The ecological dynamics of cognizant action in sport

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The ecological dynamics of cognizant action in sport

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ABSTRACT

The widespread inferential understanding of human action attributes to the brain the power of modelling actions and predicting immediate changes in environmental circumstances. However, an ecological rationale proposes that sport performance is founded on coupled perception and action, avoiding the need for the brain, as a mediator, to be lagging behind immediate corporeal contact with the sport environment. Here, a theory of cognizant action is presented where behaviour is understood in terms of self-organized action, shaped by a performer's complex skills, directed towards perceived affordances. Cognizant action is defined as the conservation of intentionality by coupled perception and action. Being oriented towards action possibilities (affordances), cognizant action self-organizes in every performance environment, and at the same time it is constrained by performers' skills. Accordingly, the study of cognizant action demands representative experimental designs and analysis of eco-physical variables to understand sport performance. Current debates include the role of knowledge, the symmetry between performer and environment, and team cognition. Future research might be directed to test tensegrity as well as 'strong' anticipation in individual and team sport tasks.

Improving performance is a key goal of sport sciences, particularly sport psychology. The starting point for such improvement is to understand performance so that hypotheses testing and interventions can be theoretically guided. There are many definitions of performance (Portenga et al., 2017). Here, we adopt the definition from Smith et al. (2014): Performance "is what people do, and it can be observed. Performance is not the consequence or result of action; it is the action itself." (p. 2). Importantly, action is an inextricable expression of the interaction of biological, psychological, and physical processes (Shaw, 2001). As Kugler and Turvey (1987, p. 407, highlight in the original) put it: "An action is (a) not a thing but a relation (among properties distributed over the acting animal and the surround); (b) not a particular aggregation of elemental anatomical mechanisms but a *specific mode of resource use* (where a resource is interpreted as a potential or a concentration of a conserved quantity); and (c) not categorized by reference to the anatomy that it involves but by reference to the function that it performs, that is, it is *functionally specific*, not anatomically specific". Therefore, more than simply capturing the output, sport scientists need to capture the process of acting or performing (Correia et al., 2013). An encompassing understanding of action should synthesise knowledge from different sub-disciplines in sport sciences, including sport psychology. In this position piece, we outline this endeavour as a theory of cognizant action in sport, framed by the ecological dynamics approach (Araújo et al., 2006, 2020; Button et al., 2020).

1. Towards a theory of cognizant action in sport

1.1. The ecological level: performer-environment system

According to the ecological approach, the influence of a performer on their environment and the influence of an environment on a performer are mutual (i.e., equivalent) and reciprocal (i.e., complementary) (Gibson, 1979). Performer and environment are considered an integrated whole, such that the performer-environment system is the preferred unit of analysis for studying behaviour (Turvey, 2019). Järvilehto (1998) suggests that behaviour (a.k.a., action or performance) is a reorganization of the performer-environment system, not an interaction between the performer and the environment as separate

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entities. Consequently, psychological (e.g., cognitive) processes are different aspects of the (re)organization and dynamics of the performer-environment system, not a phenomenon traditionally reduced to the performer's internal processes (Fig. 1). This is why, from an ecological dynamics approach, there is no need for one part of the system (e.g., the performers' mind) to represent or model another part of the system (the environment), the performer's body, and their interplay.

Cognizant action builds on the foundation of ecological dynamics. One challenge in the development of a theory of cognizant action is that cognition and action are framed in opposition to each other in prevalent psychological theories (e.g., Goldinger et al., 2016; Pylyshyn, 1980). Movement that expresses cognition is not addressed by inferential psychological models (following the Helmholtzian tradition, 1962/1866, such as Gregory, 1980; Hohwy, 2017; or Friston, 2010) because action is reduced to the final execution of some mental (internalized) plan or script. However, the regulation of action as an expression of cognitive processes, considered here, as cognizant action, should not be attributed to a commander or an 'executive' stage in a mental, chain-like sequence. A theory of cognizant action enables the psychological study of action, which in sport sciences is typically centred on metabolic energy consumption or Newtonian biomechanical descriptions. Moreover, by emphasizing action, we stress those approaches of embodied cognition which consider the coupling of perception and action (i.e., not the brain or the mind) as the foundation of goal-directed behaviour (cf., Raab & Araújo, 2019). Consequently, understanding sport performance requires capturing intentionality of behaviour at the performer-environment system level. Intentionality, or directedness of behaviour towards objects, events and others, has a long scientific tradition in psychology (Shaw, 2001). The ecological approach to intentionality suggests that behaviour is lawfully driven along a goal-path, with performers intending to realize certain possibilities for action (i.e., affordances; Gibson, 1979) by applying effective means (i.e., skills, capacities or effectivities; Shaw, 2001). Hence, the role of perception-action coupling is to conserve intention towards a task goal (Turvey, 2019), as performers orient themselves in the environment by perceiving information specifying action control (Fajen & Warren, 2003; Passos et al., 2008; Wrren a& Whang, 1987).

1.2. Perception-action coupling as the foundation of performance

Performance is constrained by action capabilities (i.e., skills), which are developed throughout the history of transactions of performers and their environments, and oriented towards action possibilities, inherently in the future (Gibson, 1979). Thus, performance is not a ready-made solution stored in memory (e.g., a motor script); instead, performance is always unique (i.e., emergent), dealing with its singular circumstances towards a task goal, and founded on perception-action couplings.

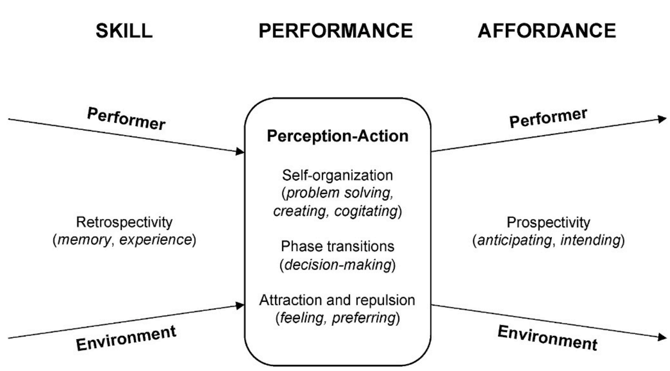

Fig. 1. Visual synthesis of a theory of cognizant action in sport
Note. Performance, defined at the ecological level, is founded on the coupling of perception and action, channelled by skill, and oriented towards affordances. Updated after Araújo (2005), Araújo and Davids (2004), and Button et al. (2020).

To explain how performers establish perceptual contact with their environment, Gibson (1966, 1979) argued that the assumption of impoverished stimuli, on which most inferential theories of perception in the Helmholtzian tradition are based, is misleading. Inferential psychological theories propose that, for perceivers to be informed about stimulation sources, they must store a large set of alternatives in memory that are deliberated upon and selected among, according to how a stimulus impacts corporeal receptors. This means that stimulation to receptors of the body does not directly inform about its sources. For stimulation to act informatively, a perceiver must have some means of interpreting such stimulation of receptor organs based on previous memories. However, the ultimate origin of this encoded knowledge has remained unexplained (Turvey, 2019). Contrary to this viewpoint, Gibson's theory of perception (1966, 1979) implies that perceptual information resides in surrounding ambient energy arrays, directly informing performers about the properties of their environment. Importantly, Gibson also stressed that performer's movement reveals the structure of the environment specifying information for action, which can be explained based on laws of modern physics (Kugler & Turvey, 1987). The evolution of perceptual systems to detect and utilize energy sources available in the environment (e.g., light and sound) as information to guide behaviour, is thus inherent to such a lawful explanation (Warren, 2021).

Gibson (1979) argued that there are properties from surrounding energy flows, which remain available for detection, notwithstanding transformations associated with movement of performers and the environment. Available information sources allow a performer to directly and unambiguously perceive properties of objects and events, within a performance environment. Gibson maintained that ambient energy changes (i.e., variants) and non-changes (i.e., invariants) are used by perceivers to control their movements relative to the environment. For example, the optical array changes when a performer moves. Everything in the array flows, with regular exchanges of array components that are revealed and hidden. However, within the flow, some relations of components to one another stay invariant. These invariants specify (i.e., inform about) stable features of the environment. Changes, or variants, specify movement of the observer relative to the stable features. Because invariants are defined only with respect to variants, it follows that change is necessary to reveal what is stable. Importantly, variants and invariants of the ambient optic array allow for separating what belongs to the environment from what belongs to the performer (Mace, 1986): As the performer moves, one can perceive when it is the performer's point of view changing and when it is the environment changing.

1.3. Perceiving-acting is towards the future: affordances

The explanation for perception-action coupling implies understanding that the environment is perceived in behavioural terms (Gibson, 1979). Notably, Gibson proposed that humans perceive action possibilities offered by the environment – affordances. Affordances are properties of the environment directly perceived according to the performers' body and action characteristics (i.e., dispositional tendencies or skills). Performers perceive objects, surfaces, or events by what they allow, invite, or demand in terms of action opportunities. Perceiving the environment in terms of affordances renders dispensable those cognitive processes that are proposed to transform action-independent perceptions into action-oriented perceptions. In perceiving, no integration and combination of cues is involved (Warren, 2021).

Importantly, perceiving is an activity of the whole body, acting on and in the environment to obtain information (Gibson, 1966; Reed, 1996). Moving brings the performer in a perceptually-controlled way to a place where nested adjustments of head turning, eye movements, lens accommodation, hand positioning can achieve their functions as a coordinated act with the environment. Perceiving is guided by the practical requirements of a performer's intentions and circumstances. People must perceive enough of their environment to accomplish task goals, which can improve over time. If there is always more environmental structure (i.e., ambient energy patterns) that can be detected with more exploration, then there is always the possibility for improved perceiving. Perception, like action, is a coordinated activity, an *achievement* of the performer-environment system. Gibson's ideas imply that affordances are goal-relevant descriptions of the environment, and perceiving an affordance is to ecologically decide how to act in a particular set of performance conditions towards a task goal.

Importantly, there is a fundamental difference between affordance perception and prediction. Dubois (2003) outlines the distinct mathematical foundations of different ways that systems may be oriented towards the future. Predictive processes which depend on internal models are referred to as a form of *weak anticipation*. Anticipation of future states which arises from the lawful embedding of the anticipating system within the environment is termed *strong anticipation* and is characterized by incursive or hyper-incursive temporal entailment. Predictive processes are a form of weak anticipation, while affordance perception is a form of strong anticipation (Stephen et al., 2008). Chemero and Turvey (2008) also show that attempting to conceptualize affordance perception as an internal process results in a significantly different set-theoretic structure than the Gibsonian account. Briefly, affordance perception requires an impredicative entailment structure, while internal processes can be characterized by predicative entailments alone. Affordances cannot be brought inside the mind of the organism as features of a predictive model.

Moreover, although predictive processing models, such as active inference and the free energy principle (Friston, 2012), reject the passive perceiver and gives action a more central role, their epistemological foundations are demonstrably distinct from those of ecological dynamics (Flament-Fultot, 2016). The active inference model does not overcome the in-principle argument against the origin of representational encoding (Bickhard, 1993) which has been shown to create issues in the explanation of hyper-priors (Bickhard, 2016). While we understand that some authors do pursue an integration of ecological and predictive processing approaches, we find that this unification is premature and leads to an incoherent metatheoretical foundation, as argued by Litwin and Miłkowski (2020).

1.4. Performer's ability to perceive-act at the next competitive event: skills

The current state of the performer-environment system can be traced through a history of interactions constraining immediate action. The synthesis of this history is what a performer can potentially do, their skills. In this way, current performance is shaped by its retrospectivity, including remembering, learned tasks, and past experiences (see E. Gibson, 1994; for an ecological view of memory, see Hambrick et al., 2021). Naturally, such skills are expressed by the performer in contexts soliciting them as means to achieve an intended task goal. Performing skilfully, thus, is not something a performer possesses but is a functional disposition (tendency to achieve a task goal) that emerges when realized (when the task goal is achieved). Hence, developing skills is to become more functionally stable with practice and experience, only expressed and adapted in each social setting (Araújo, Roquette, et al., 2023). This process of socialization in a specific cultural domain that characterizes what it is to perform skilfully implies participation, i.e., experience and engagement in relevant social practices. For example, the manifestation of skill in an athletics 400 m run is a specialization of a skill (including the socio-cultural – scientific – aspects of lactic resistance training), which contrasts with the ubiquitous skill involved in daily running to navigate through crowded streets or woodland tracks. Consequently, the distinction between ubiquitous skill and expert skill is sociological, not an epistemological nor biological distinction (Collins & Evans, 2018, Hambrick et al. 2017). Only context-specific socialization can enable a performer to share and use the collective knowledge of the group and develop skills needed for dealing with future events in that context.

Consequently, skills frame the specific experiences of performing an activity in context, such as starting, accelerating, maintaining, curving, and finishing when running a lap on an athletics track. Thus, these experiences are not isolatable into fragmented components in performance. By socially engaging in activities, performing skilfully reveals information for new actions, resulting in skill development, which reveals new information: a cyclical process. From this viewpoint, the role of practice is to enhance the search activity to continually improve the functional fit between an individual and a performance environment. Social-cultural behaviour domains like sports have been developed in such a way that they facilitate non-conventional behaviours from which new skills emerge. Therefore, skill learning is based on the specificity and adaptivity of evolving bodily engagement in a task context (Dreyfus, 2017).

1.5. Ecological self-organization of cognizant action

Cognizant action is embodied and embedded due to the reciprocal and mutual relationship between information flow and force fields (i.e., heterogeneous energetic arrays, see De Bari et al., 2020) that characterizes the link between action and perception (Warren, 2006). Perceiving information about a performance environment specifies body forces and resources use required in goal-directed behaviour (see center of Fig. 1). This means that the path to achieve a goal is lawfully controlled by systematically forcing energetic contributions that emerge at critical times (parameters such as work-, impulse-, torque-to-contact), when perceptual information (parameters such as distance-, time-, direction-to-contact) specifies when to impart energy and by how much (Shaw et al., 1995). If cognition is understood as something separated from the body and from the environment, such as if the mind predicts, models and controls action, this traditional idea rejects the view that major influences operating on most performers are from their environment, as well as from their own moving bodies (Davids et al., 1994).

As previously discussed, the precise place in the affordance landscape, to which a performer is perceptually attuned is constrained by their skills. But this precise place is also constrained by a performer's intentions. This means that the picked-up affordance is constrained by task goals towards which actions are directed, as well as the invitational character of affordances that draws performers into them and solicits actions (Withagen et al., 2017). This orientation of action towards the future is termed prospectivity (see Fig. 1; E. Gibson, 1994). Following this reasoning, behaviour is not understood as a stored response to a past stimulus but as the means of cogently acting to achieve a task goal in the future. Actions, therefore, are "true choice behaviors" (Shaw, 2001, p. 283).

Cognizant action is constrained by both its retrospectivity and prospectivity (E. Gibson, 1994), being an ecologically flexible process (i.e., self-organized, emergent) for satisfying impinging constraints (Kelso, 1995; Warren, 2006). When the performer-environment system establishes an emergent state, only because of the dynamic interactions among the system's elements, the state is self-organized. Emergent action modes (e.g., running or walking, dribbling or passing a ball) are distinct from an available system's components (e.g., a vertical surface, a track, a field and ball, opponents, and limbs of the performer, memories), and cannot be predicted solely from these properties. Consequently, many solutions to a perceptual-motor problem can emerge, given the countless ways the participating components interact under contextual constraints, exploiting interaction-based dynamics (see next section). However, instead of being a random or, on the other hand, an internally pre-programmed process, cognizant action implies that performers are perceptively attuned to affordances by detecting information that guides self-organizing action under contextual constraints towards a task goal. Cognizant action can thus be defined as the conservation of intentionality, realized by coupled perception and action.

This ecological understanding of cognition emphasizes its nature as an activity founded on perception-action couplings (Turvey, 2019). From this perspective, the physics of dynamical systems (i.e., the lawful time evolution of observable quantities) can offer relevant tools to understand cognition (Warren, 2006). For example, Withagen et al. (2017) sketched a dynamical model of the performer-environment relationship where agency is conceptualized as the capacity to modulate the strength of coupling with the environment. This model explains how the performer shapes how they are solicited by, and act upon, different available affordances. By modulating coupling strength, the performer alters the dynamics of the performer-environment system, constraining the behaviour that emerges. To modulate action, performers have available extra system degrees of freedom that may or may not be used to regulate environmental forces by exploiting personal forces. Goal-directed behaviour may intend consequences at some later time and place beyond the context in which the movements were initiated (Araújo et al., 2006). Importantly, modulation of actions means that performers are capable of a delayed reaction, in addition to an immediate reaction to environmental forces which they can modulate by self-generation of contributory forces. To achieve task goals, performers must have complex bodies, a biological potential capable of generate forces that may be used to cancel, modulate, or delay their immediate reaction to an environmental force (Araújo et al., 2006; Kugler et al., 1990).

In a sport performance environment, action choices emerge under constraints as less functional organization states are dissipated. Changes in performance constraints can lead a system towards bifurcation points where choices (i.e., phase transitions, see Fig. 1) emerge as more specific information becomes available, constraining the performer-environment system to switch to a more functional path of behavior. For example, in handball, when a performer changes from running with the ball to passing it when a defender is approaching, a transition in the performer's course of action emerged. Transitions between stable behavioral states emerge because of instabilities in a performance context, offering a universal decision-making process for switching between distinct action modes (Kelso, 1995). Such instabilities do not exist *a priori* in the performer or the environment but are co-determined by the specific confluence of performer, environment, and task constraints (Newell, 1986). Therefore, cognizant action emerges as performers search in a landscape of affordances, operationalized as attractors (Kugler et al., 1990), towards a task goal. A viable option selected is the *strongest* attractor (i.e., possibility) for a performer at a given moment, competing with others having less attraction strength. Ignoring other options is a dynamical consequence, since if a performer-environment system relaxes to one attractor, it concomitantly collapses remaining possibilities (i.e., attractors; Araújo, Hristovski, et al., 2019).

2. Evidence for cognizant action in sport

2.1. Methodological considerations

In psychological science, Brunswik's (1956) representative experimental design emphasizes the need to safeguard the need for experimental task constraints to represent those of a performance environment, which forms the specific focus of an investigation. To evaluate the representative design of experimental tasks in sport, researchers must consider the *functionality* of the constraints in supporting performers' perceiving and acting in performance contexts (Araújo et al., 2007). In performance domains, performers need to cope with a range of information sources in a multitude of noisy, messy, and emotionally changing situations that emerge in a competitive environment. Only by representing those irregular and uncertain conditions in experimental tasks can researchers discover how performers achieve a stable, patterned relationship with a sport context during performance.

However, going beyond Brunswik's representative design, and influenced by Gibson's (1979) ideas, behavioural correspondence between the experiment and the competitive event settings implies (see Araújo & Davids, 2015): (1) Selecting relevant affordances when designing the research task. The selection of affordances should be theoretically driven, if one wants to understand and generalize observed behaviours; (2) Promoting action fidelity. Since the environment is defined with respect to behaviour (affordances), action fidelity concerns the degree to which performed actions in an experimental setting are using the same skills as those solicited by a performance environment; and (3), Differentiating degrees of task goal achievement. Achievement is the successful attainment of an intended performance outcome (i.e., player's intention constrained perception-action couplings to reach the task goal). Moreover, approximation to goal achievement, or how the performers' intentionality (in channelling perception-action) converges with a task goal, should be perceptible by the performer while acting, instead of an *a posteriori* judgement (e.g., correct or incorrect) made by the researcher.

To research cognizant action in representative sport tasks implies a methodological paradigm for investigating dynamical systems at an ecological scale, where goal-directed behaviour is expressed (Araújo et al., 2006; Warren, 2006). Accordingly, psychological phenomena are emergent patterns from interaction-dominant dynamics (Van Orden et al., 2003; Wallot & Kelty-Stephen, 2018) which are non-decomposable (Bechtel & Richardson, 2010). Thus, emergent properties of a complex dynamic system cannot be deduced from its components, just as the nature of a triangle cannot be deduced from the properties of its sides (Stoffregen & Wagman, 2024). Here, we consider cognizant action as an emergent behaviour stabilizing within an affordance (attractor) landscape, which in turn constrains the states of the system's components and their ongoing (re)organizations (e.g., Kelso, 1995; Warren, 2006). These attractor landscapes imply non-proportionality between variations in the system's components and those of emergent cognizant actions, resulting in nonlinear behaviours. Such nonlinear dynamics account for some well documented decision-making patterns in sport, such as deciding to pass or to dribble a ball (Correia et al., 2013). How psychological processes are conceptualized has important consequences for research operationalization (Farrokh et al., 2025). Importantly, psychological patterns emerging from dynamic systems typically follow dynamic rules that can be expressed mathematically, generally with differential equations (e.g., Araújo et al., 2014). For the study of sport performance, ecological dynamics adds the methodological need of carefully developing representative designs and identifying eco-physical variables.

Behaviour is inherently purposeful, dynamic and context-dependent, however, sport performance metrics typically overlook performers' intentionality. Traditional psychological metrics are often organismic (e.g., related to each individual, including neurophysiological or verbal correlates), context-free (e.g., executive function variables), and discrete (e.g., reaction time), and thus neglect goal-directedness. In contrast, eco-physical variables capture how performers act towards a task goal, channelled by task-relevant, environmental properties of a performance setting (Araújo et al., 2006, 2020). Consequently, eco-physical variables embed the information sources that constrain goal-directed behaviour by measuring the continuous and coordinated movements of performers, relative to key properties of the environment that constrain task goal-paths. Next, by presenting evidence for cognizant action, we offer some illustrative examples of eco-physical variables, such as time-to-contact and goal-directed displacement index.

2.2. Evidence for skill channelling cognizant action

Correia, Araújo, Cummins, and Craig (2012) experimentally investigated how rugby performers at different skill levels acted upon perceived gap openings, from the perspective of the ball carrier, in a simulated 3 vs. 3 virtual reality (VR) task. They manipulated gap openings in a defensive line, at three locations relative to the participant's position, offering possibilities for performers to: (i) run with the ball, (ii) make a short pass, or (iii), make a long pass. Results revealed that distinct locations of the defensive gaps significantly influenced action selection, according to skill level. This finding showed how available information about affordances in context guided participants' cognizant action (Fig. 2).

Although the manipulated size was equal across gaps, optical angles from the participant's viewpoint differed, making gaps 2 and 3 more challenging to act upon. This latter finding is noteworthy since it conveys how skilled players are perceptually attuned to relevant information sources, effectively calibrating their movement system to realize those challenging affordances more frequently, than the less skilled players. Notably, when no gap was presented (i.e., circumstances did not solicit expert skill), there were no differences in action modes expressed by participants, independent of their skill level. In other words, when specific affordances were not there to solicit actions, a performer's effectivities alone could not explain performance. Hence, skill within a given task shapes how performers search for information in the affordance landscape and calibrate their skills to achieve success in rugby. This functional behaviour has also been revealed in basketball (Esteves et al., 2011), baseball (Gray, 2020), and volleyball (Caldeira et al. 2023), among other sports (Button et al., 2020).

2.3. Evidence for cognizant action being directed to affordances

A large body of research has revealed support for information- and affordance-based models in sport performance contexts like football (Gómez-Jordana et al., 2021; Peker, Böge, Bailey, Wagman, & Stoffregen, 2022; 2023; Travassos, Monteiro, Coutinho, Yousefian, & Gonçalves, 2023), martial arts (Hristovski et al., 2006), slackline walking (Montull et al., 2020), basketball (de Oliveira et al., 2008; 2007) track running (Postma et al., 2022), baseball (Oudejans et al., 1999), among other sports (Dicks et al., 2019). Strong experimental evidence has shown how perceiving affordances regulates action. For example, Fink et al. (2009) confirmed that, by manipulating trajectories of fly balls in a virtual environment, a performer gets to the right time and place to catch them by canceling the optical acceleration of the ball's image on the eyes. Hence, the optical acceleration of an approaching object informs about time-to-contact (*tau*). Importantly, the emphasis on eco-physical variables avoids a traditional tendency to search for variables that are processed by the brain or the mind to control action. In futsal, Travassos et al. (2012) determined the time-to-ball-interception (TBI) in passes performed between attackers, through the defending team's surface area, as the continuous difference between the time-to-defender interception (TD) and the time-to-ball-contact (TB). Like *tau*, TD expresses the defender's current time to intercept the ball ($TD = D_{DB}/\dot{D}_{DB}$), and TB is the current time to the ball arriving at the interception point ($TB = D_{BD}/\dot{D}_{BD}$). Travassos et al. (2012) revealed that intercepted and non-intercepted passes were associated with different TBI values, with the defenders' distance to the ball at the moment of pass initiation and their velocity adaptations, constraining a successful interception (Fig. 3).

These findings demonstrated that TBI dynamically specifies a possibility to intercept a pass, with defenders cogently acting to intercept the ball's trajectory at a future time and place. The explanatory value of this informational variable shows that action is fundamentally prospective without requiring, for instance, the input of mental inference processes and models prior to movement.

2.4. Evidence for perception-action as the foundation of performance

Carvalho et al. (2014) investigated how tennis players link affordances, stroke after stroke, to gain a competitive advantage over an opponent. Tennis is characterized by continuous co-adaptations of players' actions, resulting in simultaneous and successive available affordances (i.e., conditionally-coupled). Rally advantage is a process developed through successive actions, where nested affordances are dynamically assembled and imply perceptual attunement of skilled players to information for successive affordances (Araújo, Dicks, & Davids, 2019). Thus, Carvalho et al. (2014) developed an eco-physical variable capturing players' on-court interactions guided by nested affordances: the goal-directed displacement (GDD) index. This variable is calculated as the product of each player's distance value from the central line of the court (DCL) and their distance from the center of the

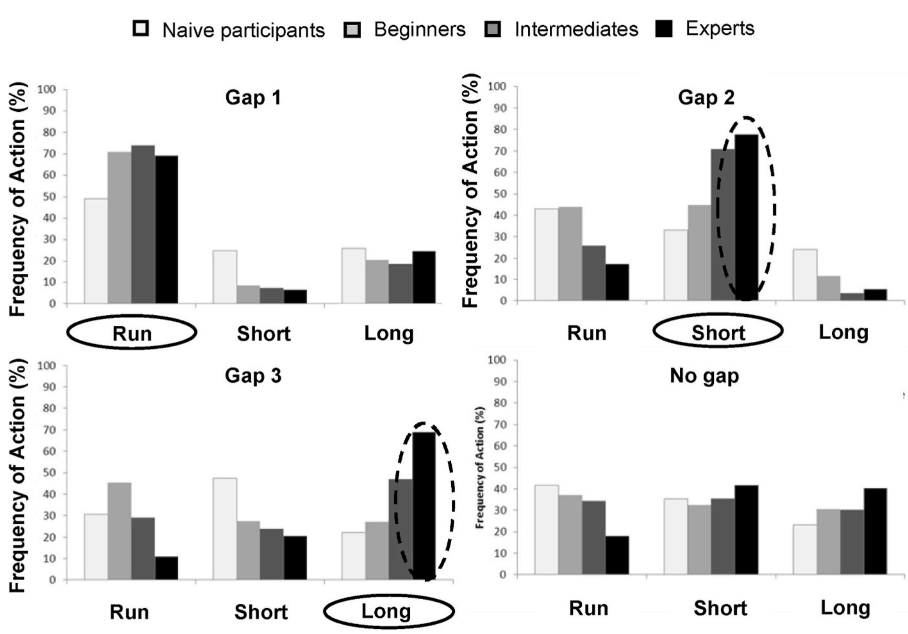

Fig. 2. Correia et al.'s (2012) demonstration of how skill constrains perception and action in a virtual reality rugby task
Note. This figure shows the effect of gap location on action mode selection (run, short pass, or long pass frequency (%). The top left panel represents condition 1 comprising a gap opening in the ball carrier's running channel. The top right panel represents condition 2 comprising a gap opening in the first receiver's running channel. The bottom left panel represents condition 3 comprising a gap opening in the second receiver's running channel. The bottom right panel corresponds to condition 4, with no gap opening. As demonstrated, each gap opening entailed a different predominance of action selection (filled ellipses). At the same time, expert rugby players performed more short and long passes in gaps 2 and 3, respectively (dashed ellipses). Data adapted from Correia, Araújo, Cummins, and Craig (2012).

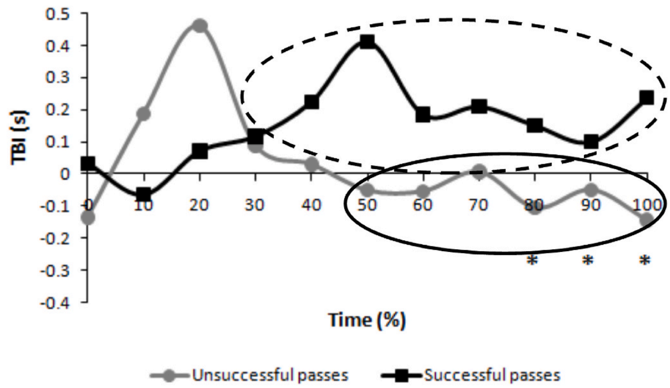

Fig. 3. Travassos et al.'s (2012) demonstration of how interceptive actions are informationally-guided in futsal

Note. This figure shows the time-to-ball-interception (TBI) of unsuccessful (i.e., intercepted) and successful (i.e., non-intercepted) passes. The black line represents the TBI of non-intercepted passes, and the gray line represents the TBI of those intercepted. As highlighted, non-intercepted passes are mainly characterized by positive TBI (dashed ellipses), indicating that the defender's current time to intercept the ball (TD) is below the current time to the ball arriving at the interception point (TB). Conversely, intercepted passes predominantly describe negative TBI (filled ellipses), expressing that the defender's TD is above the TB. Data adapted from Travassos et al. (2012).
$^{*}p < .05$.

net (DN): $GDD = DCL \times DN$. When players were moving away from stable and intertwined action courses, a system transition (i.e., a rally break) could emerge, as captured by values of the GDD index.

Carvalho et al. (2014) showed that different perception-action courses could be selected by skilled players attuned to affordances that became available in a match. Their findings also signify that a player with an advantage is perceiving and creating affordances for an opponent (see Fajen et al., 2009), inviting them (i.e., constraining) to act upon such opportunities. Moreover, the stability of the players' competitive interactions is highly constrained by their co-positioning on court and the pattern of play (e.g., cross-court or down-the-line rallies). In the affordance landscape of a match, tennis players intentionally create successively more challenging situations for an opponent, stroke after stroke, de-stabilizing the co-dependence of their action courses (Fig. 4).

As previously elucidated, ongoing cognizant actions can be sustained by perceiving and exploiting nested affordances, and not necessarily by a hierarchical mental plan (Araújo, Dicks, & Davids, 2019). Moreover, transitions in perception-action dynamics (i.e., decision-making) are self-organized, emerging under interacting task constraints of rugby union (Correia, Araújo, Duarte, et al., 2012; Passos et al., 2009; football (Welch et al., 2021) and gymnastics (Mangalam et al., 2024). Recently, Lopes et al. (2025) analysed decision-making in judo as transitions in interpersonal perception-action dynamics, showing that attacks were promoted by critical variations in relative body orientation misalignments, perceived as affordances to throw. Dyads of skilled judokas were randomly assigned to one of two representative judo tasks: (a) performing movement displacements without attacking (control condition), and (b), performing a constrained combat where only judoka could throw of an opponent (experimental condition). Participants' angular velocity values were measured to calculate their (mis)alignment (relative angular velocities, RAV) and their interpersonal coordination (running correlations, RC). In the experimental condition, transitions were analysed based on the number and type of the RC's fixed points ($dRC/dt = 0$) as a function of RAV. In the constrained combat task, RC dynamics showed abrupt switches between stable and unstable tendencies, where successive attacks disrupted interpersonal coordination by creating misalignments to throw, and defensive actions stabilized such coordination by canceling misalignments (Fig. 5).

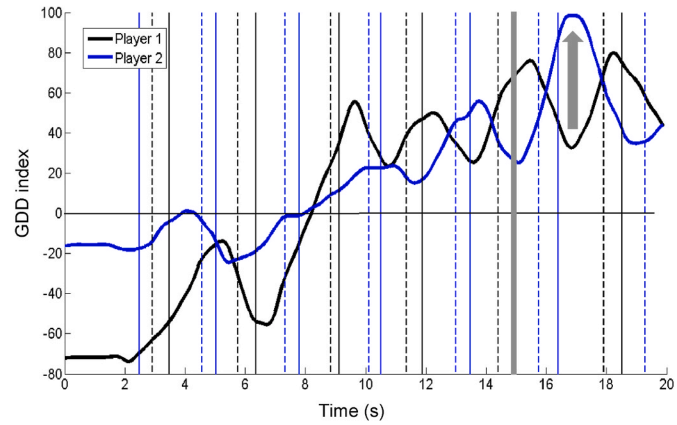

Fig. 4. Carvalho et al. (2014) demonstrating of how nested affordances guide perception-action in a tennis rally

Note. This figure shows two tennis players' GDD index, illustrating a transition involving an angle opening during a cross-court backhand rally. The black time-series represents player 1 and the blue time-series represents player 2. The vertical lines indicate the moment of each player's strokes (thick) and the ball's bounces (dashed). If the GDD index time-series are on the same side, both players are positioned on the same side of the court playing a cross-court rally. If the time series are on different sides, players are facing each other playing a down-the-line rally. As highlighted, player 1 in his fifth stroke (gray vertical thick line) constrains player 2 to increase his GDD index from 20 to 98 (gray arrow) by moving laterally out of the court and increasing DCL, opening space on the right-hand side of his court affording an attack that finished the rally. Data adapted from Carvalho et al. (2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

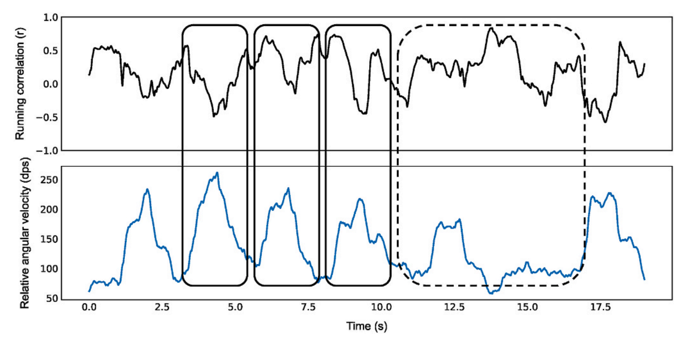

Fig. 5. Lopes et al.'s demonstration of how throwing affordances guide transitions between action modes in judo

Note. This figure shows a dyad's trial in the experimental condition with a fixed attacker and a fixed defender. Higher values of relative angular velocity (RAV), expressing misalignments to throw, co-exist with breaks in running correlation (RC), indicating that interpersonal coordination disruptions expressed attacks (black thick highlights). Conversely, lower RAV, expressing alignments canceling an attacking opportunity, co-exist with higher RC values, indicating stable interpersonal coordination tendencies (black dashed highlight). Data adapted from Lopes et al. (2025).

Notably, Lopes et al. (2025) showed that transitions were marked by changes in the number and type of the RC's fixed points, with prevalent saddle-nodes disappearing with increasing values of RAV. Saddle-nodes, representing half-stable combat dynamics, emerge from the judokas' opposing actions (i.e., to throw and avoid being thrown), constraining their actions by defining a region of common (movement) solutions based on their relative body orientation misalignment.

3. Debates about ecological dynamics of cognizant action in sport

3.1. Ecological dynamics rejects the separation between knowledge and perceptual-motor behavior

There are several longstanding debates in psychology which concern ecological dynamics. A persisting debate, championed in a meeting in Amsterdam during the 1980s, is about the role of knowledge in perceptual-motor performance. The meeting led to discussions termed 'the motor-action controversy' (Meijer & Roth, 1988). This controversy was extended to the understanding of sport performance (see Sutton & McIlwain, 2015; or more superficially, Collins et al., 2024). The prominent sport psychologist Hubert Ripoll (2009, p. 90) argued that Araújo and colleagues (2009) studied sport behaviours by the laws of physics, but two different components of a performer's actions need to be present: i) local behaviours determined by "simple physics principles"; and ii), "global behaviours which result from combining local behaviours in accordance with a frame of reference shared by all players, i.e., a playing system. It is obvious that mental representations guide the behavior of players". Ripoll (2009, p. 92) further clarifies "The distinction between location space (the space of actions) and form space (the space of representations) was proposed by Paillard back in 1971 (…). Accordingly, locating functions, which are in charge of physical relations between an organism and its environment, serve to construct the location space and are processed at the subcortical level, whereas functions in charge of form recognition or activation serve to build the form space and are processed at the cortical level." This distinction between "simple physics" and global behaviors is echoed in Simon's (2002) "vertical separation" claim about "near decomposability" and Pylyshyn's (1980) distinction between physics and representations. However, it is important to clarify that these theorists have never provided empirical evidence for their suggestions that the time-series of behaviour can be decomposed in this way: that there are no long-range temporal dependencies. In contrast, there is convincing empirical evidence of the presence and effects of such dependencies (Van Orden et al., 2003; Wallot & Kelty-Stephen, 2018).

In the ecological view, the sophistication of expert performance derives from the improved (functional) fit of performers with their environments, rather than from an increased complexity of knowledge stored in memory and mentally processed (Araújo, Hristovski, et al., 2019). Moreover, the concept of representation has been shown to suffer from a high degree of equivocation, leading even scientists who endorse representational theories of cognition to display uncertainty regarding its application to empirical data (Favela & Machery, 2023). However, if the nature of symbolic or representational processes that ecological dynamics allegedly fails to consider is clarified, a dilemma emerges. If these allegedly missing processes are physical, energy-consuming processes, there is no reason that contemporary analyses of the multiscale dynamics of the performer-environment system cannot account for them (Van Orden et al., 2003). On the other hand, if these processes are understood to be 'purely formal' or entirely disconnected from the materially embodied dynamics of action, the 'grounding problem' becomes completely intractable (Pattee, 1995) and their relevance for cognizant action becomes tenuous at best.

3.2. Ecological dynamics is not asymmetric towards the environment

Another interesting point of debate claims that ecological dynamics may be 'too ecological' (but see Sánchez-García, 2023, arguing that the social environment can be further developed in ecological dynamics). For example, Gagné (2011, p. 153) writes that: "The pool of commentators did include a few strong believers of the EB {Environmental Bias} ideology, especially Araújo & Davids (…) they argue that *'the DMGT model is biased towards the individual, based on assumptions that gifts and talents are entities to be acquired or possessed by individuals'* (p. 23). That statement, whose alleged assumption I do indeed endorse, sets the scene for a major divergence in perspective between their position and mine". Also, Poizat et al. (2023, p. 176) claim that "it is sometimes difficult to avoid the suspicion that the exhortation to more symmetry (e.g., Seifert et al., 2023) is actually a pleading for an opposite asymmetry that is, an asymmetry or a leaning towards the environment and not towards the actor". In ecological dynamics, and repeated in this manuscript for further clarity, the fundamental level of explanation for explaining performance is the inseparable performer-environment system.

3.3. Ecological dynamics considers teams as self-organizing entities

Theoretical approaches to team cognition have been formed around the idea of models being constructed within each individual which can be shared collectively in a group of performers. This notion has led to the concept of 'shared mental models', i.e., constructed on *knowledge about* the performance environment verbally shared among team members to enhance effectiveness and efficiency in performing together, founded on pre-determined actions (Cooke, 2015). Particularly, the interactive team cognition theory (ITC; Cooke, 2015), suggests that team cognition is dynamic, emergent from the interaction between team members, and linked to context. ITC proposes that, when team members interact, they are compelled to develop an interactive way of thinking that was not present before the interaction. Although this way of thinking emerges from the continuous performer-environment relationship, it still needs to be processed prior to collective group action and conveyed among players through common language and concepts to control behaviour in performance (Silva et al., 2013).

The discovery of phase stability and transitions in rhythmic coordination between two people (Schmidt et al., 1990) confirmed that self-organizing, social dynamics have an informational basis that extended across separate nervous systems (for an example in world class sprinting see Varlet & Richardson, 2015). ITC diverges from the ecological dynamics' theory of synergy formation in teams (Araújo & Davids, 2016), which explains cognizant action without relying on mental models and representations. From an ecological dynamics perspective, the control and selection of collective cognizant actions are based on direct perception of shared affordances, which can be acted upon cooperatively by the group, thereby forming team synergies (Araújo & Davids, 2016). This idea emphasizes that the perception of socially-shared affordances underpins the main (i.e., nonverbal) communication channel between team members during group tasks (Araújo & Davids, 2016, see also Wagman et al., 2017). Available affordances can be perceived by a group of individuals, trained to become perceptually attuned to them as a collective (Silva et al., 2013). Ecological dynamics hypothesizes that the presence of others extends affordances that are realizable by individual performers to affordances realizable by teams.

4. Future directions for cognizant action research guided by ecological dynamics

In addition to the substantial body of empirical research reviewed here, we anticipate the fruitfulness of the ecological dynamics framework will be demonstrated by continued progress in multiple areas, several of which we outline here. To exemplify, the multifractal tensegrity hypothesis (Turvey & Fonseca, 2014), motivated by the theoretical underpinnings of the ecological approach, is now being introduced to sport science (Caldeira et al., 2020, 2021). The pre-stressed tuning of multifractal tensegrity structure facilitates rapid movement through instantaneous global distribution of force throughout the body and will likely provide a valuable framework for further study of cognizant actions in sport. For example, Mangalam et al. (2024) showed that the dexterous postural control exhibited by gymnasts is well captured by the multifractal fluctuations of movement. The multifractal tensegrity hypothesis may be uniquely positioned to offer empirical insight into the "fingertip feel" of haptic perception in sport. More generally, these results indicate that the principle of action-perception coupling extends beyond scales of analysis at which the coupling is intuitive or obvious. In the case of multifractal tensegrity, movement fluctuations that occur at a very fine grain level have been shown to support the perception of affordances (Hajnal et al., 2018). Evidence of fractal nesting of longer timescales events in sports (Ramos et al., 2020) should be followed up with surrogate analyses that can confirm the non-decomposability of timescales in these events (Wallot & Kelty-Stephen, 2018).

Affordances can be utilized with respect to forthcoming events and up-coming actions (Turvey, 2019), rejecting the need for an internalized predictive model (cf. Friston et al., 2017). In football team performance, anticipation that extends beyond the current information about a future event was recently studied (Carrilho et al., 2025). Such *strong anticipation* depends on causal relations in the system in which the performer belongs (Stepp & Turvey, 2010) and is expressed by delay-coupled dynamics that exhibit anticipatory synchronization. Carrilho et al. (under review) captured anticipation as the players' prospective coordination within the performance environment towards task goals. Particularly, team synergies emerged from players' anticipatory movements relative to key environmental properties, guiding the team's' ability to maintain goal-directed behavior. The angles formed by defender-ball-goal relationships during team game performance were computed from game positional data and submitted to cluster phase analysis to express how defenders collectively sought to impede the progression of the ball towards the goal. Cross-correlation analysis measured defender-ball coupling strength and delay, examining how defenders coordinated their movements with the ball trajectory to sustain and interchange between blocking roles, so the team could maintain defensive stability. Higher values of coupling strengths were associated with negative coupling delays, meaning that defenders coordinated their actions, anticipating future ball positions to anticipate and interchange positioning between blocking roles. This line of inquiry brings an ecological alternative to contemporary predictive processing models, both at the individual and group levels.

In addition to the distinct mathematical foundations of strong and weak anticipation (Dubois, 2003) highlighted in section 1.3, strong anticipation has been empirically documented in non-living, dissipative systems (Voss, 2000). It is, therefore, more general than explanations of pattern recognition, for example, provided in anticipation research within cognitive psychology. Further, empirical tests of strong anticipation have controlled for standard pattern-recognition explanations in experimental design and concluded they did not explain their findings (Stephen et al., 2008, 2011). The strong anticipation account has also been shown to contradict predictions of predictive processing models in some tasks (Mangalam et al., 2023). Finally, this research program has gone beyond correlational modeling to experimentally test the influence of multifractal stimulation on spatial perception (Kelty-Stephen et al., 2023).

The body of empirical research supported by the ecological dynamics framework has firmly established the utility of many core concepts such as affordances, bifurcations, and information regulation in the study of cognizant action in sport. In this position paper, a theory of cognizant action has been advanced, re-iterating the theoretical bases for studying the conservation of intentionality by coupled perception and action. As we argued here, this is not a new concept that proposes human action as fundamentally intentional (instead of automatic, or voluntarily controlled by the mind, or as mechanistically implementing the predictive processing and modelling of the brain). Rather, the implication is that cognition cannot be studied as disembodied and dis-embedded as proposed in inferential psychological models (e.g. predictive processing). Therefore, for the purposes of studying cognizant action in sport, a new coherent link between affordances from ecological psychology (Gibson, 1979), self-organization from dynamical systems theory (Kelso, 1995), and skills from a complex systems approach to expertise (e.g., Hambrick, Campitelli & Macnamara, 2017) has been presented.

We also emphasized that ecological dynamics has progressed the study of cognizant action in settings representative of a competitive performance environment. These are important aims for continuing the vibrant development of the conceptual framework of ecological dynamics, of relevance to sport scientists including sport psychologists, supported by the ongoing production of a rich body of data on sport performance and development.

CRediT authorship contribution statement

Duarte Araújo: Writing – review & editing, Writing – original draft, Project administration, Investigation, Funding acquisition, Conceptualization. **Henrique Lopes:** Writing – review & editing, Investigation. **David Farrokh:** Writing – review & editing, Investigation. **Keith Davids:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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