starting place' could be made in advance, this tactic was inherently misleading. There is a need to consider and interact with instantaneously changing task (e.g., movements of opposing boats) and environmental constraints (e.g., ocean currents) (Araújo et al., 2005, Pluijms et al., 2013). This particular process of decision-making (the selection of a path to an advantageous starting point) clearly cannot be based on mental comparisons between optimal and actual states mentally represented, because they emerge under the interaction of emerging constraints including an adversary's actions, wind changes, ocean currents, and boat manoeuvring skills. Due to high computation loads required, this level of action programming would be highly infeasible, perhaps needless. It would be impossible to precisely calculate the exact relational state of each source of constraint such as opponent manoeuvres, winds, tides and currents, and personal/boat movements, and predict their changes, and plan how to act accordingly, on a momentary basis (see also Araújo et al., 2014 for a model in decision-making in Rugby Union).

Rather, action modes are chosen when affordances are selected, but they can change, guided by appearance and disappearance of affordances in the performance landscape. As Turvey and Shaw put it ''to see the distance-to-contact is to see the work required, to see the time-to-contact is to see the impulse forces required, to see the direction to-contact is to see the torques required'' (Turvey & Shaw, 1995, p. 158). During performance, an athlete's actions generate perceptual information, which, in turn, constrains the emergence of further movements. For example, in ice climbing, Seifert and colleagues (2014) observed how skilled climbers perceived different properties of ice surface structures to adapt their inter-limb coordination patterns with ice tools and crampons. When they detected holes in the ice surface left by previous climbers, hooking actions emerged. Conversely, when the ice was smooth and dense, climbers used swinging actions to create holes needed for a safe and rapid traversal. In turn, a climber's movements continuously change his/her relationship with the ice surface. Decision-making in this climbing task is facilitated by multi-stability of the perception-action system. Multistability refers to the principle of “functional equivalence” (Kelso, 2012, p.907), also known as "degeneracy" (Edelman & Gally, 2001). Degeneracy corresponds to “the ability of elements that are structurally different to perform the same function or yield the same output” (Edelman and Gally, 2001, p. 13763). It signifies that an individual can vary action-perception without compromising function (Mason, 2010; Price & Friston, 2002), as an expression of the adaptive and functional role of coordination pattern variability in order to satisfy interacting constraints (Seifert et al., 2016b). A higher level of skill reflects greater adaptive capacity to achieve similar performance outcomes with different movements and coordination patterns, rather than relying on a single (programmed, represented) ready-made solution. The presence of degeneracy in sport actions increases an athlete's complexity and robustness against perturbations and ensures a functional ongoing engagement (decision-making) with a dynamic environment.

Selecting an affordance in a world full of affordances

Behaviours can be sustained by simultaneous and successive affordances, and not necessarily by a hierarchical plan or representation capturing a sequence of performance operations (Araújo, Dicks, Davids, in press). Reed (1993) argued that these patterns of behavioral organization emerge in situations in which different affordances can be utilized to enhance performance in contexts like sport. This performer-environment basis of conceptualizing behaviour indicates that affordances can be used, motivating an organism to act, but they are not to be viewed as unique causes for behaviour because a person may not act on a perceived affordance. Affordances favour certain behaviours and select against others (Withagen et al., 2012). The factors underlying the tendency for favoured behaviours to be realized are multiple. For example, in climbing, a rock surface may be traversable for an individual climber in a specific way, depending on the availability and spatial organization of surface texture properties (holes shape, size and orientation, offering more or less stability) (Seifert et al 2015). Indeed, each surface property has many affordances, and it is from this selection of which affordance to act upon that it is possible to understand behavioural dynamics in different climbers. Whether the individual takes up these possibilities or not is a separate matter since affordances are not deterministic causes, i.e., one can decline or accept an invitation to act in a specific way (Withagen et al. 2012, 2017). Since affordances do not select themselves, the intention to use an affordance, as Reed (1993) put it, like other biological phenomena, emerges out of a process of variation and selection. In this way, people are 'drawn into' interactions with affordances offered by a performance environment (Withagen et al., 2017).

Relatedly, Kiverstein and Rietveld (2015) defined skilled intentionality as "the individual's selective openness and responsiveness to a rich landscape of affordances" (p.701). This notion indicates that the everyday environment offers a range of more or less inviting affordances (Withagen et al. 2012). However, these affordances are relational: accessible to individuals with necessary skills (e.g., developed through previous experiences) to act on them. For example, where one tennis player with an excellent backhand shot may perceive an opportunity to force cross-court shots when using it, another player who is highly-skilled at volleying may perceive every ball as an opportunity to approach the net. Thus, sports people interact with a surrounding environment through skilled engagement with the concrete affordances that a specific environment offers them. because of their unique skill set. From this viewpoint perceptual attunement developed through experience brings an 'openness' to affordances that, without skill, would not be accessible, since it is skill that opens up possibilities for action to an individual.

Moreover, individuals act relative to multiple relevant affordances simultaneously, or to what Rietveld and colleagues (Kiverstein & Rietveld, 2015; van Dijk & Rietveld, 2017) call a "field of affordances", each of which is of greater or lesser significance to the performer. For example, the field of affordances of significance for a goalkeeper in hockey or football only marginally overlaps with the field of affordances for an attacking player in these invasion games. This idea justifies why an individual is open to and ready to act on multiple affordances at the same time,, which needs to underpin practice design in sport. Through experience, training and practice, individuals can display tendencies towards a specific link with the environment in a field of affordances. Additionally, the existence of *constellations of constraints*, maximizing the availability of affordances, has been identified in different sports settings (e.g., Barsingerhorn et al.2013; Pepping et al, 2011; Hristovski et al, 2006, Paulo et al, 2016). These regions of 'hyper-link' in a field of affordances may be important in sensitizing performers to subtle differences in an opponent's actions, and thus in the process of calibration to a perceived affordance. In learning design, the perception of a new affordance in a landscape of temporally nested affordances (Hristovski et al., 2011; Torrents et al, 2015) can bring about higher adaptive capacities of performers.

We recently suggested that one important way to explain how affordances are selected is based on information for the next affordance (Araújo, Dicks & Davids, in press). This is the informational basis for the selection of affordances in multi-scale dynamics (Keijzer, 2001). This means that affordances are conditionally-coupled (van Geert 1994), allowing a dynamic assembly of overall behavioural sequences. In tennis, Carvalho and colleagues (2014) studied how sequential behaviours, expressed as successive strokes in a rally, was based on conditionally-coupled affordances. The *goal-directed displacement index*, was developed as a measure to simultaneously consider the distance of competing players in relation to two on-court reference points –the central line of the court and the net- during competitive performance. This eco-biophysical variable reflects the state of the individual-environment system. This study showed that different functional relations could be established between skilled players attuned, open, and responsive to match affordances. A player with an advantage is perceiving and creating affordances for the other (see Fajen, et al, 2009), where the other is invited (pressured) to act upon such affordances, since he/she is open and responsive to play in the rally. The stability of the interactions between players is highly constrained by the co-adaptations (co-positioning) of the players (near or away from the central line of the court, or from the net) and the pattern of interactions developed during play (cross-court or down-the-line rallies). In such a field of affordances, a player with an advantage tries to create a successively more unstable situation for the other player, stroke after stoke, in an effort to de-stabilize the existing spatial-temporal coordination between them. The advantage in a rally is a process that is developed though successive actions, where nested affordances are dynamically assembled and imply perceptual attunement of skilled players to information for the next affordance.

Conclusion

In sport, coordination of whole body actions emerges with events, objects and surfaces and other athletes in the environment, is a requisite of performance. In other social-cultural activities, such as chess or playing piano, expert action tends to reside in micro-movements. A generalized interest of the scientific community on the topic of action has been around for no more than two decades (Herwig et al., 2013). However, sport performance is not typically predicated on performance of micro- or simple movements. It is a phenomenon that capitalises on detailed interactions between an individual and a performance environment. This is why the structure of action, during ongoing interactions of a performer in a performance environment, is a key issue for understanding expert cognition in sport.

From this viewpoint, the study of decision-making in sport involves selecting among affordances. However, once an affordance is perceived, its selection embodies an action mode, i.e., the action mode is chosen in the perception of an affordance. Interestingly, this action mode can change to other action modes guided by the information conveyed by the affordance (e.g., from walking to running when fielding in cricket or baseball if a ball's trajectory is perceived as falling to ground earlier). A few models of decision making already exist in ecological dynamics (e.g., Araújo et al., 2014; 2015). But there are many other courses of action, competition sub-phases and sports to address. Moreover, action modes bring about new affordances among which new selections may emerge. Therefore, the two instances of decision-making are intimately connected and future research is needed to investigate this relationship.

Ecological dynamics is focused in the performer-environment system as an explanatory level of analysis, not on inferred internal variables. Ecological dynamics research is needed to understand how environmental manipulations (e.g., match status in competition, effects of differences in heights between a competing attacker and defender or the influence on performance of variations in holds designed into a climbing wall) influence the behavioral dynamics of the participants (Cordovil et al., 2009).

The understanding of action, and therefore cognition, as an emergent process under individual, environmental and task constraints has consequences for how decision-making behaviour is understood and enhanced by experience and training (Araújo et al., 2009b) by sport psychologists and sport practitioners. Also, such an approach has consequences for understanding of cognition and agency (Withagen et al., 2017), and creativity (Hristovski et al. 2011), in general psychology, as well as performance analysis in sport (Passos et al., 2017), sport pedagogy (Chow et al., 2015; Renshaw et al., 2015), team sport expertise (Araújo, Silva & Davids, 2015) and talent development (Araújo et al., 2010; Davids et al., 2017). Indeed, sport psychology is located in an exciting position, to reveal how action is not a ready-made implementation selected 'off the shelf', but a true choice behaviour emerging from a range of opportunities.

References

Abernethy, B., & Russell, D. G. (1987). Expertise-novice differences in an applied selective attention task. *Journal of Sport Psychology, 9*, 326-345.

Abernethy, B., Gill, D.P., Parks, S.L., & Packer, S.T. (2001). Expertise and the perception of kinematic and situational probability information. *Perception, 30*, 233-252.

Aglioti, S., Cesari, P., Romani, M., & Urgesi, C. (2008). Action anticipation and motor resonance in elite basketball players. Nature Neuroscience, 11, 1109-1116.

Alain, C., & Proteau, L. (1980). Decision making in sport. In C. H. Nadeau, W. R. Haliwell, K. M. Newell, & G. C. Roberts (Ed.), *Psychology of motor behaviour and sport* (pp. 465-477). Champaign, IL: Human Kinetics.

Allard, F., & Starkes, J. (1980). Perception in sport: Volleyball. *Journal of sport psychology, 2*, 22-33.

Araújo, D. (2007). Promoting ecologies where performers exhibit expert interactions. *International Journal of Sport Psychology*, *38*(1), 73-77.

Araújo, D., & Bourbousson, J. (2016). Theoretical perspectives on interpersonal coordination for team behaviour. In P. Passos, K. Davids, & J.Y. Chow (Eds.), *Interpersonal Coordination and Performance in Social Systems (*pp. 126–139). London: Routledge

Araújo, D., & Davids, K. (2011). Talent Development: From Possessing Gifts, to Funcional Environmental Interactions. *Talent Development & Excellence Interactions, 3*(1), 23-25.

Araújo, D., & Davids, K. (2011). What exactly is acquired during skill acquisition? *Journal of Consciousness Studies, 18*(3-4), 7-23.

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,* 268-280.

Araújo, D., & Davids, K. (2016). Team synergies in sport: theory and measures. *F*ront. Psychol., 7:1449. doi: 10.3389/fpsyg.2016.01449

Araújo, D., Davids, K., Chow, J., & Passos, P., (2009b). The development of decision making skill in sport: an ecological dynamics perspective. In Araújo, D., Ripoll, H., & Raab, M. (Eds.), Perspectives on cognition and action in sport (pp. 157-170). New York: Nova Science Publishers.

Araújo, D., & Kirlik, A. (2008). Towards an ecological approach to visual anticipation for expert performance in sport. *International Journal of Sport Psychology*, *39*(2), 157-165.

Araújo, D., Cordovil, R., Ribeiro, J., Davids, K., & Fernandes, O. (2009a). How does knowledge constrain sport performance? An ecological perspective. In D. Araújo, H.

Ripoll, M. Raab (Eds.). Perspectives on Cognition and Action in Sport (pp100 – 120) . Hauppauge NY: Nova Science Publishers.

Araújo, D., Davids, K., & Serpa, S. (2005). An ecological approach to expertise effects in decision making in a simulated sailing regatta. *Psychol Sport Exerc., 6*, 671–92.

Araújo, D., Davids, K., & Hristovski, R. (2006). The ecological dynamics of decision making in sport. *Psychology of Sport and Exercise, 7*, 653-676.

Araújo, D., Davids, K., & McGivern, P. (in press). The irreducible embeddedness of action choice in sport. In M. L. Cappuccio (Ed.) The MIT Press Handbook of Embodied Cognition and Sport Psychology. Boston: MIT Press.

Araújo, D., Davids, K., Diniz, A., Rocha, L., Santos, J.C., Dias, G., & Fernandes, O. (2015). Ecological dynamics of continuous and categorical decision-making: The regatta start in sailing. *European Journal of Sport Science, 15*(3), 195-202.

Araújo, D., Dicks, M., & Davids, K. (in press). 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. Boston: MIT Press

Araújo, D., Diniz, A., Passos, P., & Davids, K. (2014). Decision making in social neurobiological systems modelled as transitions in dynamic pattern formation. *Adaptive Behaviour, 22*(1), 21-30.

Araújo, D., Silva, P., & Davids, K. (2015). Capturing group tactical behaviors in expert team players. In J. Baker & D. Farrow (Eds.), *Routledge Handbook of Sport Expertise* (209-220). London: Routledge.

Araújo, D., Travassos, B., & Vilar, L. (2010). Tactical skills are not verbal skills: a comment on Kannekens and colleagues. *Perceptual and Motor Skills*, *110*(3), 1086-1088.

Bar-Eli, M., Plessner, H., & Raab, M. (2011). Judgement, Decision Making and Success in Sport. Sussex, UK: Wiley.

Barab, S., & Plucker, J. (2002). Smart people or smart contexts? Cognition, ability, and talent development in an age of situated approaches to knowing and learning. Educational psychologist, 37(1), 165-182.

Barsingerhorn,A.D., Zaal,F.T., dePoel,H.J., & Pepping,G.-J. (2013). Shaping decisions in volleyball: an ecological approach to decision-making in volleyball passing. International Journal of Sport Psychology, 44,197–214. doi:10.7352/IJSP2013. 44.197

Beek, P., Dessing, J., Peper, C., & Bullock, D. (2003). Modelling the control of interceptive actions. *Philosophical Transactions of the Royal Society of London, 358*, 1511-1523.

Beer, R.D. (2003). The dynamics of active categorical perception in an evolved model agent. *Adaptive Behaviour, 11*(4), 209-243.

Beise, D. & Peasley, V. (1937). The relation of reaction time, speed, and agility of big muscle groups to certain sport skills. *Research Quarterly, 8*, 133-142

Bernstein, N. (1996). "Dexterity and Its Development." In M. Latash and M. Turvey (Eds.), *Dexterity and Its Development*, (pp. 3–237, originally published in 1950). Mahwah, NJ: Laurence Erlbaum.

Bernstein, N. A. 1967. The Co-ordination and Regulation of Movements. Oxford: Pergamon Press.

Brooks, R.A. (1991). Intelligence without representation. *Artificial Intelligence,* 47, 139–159.

Brunswik, E. (1944). Distal focusing of perception: Size constancy in a representative sample of situations. Psychological Monographs, 56(254), 1-49.

Brunswik, E. (1956).*Perception and the representative design of psychological experiments* (2nd ed.). Berkeley: University of California Press.

Carvalho, J., Araújo, D., Travassos, B., Esteves, P., Pessanha, L., Pereira, F., Davids, K. (2013). Dynamics of player's relative positioning during baseline rallies. *Journal of Sports Sciences*, *31*(14), 1596-1605. doi: 10.1080/02640414.2013.792944

Carvalho, J., Araújo, D., Travassos, B., Fernandes, O., Pereira, F., & Davids, K. (2014). Interpersonal Dynamics in Baseline Rallies in Tennis. *International Journal of Sports Science & Coaching*, *9* (5), 1043-1056.

Chase, W., & Simon, H. (1973). Perception in chess. *Cognitive Psychology, 4*, 55-81.

Chow, J. Y., Davids, K., Button, C., & Renshaw, I. (2015). Nonlinear pedagogy in skill acquisition: An introduction. London: Routledge.

Churchland, P. & Sejnowski, T. (1989). Brain and cognition., In M. Posner Ed.). *Foundations of cognitive science* (pp.245-300). Cambridge, Mass: MIT Press.

Cordovil, R., Araújo, D., Davids, K., Gouveia, L., Barreiros, J., Fernandes, O., & Serpa, S. (2009). The influence of instructions and bodyscaling as constraints on decision-making processes in team sports. *European Journal of Sport Science*, *9*(3), 169-179.

Correia, V., Araújo, D., Vilar, L., & Davids, K. (2013). From recording discrete actions to studying continuous goal-directed behaviours in team sports. *Journal of Spots Sciences*, *31*, 546-553.

Craig, C., & Watson, G. (2011). An Affordance Based Approach to Decision Making in Sport: Discussing a Novel Methodological Framework. *Revista de Psicología del Deporte, 20*(2), 689-708.

Davids, K., & Araújo,. D. (2010). the concept of 'Organismic asymmetry' in sport science. *Journal of Science and Medicine in Sport, 13*(6), 633-640.

Davids, K., Handford, C. & Williams, M. (1994). The natural physical alternative to cognitive theories of motor behaviour: an invitation for interdisciplinary research in sports science? *Journal of Sports Sciences, 12*, 495-528.

de Groot, A. D. (1965). *Thought and choice in chess*. The Hague: Mouton Publishers.

Diedrich, F., & Warren, W. (1998). Dynamics of human gait transitions. In D. Rosenbaum, & C. Collyer (Eds.), *Timing of behaviour* (pp. 323-343). Cambridge: MIT.

Edelman, G.M., Gally, J., 2001. Degeneracy and complexity in biological systems. Proc. Natl. Acad. Sci. U. S. A. 98, 13763–8. doi:10.1073/pnas.231499798

Ericsson, K. A. & Kintsch, W. (1995). Long-term working memory. *Phychological Review, 102*, 211- 245.

Ericsson, K. A., & Simon, H. A. (1993). *Protocol analysis: Verbal reports as data (revised edition)*. Cambridge, MA: MIT Press.

Ericsson, K. A., & Williams, A. M. (2007). Capturing naturally occurring superior performance in the laboratory: translational research on expert performance. *Journal of Experimental Psychology: Applied, 13*(3), 115-123.

Fajen, B., Riley, M., & Turvey, M. (2009). Information, affordances, and the control of action in sport. *International Journal of Sport Psychology, 40*(1), 79-107.

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

Gibson, J. J., (1966b). The problem of temporal order in stimulation and perception. *The Journal of Psycholology*, 62, 141-149.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston, MA: Houghton Mifflin.

Gigerenzer, G., Todd, P.M., & ABC Research Group. (1999). *Simple heuristics that make us smar*t. Oxford: Oxford University Press.

Gilovich, T. (1984). Judgmental biases in the world of sport. In. W. F. Straub and J. M. Williams (eds), Cognitive Sport Psychology. Lansing, New York: Sport Science Associates

Gilovich, T.; Tversky, A.; Vallone, R. (1985). "The Hot Hand in Basketball: On the Misperception of Random Sequences". *Cognitive Psychology*. **17** (3): 295–314

Gobet. F. (2016). Understanding expertise. A multi-disciplinary approach. London: Palgrave.

Haken, H. (1977). Synergetics: An introduction. Heidelberg: Springer Verlag.

Haken, H., Kelso, J. A. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biological Cybernetics, 51*, 347-356.

Hatfield, B. D., & Hillman, C. H. (2001). The psychophysiology of sport: a mechanistic understanding of the psychology of superior performance. In R. N. Singer, C. H. Hausenblas, & C. M. Janelle (Eds.), *Handbook of sport psychology* (2nd ed., pp. 362–386). New York: John Wiley & Sons.

Headrick, J., Renshaw, I., Davids, K., Pinder, R.A., & Araújo, D. (2015). The dynamics of expertise acquisition in sport: The role of affective learning design. *Psychology of Sport and Exercise*, 16, 83-90

Herwig, A., Beisert., M., & Printz, W. (2013). Action science emerging: Introduction and leitmotifs. In Prinz, W., Beisert, M., & Herwig, A. (2013). Action science: Foundations of an emerging discipline (pp.1-34). Cambridge: The MIT Press.

Hodges, N. J., Huys, R., & Starkes, J. L. (2007). Methodological review and evaluation of research in expert performance in sport. In G. Tenenbaum and R. C. Eklund (Eds.), Handbook of sport psychology (pp. 161-184). Hoboken, NJ: John Wiley & Sons.

Hristovski, R., Davids, K., Araújo, D. & Button, C. (2006). How boxers decide to punch a target: emergent behaviour in nonlinear dynamical movement systems. *Journal of Sports Science and Medicine, Combat Sports Special Issue,* 60-73.

Hristovski, R., Davids, K., Araújo, D. & Passos, P. (2011). Constraints-Induced Emergence of Functional Novelty in Complex Neurobiological Systems: A Basis for Creativity in Sport. *Nonlinear Dynamics, Psychol. Life Sci., 15*(2), 175-206.

Iberall, A. (1977). A field and circuit thermodynamics for integrative physiology: I. Introduction to general notion. *American Journal of Physiology*, 233, R171-R180.

Järvilehto, T. (1998) The theory of the organism-environment system: II. Significance of nervous activity in the organism-environment system. *Integrative Physiol. Behav. Sci., 33*(4), 335-42.

Johnson, J., & Raab, M. (2003). Take the first: option generation and resulting choices. *Organisational Behaviour and Human Decision Processes, 91*, 215-223.

Kannekens R., Elferink-Gemser M. T., Visscher C. (2009) Tactical skills of world-class youth soccer teams. Journal of Sports Sciences, 27, 807–812

Keijzer, F. (2001). Representation and behaviour. Cambridge: MIT Press

Kelso, J. A. S. (1995). *Dynamic patterns: The self-organization of brain and behaviour*. Cambridge: MIT Press.

Kiverstein, J. & Rietveld, E. (2015) The Primacy of Skilled Intentionality: On Hutto & Satne's The Natural Origins of Content. Philosophia 43 (3). DOI 10.1007/s11406-015-9645-z

Klein, G. (1998). Sources of Power: How people make decisions. Cambridge: MIT Press.

Kording, K.P., & Wolpert, D.M. (2006). Bayesian decision theory in sensorimotor control. Trends in Cognitive Sciences 10(7), 320–326.

Kugler, N. P., Kelso, J. A. S., & Turvey, M. T. (1980). On the concept of coordinative structures as dissipative structures: I. Theoretical lines of convergence. *Tutorials in Motor Behavior*, G. E. Stelmach and J. Requin (eds.). Amsterdam: North-Holland Pub..

Lee, D. N., Young, D. S., Reddish, P. E., Lough, S., & Clayton, T. M. (1983). Visual timing in hitting an accelerating ball. *Quarterly Journal of Experimental Psychology, 35*(2), 333-346.

MacMahon, C. y McPherson, S. L. (2009). Knowledge base as a mechanism for perceptual-cognitive tasks: Skills is in the details!. *International Journal of Sport Psychology, 40*, 565-579.

Mason, P.H., 2010. Degeneracy at Multiple Levels of Complexity. Biol. Theory 5, 277–288.

McPherson, S. L., & Kernodle, M. W. (2007). Mapping two new points on the tennis expertise continuum: Tactical skills of adult advanced beginners and entry-level professionals during competition. *Journal of Sports Sciences*, *25*(8), 945-959.

McRobert, A. P., Ward, P., Eccles, D., & Williams, A. M. (2011). The effect of manipulating context-specific information on perceptual-cognitive processes during a simulated anticipation task. *British Journal of Psychology*, 102, 519-534.

Michaels, C. (2000). Information, Perception, and Action: What Should Ecological Psychologists Learn From Milner and Goodale (1995)? *Ecological Psychology, 12*(3), 241-258.

Milton, J., Solodkin, A., Hlustik, P., & Small, S. (2007). The mind of expert motor performance is cool and focused. *Neuroimage*, 35, 804-813.

Neisser, U. (1976). *Cognition and Reality.* San Francisco: WH Freeman.

North, J. S., Ward, P., Ericsson, A., & Williams, A.M. (2011). Mechanisms underlying skilled anticipation and recognition in a dynamic and temporally constrained domain. *Memory*, 19, 155–68

O'Brien, M. & Ahmed, A. (2015). Rationality in Human Movement. *Exercise and Sport Sciences Reviews*, 44:20-28.

Passos, P., Araújo, D., & Volossovitch, A. (2017). Performance analysis in team sports. London: Routledge.

Paulo, A., Zaal, F., Fonseca, S., & Araújo, D. (2016). Predicting Volleyball Serve-Reception. *Frontiers in Psychology, 7*:1694. doi: 10.3389/fpsyg.2016.01694

Pepping, G.-J., Heijmerikx, J., & de Poel, H. J. (2011). Affordances shape pass kick behaviour in association football: effects of distance and social context. Revista de Psicologia del Deporte, 20 (2), 709-727.

Pinder, R., Davids, K., Renshaw, I. & Araújo, D. (2011). Manipulating informational constraints shapes movement re-organisation in interceptive actions. *Attention, Perception, & Psychophysics, 73*, 1242-1254.

Pluijms, J., Cañal-Bruland, R., Kats, S., & Savelsbergh, G. (2013). Translating key methodological issues into technological advancements when running in-situ experiments in sports: an example from sailing. *International Journal of Sports Science & Coaching*, *8*, 1, 89-103. doi:10.1260/1747- 9541.8.1.89.

Price, C.J., & Friston, K.J., 2002. Degeneracy and cognitive anatomy. Trends in Cognitive Sciences 6, 416–421.

Prigogine, I., & Nicholis, G. (1971). Biological order, structure and instabilities. *Research Quarterly of Biophysics*, 4, 107-148.

Prinz, W., Beisert, M., & Herwig, A. (2013). Action science: Foundations of an emerging discipline. Cambridge: The MIT Press.

Raab, M. (2012). Simple heuristics in sports. *International Review of Sport and Exercise Psychology*, 1–17.

Raab, M. & Johnson, J. (2007). Implicit learning as a means to intuitive decision making in sports. In H. Plessner, T. Betsch, & C. Betsch (Eds.), *Intuition in Judgment and Decision Making*. Londres: Routledge.

Raab, M., & Helsen, W., (2015). How Experts Make Decisions in Dynamic, Time-Constrained Sporting Environments. In J. Baker & D. Farrow (Eds). Routledge Handbook of Sport Expertise (pp. 64-73). London: Routledge.

Reed, E. S. (1993). The intention to use a specific affordance: a conceptual framework for psychology. In R. M. Wozniak, & K. W. Fischer (Eds.), *Development in context: acting and thinking in specific environments* (pp. 45-76). Hillsdale, NJ: Erlbaum.

Reed, E.S. (1991). James Gibson's ecological approach to cognition. In A. Still, & A. Costall (Eds.), *Against cognitivism: alternative foundations for cognitive psychology*. New York: Harvester Wheatsheaf.

Renshaw, I., Araújo, D., Button, C., Chow, J.Y., Davids, K., Moy, B. (2016). Why the constraints-led approach is not teaching games for understanding: a clarification. Phys. Educ. Sport Pedag. 21, 459-480.

Richardson, M., Shockley, K., Fajen, B.R., Riley, M.A., and Turvey, M.T. (2008). Ecological psychology: Six principles for an embodied-embedded approach to behaviour. In P. Calvo, & T. Gomila *(Eds.), Handbook of cognitive science: An embodied approach* (pp. 161-187). New York: Elsevier.

Ripoll, H. (2009). What is the impact of knowledge on player's behaviour?. In D. Araújo, H. Ripoll, M. Raab (Eds.). Perspectives on Cognition and Action in Sport (pp.89-94) . Hauppauge NY: Nova Science Publishers.

Ripoll, H., Kerlirzin, Y., Stein, J.-F., and Reine, B. (1995). Analysis of information processing, decision making, and visual strategies in complex problem solving sport

Rizzolatti, G. & Sinigaglia, C. (2016) The mirror mechanism: a basic principle of brain function. Nature Reviews Neuroscience, 17, 757-765. doi:10.1038/nrn.2016.135

Rowlands, M. (2009) Extended cognition and the mark of the cognitive, Philosophical Psychology, 22:1, 1-19, DOI: 10.1080/09515080802703620

Scholz, J.P., Kelso, J.A.S., & Schöner, G. (1987). Nonequilibrium phase transitions in coordinated biological motion: Critical slowing down and switching time. Physics Letters. [Part A], 123(8), 390–398. doi:10.1016/0375-9601(87)90038-7

Seifert L., Boulanger J., Orth D., Davids K. (2015). Environmental design shapes perceptual-motor exploration, learning and transfer in climbing. *Frontiers in Psychology.* 6:1819. doi: 10.3389/fpsyg.2015.01819

Seifert L., Komar J., Araujo D., Davids K. (2016). Neurobiological degeneracy: A key property for functional adaptations of perception and action to constraints. Neuroscience and Biobehavioural Reviews. 69, 159–165

Seifert L., Wattebled L., L'Hermette M, Bideault G., Hérault R., Davids K. (2013). Skill transfer, affordances and dexterity in different climbing environments. *Human Movement Science*. 32, 1339-1352.

Seifert L., Wattebled L., Orth D., L'Hermette M, Boulanger J., Davids K. (2016). Skill transfer specificity shapes perception and action under varying environmental constraints. *Human Movement Science*. 48, 132-141

Seifert, L., Wattebled, L., Herault, R., Poizat, G., Adé, D., Gal-Petitfaux, N., Davids, K., (2014). Neurobiological Degeneracy and Affordance Perception Support Functional Intra-Individual Variability of Inter-Limb Coordination during Ice Climbing. PLoS One 9, e89865. doi:10.1371/journal.pone.0089865

Shaw, R. (2003). The agent-environment interface: Simon's indirect or Gibson´s direct coupling? *Ecological Psychology, 15*, 37-106.

Simon, H. (1956). Rational choice and the structure of the environment. Psychological Review, 63, 129-138.

situations. *Human Movement Science, 14,* 325-349.

Smeeton, N., Ward, P., & Williams, M. (2004). Transfer of perceptual skill in sport. Journal of Sports Sciences, 20, 279-287.

Stepp, N., Chemero, A., & Turvey, M. T. (2011). Philosophy for the Rest of Cognitive Science. Topics in Cognitive Science, 3, 425-437.

Straub, W.F. & Williams, J.M. (Eds.). (1984). *Cognitive sport psychology*. Lansing, MI: Sport Science.

Sutton, J. & McIlwain, D. (2015). Breath and depth of knowledge in expert versus novice athletes. In J. Baker & D. Farrow (Eds). Routledge Handbook of Sport Expertise (pp. 95-105). London: Routledge.

Tenenbaum, G., & Gershgoren, L. (2014). Individual and team decision-making. In A. Papaioannou, & D. Hackfort, D. (2014) Routledge Companion to Sport and Exercise Psychology. (pp.460-479). London: Routledge.

Tenenbaum, G., Hatfield, B., Eklund, R., Land, W., Camielo, L., Razon, S. & Schack, T. (2009). Conceptual framework for studying emotions-cognitions-performance linkage under conditions, which vary in perceived pressure. In M. Raab, J. Johnson, & H. Heekeren (Eds.). *Progress in brain research: mind and motion – The bidirectional link between thought and action*, Volume 174 (pp.159-178). Amsterdam: Academic Press.

Teques, P., Araújo, D., Seifert, L., Campo, L., & Davids, K. (in press). The resonant system: Linking brain-body-environment in sport performance. In V. Walsh, M. Wilson,

& B. Parkin (Eds.) *Progress in Brain Research*: *Sport and the Brain: The science of preparing, enduring and winning. Part B, Volume 232*. Amsterdam: Academic Press.

Torrents, C., Ric, A. & Hristovski, R. (2015) Creativity and emergence of specific dance movements using instructional constraints. *Psychology of Aesthetics, Creativity and the Arts, 9*, 65–74.

Travassos, B., Araújo, D., Davids, K., O'Hara, K., Leitão, J., & Cortinhas, A. (2013). Expertise effects on decision-making in sport are constrained by requisite response behaviours-A meta-analysis. *Psychology of Sport and Exercise, 14*(2), 211–219. doi:10.1016/j.psychsport.2012.11.002

Tuller, B., Case, P., Ding, M., & Kelso, J. A. S. (1994). The nonlinear dynamics of speech categorization. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 1-14.

Turvey, M. (1992). Affordances and Prospective Control: An Outline of the Ontology. *Ecological Psychology, 4*(3), 173 - 187.

Turvey, M. T. & Shaw, R. E. (1995). Toward an ecological physics and a physical psychology. In R. L. Solso, & D. W. Massaro (Eds.), *The science of the mind: 2001 and beyond* (pp. 144-169). New York: Oxford University Press.

Turvey, M.T. (1977) Preliminaries to a theory of action with reference to vision. In Shaw, R.E., & Bransford, J. (eds) *Perceiving, acting and knowing: toward an ecological psychology*. Erlbaum: Hillsdale, NJ

Vaeyens, R., Lenoir, M., Williams, A., & Philippaerts, R. (2007). Mechanisms underpinning successful decision making in skilled youth soccer players: an analysis of visual search behaviours. *Journal of Motor Behaviour, 39*(5), 395-408.

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

van Dijk, L., & Rietveld, E. (2017). Foregrounding Sociomaterial Practice in Our Understanding of Affordances: The Skilled Intentionality Framework. *Frontiers in Psychology, 7,* 1969. doi: 10.3389/fpsyg.2016.01969

van Geert, P. (1994). *Dynamic systems of development. Change between complexity and chaos.* New York: Harvester,.

Vickers, J. N. (2016). Origins and current issues in Quiet Eye research. Current Issues in Sport Science, 1:101. doi: 10.15203/CISS_2016.101

Walsh, V. (2014). Is sport the brain's biggest challenge? Curr. Biol. 24, R859-R860.

Warren, W. H. (2006). The dynamics of perception and action. *Psychological review, 113*(2), 358-389.

Williams, A. M., & Ward, P. (2007). Anticipation and decision-making: Exploring new horizons. In G. Tenenabum, & R. Eklund (Eds.), *Handbook of sport psychology* (pp. 203-223). New York: Wiley.

Williams, A. M., Davids, K., & Williams, J. G. (1999). *Visual perception and action in sport*. Londres: E & FN Spon.

Williams, A. M., Davids, K., Burwitz, L., & Williams, J. G. (1992). Perception and action in sport. *Journal of Human Movement Studies*, *22*, 147-205.

Williams, A. M., Ward, P., Knowles, J. M., & Smeeton, N. J. (2002). Anticipation skill in a real- world task: measurement, training, and transfer in tennis. *Journal of Experimental Psychology: Applied, 8*(4), 259-270.

Williams, M. & Abernethy, B. (2012). Anticipation and decision-making: Skills, methods, and measures. In G. Tenenbaum, R. Eklund, & A. Kamata (Eds.). Measurement in psort and exercise psychology. Champaingn, Il: Human Kinetics.

Williams, M., Janelle, C., & Davids, K. (2004). Constraints on the search for visual information in sport. International Journal of Sport and Exercise Psychology, 2, 301-318.

Withagen, R., Araújo, D., & de Poel, H.J. (2017). Inviting affordances and agency. *New Ideas in Psychology*, 45, 11-18.

Withagen, R., de Poel, H.J., Araújo, D., and Pepping, G.J. (2012). Affordances can invite behaviour: Reconsidering the relationship between affordances and agency. *New Ideas in Psychology, 30*, 250–258.

Wolpert, D. M., & Landy, M. S. (2012). Motor control is decision-making. Current Opinion in Neurobiology, 22, 996–1003.

Wright, M., Bishop, D., Jackson, R., & Abernethy, B. (2011). Cortical fRMI activation to opponents' body kinematics in sport-related anticipation: Expert-novices differences with normal and point-light video. Neuroscience letters, 500, 216-221.

Yarrow, K., Brown, P., & Krakauer, J. (2009). Inside the brain of an elite athlete: The neural processes that support high achievement in sports. *Nature Reviews Neuroscience, 10*, 585-596.

Zourbanos, N., Tzioumakis, Y., Araújo, D., Kalaroglou, S., Hatzigeorgiadis, A., Papaioannou, A., & Theodorakis, Y. (2015). The intricacies of verbalizations, gestures, and game outcome using sequential analysis, *Psychology of Sport and Exercise*, 18, 32-41