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Embodied Cognition and Emergent Decision-Making in Dynamical Movement Systems

INTRODUCTION

The aim of this article is to overview research on decision-making skills and to consider the whole decision-making process as an integral part of goal-directed behaviour influenced by bodily constraints at the scale of the environment-athlete relationship. In this article we propose how dynamical systems theory applied to human movement helps us to understand how embodied cognition influences decision-making. We use the context of sport in order to illustrate how decision-making emerges from dynamical movement systems. In traditional information processing approaches to decision-making, humans have been modelled as rational decision makers selecting options according to mental models of the world designed to maximise utility for performance in contexts such as sport and work.[1] Traditional approaches focus on the mental level of human behaviour and brought about significant advances in comprehending decision-making behaviour. This body of work also exhibited limitations for understanding decision-making processes, stimulating questions over alternative approaches.

Some alternative views have emerged from ecological psychology and dynamical systems theory, emphasising human movement systems (i.e. the body) as dynamical systems, surmising that decision-making does not exclusively arise from mental models of the world. Rather, decision-making behaviour is considered at the level of the performer-environment relationship and is seen to emerge from the interaction of individuals with different tasks and environmental constraints over time. We propose how dynamical systems theory applied to human movement helps us to understand how embodied cognition influences decision-making. We use the context of sport in order to illustrate how decision-making emerges from dynamical movement systems. We examine explanations of the decision-making process in sport as a symmetry-breaking process within complex, dynamical systems formed by the athlete and the environment.

SOME CHARACTERISTICS OF DYNAMICAL MOVEMENT SYSTEMS

As recently noted,[2] human movement systems can be considered as dynamical systems composed of many interacting parts. A systems view of human behaviour is espoused, and the core ideas behind a dynamical systems perspective include: (i) the concept of state space (i.e., the hypothetical totality of all the possible states of order (in other words, states of coordination which are achievable by a movement system); (ii) the idea of a set of possible trajectories that a movement system can take through state space; and (iii), the use of mathematics to describe the laws that determine the shapes of these movement system trajectories.

With respect to the theme of this issue of *Junctures*, what makes a dynamical systems interpretation of human movement behaviour attractive is its capacity to transcend brain/body/environment boundaries. Emergent cognitive phenomena are rooted in factors that spread across an individual performer (e.g., an athlete's body and his or her environment). Such an explanatory framework is suitable for modelling parameters related to both the individual performer and the environment in a uniform vocabulary and framework, thus facilitating an understanding of the complex interactions between the two. Whereas the traditional framework is geared to describing computation and representation as a result of a mental model of the world, invoking criticisms of agency in biological systems, dynamical systems theoretical constructs apply as easily to environmental features and individual movement systems.

The traditional rational approach is the result of many years of scholarly activity, and is, by any standard, a major intellectual achievement. Because it is the dominant paradigm on decision-making in psychology, challengers are required to offer a great deal before criticisms and alternative views are taken seriously. In this article, we will not review traditional approaches to decision-making. Recent reviews can be found in Mellers, Schwartz, and Cooke[3] and Williams, Davids and Williams.[4] In the following sections of this article it will become clear that it seems necessary to include in the study of decision-making in sports: (1) emergent situations evolving in time showing interdependency between performers; (2) interrelated decisions analysed at the level of the person-environment system, expressed by emergent whole-body behaviours in the form of perception-movement cycles; and (3), the capacity to explain how expertise effects influence decision-making. Specifically, it is important to consider, not just stored knowledge about action as constraint, but action itself as part of a continuous dynamic process in the athlete-environment relationship.

DECISION-MAKING AS AN EMERGENT PROCESS IN DYNAMICAL MOVEMENT SYSTEMS

Whereas traditional psychological theories have emphasised essentially individual psychological constraints for understanding decision-making as a normative rational process, skilled behaviour from an ecological perspective consists of intentional adaptation to the constraints imposed by the environment during task performance.[5] The influential work of Kugler and Turvey[6] drew attention to the role of information in guiding action, as originally argued by Gibson,[7] but went further in modelling how human action is constrained by laws of non-equilibrium thermodynamics and non-linear dynamics.

From this perspective, the role of cognitions and intentions is viewed as "setting up self-assembly (i.e., leading to the emergence of self-organized behaviour), not explicitly controlling such processes during movement coordination."[8] Thus, cognitive processes constrain but are not mandatory for intentional behaviour. Intentions in humans are based in the real world and are constrained by mind, body, social, and biological contexts. This constraints-led perspective "promotes functional behaviours such as formative creativity and exploration in movement systems during learning, and helps avoid stereotypical, unvarying responses that are maladaptive during goal-directed behaviour." [9]

With regards to the theme of this issue of *Junctures*, it is somewhat misleading to refer to the generation of a willed action as if intentional behaviour could exist separate from an environment, or separate from a body. It makes little sense to propose such a hierarchical relationship between intentions and actions because it is not possible to separate the influence on movement system behaviour from the embodiment of perception, action, and cognition.[10] To intend a goal (i.e., a final condition) means that the performer selects the initial condition that permits attainment of the specified final condition under the existing (physical) law domain. With each step closer to the goal the information must become ever more specific, narrowing the possible action paths, until ultimately, at the last moment of goal accomplishment, the path becomes uniquely defined.[11] "These decisions emerge from the system depending on fluctuations in the initial task conditions and any higher-order goals impinging on action."[12] This idea implies that decision-making and intentional action is influenced by the instantaneous constraints impinging on the movement system, which in turn is constrained by intentions.

In order to achieve a movement goal, non-linear behaviour will result if there is a competition between attractors in a dynamical movement system (i.e., if there are multiple sub-goals to be satisfied). Given this view, decision-making can be defined as a choice among converging trajectories for an intended goal. This choice is made at a bifurcation point where there is not enough information to specify the most functional trajectory for the dynamical movement system. Consider the example of dribbling in ball games like basketball or hockey. The player-environment system that is established during dribbling can facilitate our understanding of how selected actions that emerge from a specific player-environment relationship can contribute to achievement of an intended goal.

INTRINSIC METRICS IN DECISION-MAKING

In ecological psychology, information is a physical variable available in the environment.[13] To detect such information the performer perceives properties of the environment not in extrinsic units (such as metres, inches, etc.), but scaled in relation to his or her body or body parts, own action capabilities, and relative in location to other important objects, surfaces and people in the environment.[14] Such an approach to perception and decision-making captures how important the concept of embodied cognition is in analysing human behaviour.

For example, evidence has shown that the 'climbability' of a stair is perceived relative to the scale of an individual's leg length. Warren found that young adults of a wide range of statures could, by visual inspection alone, determine which in a series of stairs of varied riser heights afforded bi-pedal climbing and which was most energy efficient.[15] This study showed that the affordance (i.e., action possibility) of a particular stair for an individual can be described as a function of the riser height (RH) of a stair and the leg length (LEGL) of the perceiver: π = RH/LEGL. The perceived critical point at which riser height no longer afforded upright locomotion was stable at 0.88-0.89 of leg length. At this point, climbers were unable to ascend the stair bi-pedally and a 'phase transition' (sudden change) in behaviour occurred. On the other hand, a ratio smaller than the reported critical ratio specifies climbability of stairs for an individual. In this experiment, Ulrich, Thelen and Niles[16] noted that: "Individual *choices* varied but were body-scaled; subjects' *choices* were the same mathematical function of the leg length, regardless of stature" (our emphasis). Therefore, as van der Kamp, Savelsbergh and Davis[17] argued, "body-scaled ratios can be used as a critical determinant of action choice – a change beyond the critical ratio value demands a new class of action."

It is the area of transition rather than the critical ratio that is of greatest importance. Furthermore, contrary to the traditional cognitive approach, van der Kamp (et al.) highlighted that switching between movement patterns emerges from changes in the constraints imposed upon action.[18] From this perspective, it becomes apparent that individuals do not engage in conscious and rational mental calculations, comparing the current limb-obstacle ratios with an internal representation of a critical ratio, and deciding on the basis of this comparison which action to execute. In order to develop our arguments, we next explore how decision-making may be considered an emergent process under constraint due to self-organisation processes in individual movement systems.

ACTION SELF-ORGANISATION

To summarise so far, we have argued that actions, inherently goal directed, are embedded in specific performance contexts, and embodied in each individual performer's movement system. Action may be conceived, according to Kugler and Turvey, as being not something abstract (a "thing"), but a relation between the individual and the surround, when he or she is performing a task.[19] An action is functionally specific, implying that it needs to be understood in relation to a function to be achieved in the environment. Also, an action is a specific mode of resource use, where these resources can emerge from the person (e.g., height, velocity, impulsivity) or from the environment (e.g., adherent floor, jumpable obstacle). Thus an action is not an aggregation of anatomic mechanisms, because complex biological systems exhibit the capacity for stable and unstable patterned relationships to emerge between system parts through self-organisation.[20] As Kelso argued: "A spontaneous pattern formation is self-organization: the system organizes itself, but there is no 'self', no agent inside the system doing the organizing."[21]

Using the previous example of stair climbability, at the point of bifurcation (i.e., the critical ratio) the probability of using bi-pedal and quadrupedal locomotion is the same. An accidental fluctuation or perturbation to the system constrains the decision to use one or the other mode of locomotion, so no agent inside the person-stairs system 'decides' which mode to use. "Certainly, a decision appears to be made, but no decision maker tells what to do."[22] Bifurcations show how open systems (e.g., biological systems which are sensitive to energy exchanges with the surrounding environment) often have several options for particular environmental conditions. This theoretical approach shows how agency can be avoided in explanations of decision-making in biological systems. For example, when an athlete is running to gain possession of a ball in soccer, and suddenly slips, self-organised inter-limb coordination can occur, to compensate for the effects of gravity, and to re-equilibrate the performer to the vertical position. In non-linear dynamical systems, re-organisation can occur in several functionally appropriate ways and, in the case of a falling soccer player, there is no need for recourse to a mental plan to re-equilibrate. Furthermore, self-organisation in biological systems implies some requisites such as equilibrium and non-equilibrium attractors, as we are about to discuss.

ATTRACTORS AND SYSTEM ORGANISATION

Non-linear dynamics is a branch of physics that deals with the formal treatment of any system which is continually evolving over time, and which can, therefore, be formally modelled as a numerical system with its own equations of motion.[23] Within this framework, as we noted earlier, the behaviour of any living system can be plotted as a trajectory in a state space. We need to recall here that the state space is the set of all states attainable by the system, together with the paths to them. The resting states of the system are referred to as equilibrium points or attractors, as we noted earlier. A physical system can have one or more attractors, and it is the number and layout of these attractors that influence the overall functioning and behaviour of the system.[24] In the human movement system, attractors are roughly equivalent to functional states of coordination between the system components or degrees of freedom.[25]

Self-organisation processes refer to the dynamics of open systems that intrinsically and autonomously create and annihilate equilibrium points (i.e., attractors). Under appropriate conditions it appears that such systems can switch and become oriented towards a well-defined non-equilibrium state, resistant to perturbations.[26] For example, in team ball sports, when a strategic pattern of play of the team is well rehearsed, the initiation of a recognised link between two players will trigger a combination play in the whole team, i.e., the system will more easily fall into a stable, non-equilibrium attractor.

Transitions between states of organisation (known as order-order transitions) occur at the timescale of perception and action and are exemplified through the interactions between athletes and the environment. These interactions initiate the trajectories from one marginally stable dynamic mode to another, forming the basis of decision-making to select appropriate coordination modes in athletes. Structurally stable states of ordered behaviour (i.e., attractors) are created or annihilated in association with variations in the perceptual field allowing the performer to switch to different stable modes of behaviour. This capacity to be sensitive to environmental constraints (as we stated earlier, typical of an open, biological system) fits with the emergence of order in a dynamical movement system and underpins successful decision-making in complex environments.[27]

CONSTRAINTS ON MOVEMENT SYSTEMS

The role of constraints in channelling motor behaviour became prominent in the last two decades because it was realised that the stability of functional co-ordination patterns can be altered by constraints imposed on performers, such as the nature of the information available to channel movement dynamics, and the structural organisation of the performance environment including intentions and instructions to act.[28]

In order to understand the role of constraints in a theoretical explanation of skilled behaviour in sport, one needs to understand the relationship between stability and flexibility in the behaviour of natural dynamical systems. As we noted earlier, the learner in sport may be conceptualised as a dynamical movement system searching for stable and functional states of coordination (or 'attractors') during goal-directed activity.[29] The term 'functional' in this description signifies a pattern of behaviour that will support the performer in achieving a specific task goal such as to score a goal. Dynamical systems can evolve along different pathways, primarily because they are 'open' systems, meaning that their form can be influenced by many factors in the environment. In studying open, dynamical systems it has become clear that the influences that guide the form emerging from the system should be considered as constraints on system behaviour.[30]

From a constraints-led perspective, skill acquisition may be viewed as a process of stabilising a functionally appropriate attractor that a movement system can settle into during task performance. That is, a state of coordination emerges which is relatively resistant to the environmental forces or constraints that might perturb the stability of the motor system during goal-directed activity. Therefore, learning is a process in which athletes search for specific, functional coordination states, that they assemble and stabilise over extended periods of time. Athletes typically develop a repertoire or landscape of stable, functional attractors to satisfy the constraints of complex environments. According to Newell, constraints can be classified into three distinct categories to provide a coherent framework for understanding how movement behaviours emerge during performance (see diagram below).[31]

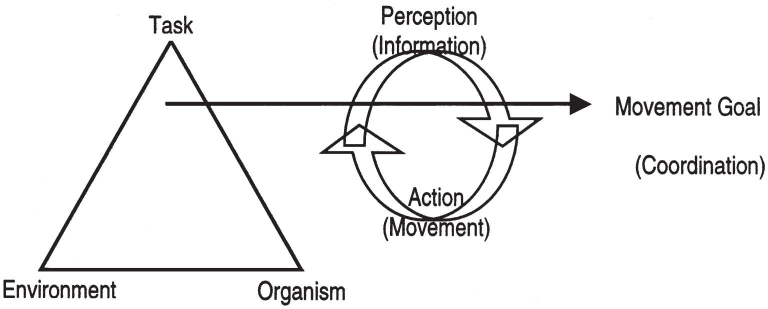

Figure 1: Newell's model of constraints depicts how individual performer, task, and environmental constraints all interact to channel behaviour (adapted from Newell, 1996).

INDIVIDUAL PERFORMER CONSTRAINTS

Individual performer constraints refer to the existing structural characteristics of the individual, such as height, body mass composition; and, the functional characteristics such as neural paths in the brain, emotions, fatigue, injury status, etc. Such unique characteristics represent resources that are brought to bear on the task problem or limitations that lead to individual-specific adaptations by the performer.

ENVIRONMENTAL CONSTRAINTS

Many environmental constraints are physical in nature and include energy flows such as sound (the auditory information available to the performer), temperature or the ambient light in a performance context. Gravity is a key environmental constraint on movement coordination in all tasks. Of course, some environmental constraints are social rather than physical. Socio-cultural factors are key environmental constraints including family support networks, peer groups, financial rewards, societal expectations and values as well as cultural norms.

TASK CONSTRAINTS

Task constraints are usually more specific than environmental constraints and include goals, rules of a sport, implements or tools to use during performance, pitch and boundary markings, augmented information sources and other instructional aids such as video. Adaptive learning allows athletes to cope with novel task constraints as performance conditions change.

It needs to be emphasised that the interaction of the main classes of constraints on the neuromuscular system during goal-directed activity results in the emergence of optimal behaviours. For example, how a basketball dribbler decides to act in a 1 v 1 sub-phase depends on relevant constraints at any one time, including the information available on court, current fitness levels, physiological status, the nature of the practice surface, and intentions (e.g., to score points quickly or to maintain possession of the ball). To summarise so far, skilled behaviour can be characterised as movements that are flexible yet robust to changing environmental forces. Movement solutions evolve over time as a consequence of the constraints on system behaviour in any given context.

To further summarise so far, it is clear that attractors act like ‘magnets’ for the behaviour of the many dynamic parts of the whole system. They represent ‘attractive’ functional states for a system to settle into. In intentional movement systems, these states are functional in the sense that they are formed to achieve a desired goal. Individual elements of the system spontaneously ‘enslave’[32] or attract other components so that, typically, large amounts of symmetry emerge in system behaviour. Self-organisation in dynamical systems theory emphasises the interaction between different levels of a system: the microscopic (or small scale) and the macroscopic (or large scale). Movement patterns at a macroscopic level spontaneously emerge from non-linear interactions (or the dynamics) of various components at a more microscopic level of organisation. As we noted, discontinuous changes in macroscopic order, induced by the continuous scaling of a control parameter, are called phase transitions, and are based on a symmetry-breaking process, where the current organisational state of a biological system is disrupted, leading to a dramatic change in system structure.

To consider an example from dribbling in ball games, a player who dribbles past an opponent, near a goal area in hockey, creates an irreversible process (i.e., a symmetry break). In order to facilitate this transition, the attacker has to de-stabilise the current state of system organisation (i.e., being further from the goal than the defender) until he or she can dribble past the defender, changing to a new state where he or she is approaching the goal. Thus decisions are embedded in an environment, embodied in a body and embrained in a brain.[33] This notion is further explored in sport.

EMBODIED DECISIONS

In football, Gréhaigne and colleagues argued that changes in the momentary configuration of the game have to be examined in the light of the previous configurations.[34] This way, each game is a unique phenomenon, "reducing the efficiency of ready-made motor or strategic solutions".[35] A consequence of a dynamical systems analysis of team ball sports is that it becomes obvious that players reduce the 'information-processing' load by being sensitised to particular aspects of the environment – aspects that have special significance because of the tasks that characterises players' activity. Practice should attune players to the variables that reliably specify states of affairs that matter to a specific task.[36] This way, players can use the "situation as its own best model"[37] and actively explore it, sampling it in detail at specific locations according to the particular needs of the moment. This is in line with the views of Gréhaigne et al., who concluded that: "With the opposition relationship, order and disorder can emerge from the play at any moment. In this way, the energy and *choices* of the players serve to create the conditions for transitions between configurations of play and thus transform the play"[38] (our emphasis). These transitions may be best understood in terms of the interactions of multiple local factors (place of the players and of the ball, their speed, player's cognitions and morphology, the slipperiness of the floor, etc.). To focus on any one of these parameters in isolation is to miss the valid explanation of performance, which consists of understanding the interplay of forces in a way that eliminates the need to posit any single controlling factor.[39] Players' embodied intelligence is fundamentally a means of using active strategies that leave much of the information out in the world, and carefully using real-time sequences of body-world interactions to solve problems in a robust and flexible way. The image here is of coupled complex systems (e.g., a player and the environment) whose joint activity solves the problem. In such cases, "it may make little sense to speak of one system's representing the other".[40]

To exemplify these arguments we now refer to data from studies of the interaction of an attacker and a defender in a 1 v 1 situation in basketball. According to Araújo and colleagues we may consider the relative positioning of an attacker with the ball and a marking defender near the basket.[41] Such a 1 v 1 sub-phase of team ball sports is very common and can be referred to as a dyad.[42] The dyad formed by an attacker and defender, plus the basket, comprises a system for the purposes of analysing decision-making behaviour. The aim of the attacker is to disrupt the stability of this system. When the defender matches the movements of his or her opponent and remains in position between the attacker and the basket, the form or symmetry of the system remains stable. When an attacking player dribbles past an opponent, near the basket, he or she creates a break in the symmetry of the system. That is, symmetry-breaking occurs as the previous stable interpersonal state transits to a new dynamic state.[43] According to Araújo and colleagues, due to the dynamics of competitive ball games, there is typically not enough information to specify a goal path completely in advance for attackers.[44] Consequently, goal path selection, or decision-making in de-stabilising dyads formed with defenders, can be viewed as an emergent process for attackers. A dynamical systems interpretation of this transition process showed that the attacker-defender system exhibited initial symmetry, which was broken during transition to a new state at a certain value of the control parameter. Our analysis of the dynamics showed that the attacker was trying to break system symmetry by dribbling past the defender, but the defender was attempting to maintain the initial steady state. The attacker increased the variability of his dribbling actions in order to augment the probability of emergence of the 'decision when to go'. Suddenly (when the symmetry was broken), the decision emerged in the "intending-perceiving-acting cycle."[45] Opposed to this, when the defender has the supremacy, the system maintains its symmetry or stability.

Another study, in sailing, showed how the local environment plays a large role in selecting behaviours.[46] As we argued earlier, athletes' decision-making is a means of using active strategies that leave much of the information out in the context, and carefully using real-time sequences of body-world interactions to solve problems in a robust and flexible way. Solutions emerge from this interaction of performer and contextual constraints. The purpose of a sailing regatta can be described as attempting to obtain the best use of the available wind to arrive at the finish line as quickly as possible. This goal must be obtained through performance manoeuvres that aim to control the direction and the speed of the boat. According to regatta rules, five decreasing minutes before the start sailors initiate the so-called 'starting procedures' in order to be in the best position at the starting line ('second zero'). This position is selected according to wind shift tendencies and the actions of other boats. Araújo (et al.)'s (in press) interpretation identified a phase transition phenomenon in the decision 'where to start' according to the manipulation of the angle between the wind direction and the line. These findings suggest that decision-making in sports like sailing is an emergent embodied process.

However, we think that it is important to remember that dynamical systems explanations can be arbitrarily far removed from facts about the real internal structure and processing of the agent. It tells us how the values of the parameters of the system evolve over time, not what it is about the way the system itself is constituted that causes those parameters to evolve in the specified fashion. But we should understand something of how the larger-scale properties are rooted in the interactions of the parts. To really understand a complex phenomenon it is at least necessary that we understand something of how it is rooted in the more basic properties of its biologically or physically proper parts. What this ultimately requires is continually probing beyond the level of collective variables and the like so as to understand the deeper roots of the collective dynamics themselves.[47] This can be done only if we clearly understand the constraints implied in the emergence of embodied decision-making.

HOW CONSTRAINTS INFLUENCE BEHAVIOURAL CHANGE OVER DIFFERENT TIME SCALES

We conclude this article by discussing how changing constraints shape emerging behaviour in dynamical movement systems. It is clear that a particular set of interactions of an individual performer, environment, and task over time can produce a particular function of behavioural change. Newell's model describes how emergence in movement systems occurs, and it was argued that "the relative impact of these three categories of constraint on the pattern of coordination varies according to the specific situation."[48] We can visualise how their relative impact changes with time in Figure 2. Here we can see how constraints are channelling the system to define the goal's path.

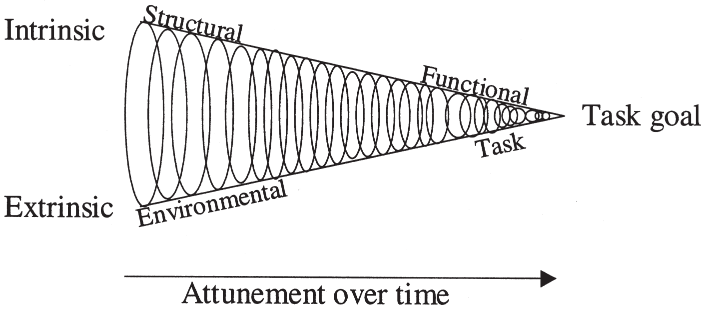

Figure 2: The relative impact of constraints on the evolving system dynamics

According to Newell, "Environmental constraints are generally recognised as those constraints that are external to the individual performer. Any constraint on the performer-environment interaction that is not internal to the individual performer can be viewed as an environmental constraint".[49] However, task constraints are a specific set of environmental constraints. Following a similar reasoning we can consider that the functional constraints (as opposed to structural constraints) of the individual performer, since they are more time dependent, are the ones that should be progressively tuned to task goal. As Newell argued, "It is clear that a variety of individual performer constraints converge to *specify* the appropriate pattern of coordination"[50] (our emphasis) and that, "Environmental constraints reflect the ambient conditions for the task, whereas the focus of task constraints is the goal of the activity and the *specific* constraints imposed"[51] (our emphasis). So, the more defined the goal path, the more the functional constraints and the task constraints specify the emergent behaviour. In seeking solutions to behavioural task goals, the performer is attempting to discover the dynamic characteristics of the system, where the system is defined over the individual performer, environment, and task.

We will end by using an example from sport to illustrate emergent decision-making processes in dynamical movement systems. When a soccer player is at home before the game, environmental constraints will have a dominant impact on the athlete, but when he or she is at the ground preparing to perform a penalty kick, task constraints are much more influential. The cultural and social constraints are more influential over a long range than the relative position of the ball and the goalkeeper. During the beginning of his or her career, the structural constraints of the player are very influential in the emergence of control, coordination and skill. But during a competitive game it is his or her level of fatigue, emotional state, and other functional constraints that will be most influential for achieving the movement goal of scoring the penalty kick.

This reasoning reveals a new way of looking at decision-making in sport. It is new because, contrary to the traditional computational approach that places all the complexity of the problem into internal states of the individual performer,[52] a constraints-led approach to intentionality and decision-making tends to distribute the complexity over both the individual performer and the environment.[53] Also, the literature suggests that it may be possible to answer questions that a theory of embodied decision-making must address:

> When (and where) will decision-making happen?
> What effect does expertise have on decision making?
> What factors determine how large those effects will be?

The theoretical analysis of how embodied cognition can be captured in a dynamical systems theoretical framework on decision-making in sport is in its infancy, but it is becoming clear that concepts such as affordances, body-scaling of actions, fluctuations in movement through exploration, and symmetry-breaking in order to seek phase transitions are potentially useful ideas from an ecological approach that need to be investigated in future research. These, and many other issues, are likely to form the basis of a theoretico-practical programme of work on embodied decision-making from a constraints-led perspective for many years to come.

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1 For example see D von Winterfeldt and W Edwards, *Decision Analysis and Behavioral Research* (Cambridge, UK: Cambridge University Press, 1986).

2 For example see D Araújo, K Davids, S Bennett, C Button and G Chapman, “Emergence of Sport Skills under Constraints,” in AM Williams and NJ Hodges (eds), *Skill Acquisition in Sport: Research, Theory and Practice* (London: Routledge, Taylor & Francis, 2003), 409-33.

3 B Mellers, A Schwartz and A Cooke, “Judgment and Decision Making”, *Annual Review of Psychology,* 49 (1998), 447-77.

4 AM Williams, K Davids and JG Williams, *Visual Perception and Action in Sport* (London: E & FN Spon, 1999).

5 For example KM Newell, YT Liu and G Mayer-Kress, G. “Time Scales in Motor Learning and Development” , *Psychological Review* 108 (2001), 57-82.

6 PN Kugler and MT Turvey, *Information, Natural Law, and the Self-Assembly of Rhythmic Movement* (Hillsdale, New Jersey: Lawrence Erlbaum Associates, 1987).

7 JJ Gibson, *The Ecological Approach to Visual Perception* (Hillsdale, New Jersey: Lawrence Erlbaum Associates, 1979).

8 K Davids, M Williams, C Button and M Court "An Integrative Modelling Approach to the Study of Intentional Movement Behavior," in R Singer, H Housenblas and C Janelle (eds), *Handbook of Sport Psychology* (New York: John Wiley, 2001), 144-73.

9 Ibid., 154.

10 E Thelen and L Smith, *A Dynamic Systems Approach to the Development of Cognition and Action* (Cambridge, MA: MIT Press, 1994).

11 P Kugler, R Shaw, K Vincente and J Kinsella-Shaw, "Inquiry into Intentional Systems I: Issues in Ecological Physics", *Psychological Research* 52 (1990), 98-121.

12 Davids et al., *Integrative Modelling*, 156.

13 MT Turvey, & RE Shaw, "Toward an Ecological Physics and a Physical Psychology," in RL Solso and DW Massaro (eds), *The Science of the Mind: 2001 and Beyond*, (New York: Oxford University Press, 1995), 144-69.

14 For example see: J Konczak, H Meeuwsen and M Cress, "Changing Affordances in Stair Climbing: The Perception of Maximum Climbability in Young and Older Adults", *Journal of Experimental Psychology: Human Perception and Performance* 18 (1992), 691-97.

15 W Warren, "Perceiving Affordances: Visual Guidance of Stair Climbing", *Journal of Experimental Psychology: Human Perception and Performance* 10 (1984), 683-703.

16 B Ulrich, E Thelen and D Niles, "Perceptual Determinants of Action: Stair-Climbing Choices of Infants and Toddlers", in J Clark and J Humphrey (eds), *Advances in Motor Research*, (New York: AMS Press, 1990), 2.

17 J van der Kamp, G Savelsbergh and W Davis, "Body-Scaled Ratio as a Control Parameter for Prehension in 5- to 9-Year-Old Children", *Developmental Psychobiology* 33 (1998), 352.

18 Ibid.

19 Kugler and Turvey, *Information*.

20 Williams et al., *Visual Perception*.

21 JS Kelso, *Dynamic Patterns: The Self-Organization of Brain and Behaviour* (Cambridge: MIT, 1995), 8.

22 Kelso, *Dynamic Patterns*, 10.

23 T van Gelder, "The Dynamical Hypothesis in Cognitive Science", *Behavioral and Brain Sciences* 21 (1998), 615-65.

24 Kugler et al., *Inquiry.*

25 Kelso, *Dynamic Patterns*.

26 Kugler and Tulvey, *Information.*

27 Davids et al., *Integrative Model*.

28 For example, see KM Newell, "Constraints on the Development of Coordination", in M. Wade and HTA Whiting (eds), *Motor Development in Children: Aspects of Coordination* and *Control.* (Dordrecht, Martinus Nijhoff, 1986), 341-61.

29 Davids et al., *Integrative Modelling*.

30 Newell, *Constraints*.

31 Newell, *Constraints*.

32 Kelso, *Dynamic Patterns*.

33 Van Gelder, *Dynamical Hypothesis*.

34 JF Gréhaigne, D Bouthier and B David, B. "Dynamic-System Analysis of Opponent Relationships in Collective Actions in Soccer", *Journal of Sports Sciences* 15 (1997), 137-49.

35 Ibid., 140.

36 Gibson, *Ecological Approach*.

37 R Brooks, “Intelligence without Representation.” *Artificial Intelligence 47* (1991), 139-59.
38 Gréhaigne et al., *Dynamic Systems*, 148.
39 A Clark, *Being There: Putting Brain, Body, and World Together Again* (Cambridge, MA: MIT Press, 1997).
40 Ibid., 140.
41 D Araújo, K Davids, L Rocha, S Serpa and O Fernandes, “Decision Making in Sport as Phase Transitions”, *International Journal of Computer Sciences in Sport* 2 (2003), 87-88.
42 RC Schmidt, B O’Brien and R Sysko, “Self-Organization of Between-Persons Cooperative Tasks and Possible Applications to Sport”, *International Journal of Sport Psychology* 30 (1999), 558-79.
43 Kugler & Turvey, *Information*.
44 Araújo et al., *Decision Making*.
45 Kugler et al., *Inquiry*.
46 Araújo et al., *Decision Making*.
47 See Kelso, D*ynamic Patterns.*
48 Newell, *Constraints,* 354.
49 Ibid., 350.
50 Ibid., 348.
51 Ibid., 352.
52 See for example G Tenenbaum and M Bar-Eli,”Decision-Making in Sport: A Cognitive Perspective”, in R Singer, M Murphy and L Tennant (eds), *Handbook of Research on Sport Psychology* (New York: Macmillan, 1993), 171-92.
53 See, for example, Davids et al., *Integrative Model*.

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