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Running Head: ECOLOGICAL DYNAMICS OF DECISION-MAKING

The ecological dynamics of decision making in sport

Abstract

Objectives: The aim of this position paper is to consider the decision-making process as an integral part of goal-directed behaviour influenced by functional constraints at the scale of the environment-athlete relationship. To achieve this aim we discuss relevant theoretical ideas from ecological psychology, focusing particularly on ecological dynamics, as a contrast to more traditional perspectives on decision making behaviour. To support the argumentation we briefly describe some recent empirical data from studies of sports that emphasize this alternative perspective on decision making. We conclude that traditional approaches analyse decisions as if they were not grounded, i.e., expressed behaviourally through actions in performance contexts. It is argued that an ecological approach should analyse affordances or action possibilities, when studying cognition in sport, demanding an integration of theories and ideas from the natural sciences in order to understand concepts like information and intentionality.

Conclusion: Decision-making behaviour is best considered at the level of the performer-environment relationship and viewed as emerging from the interactions of individuals with environmental constraints over time towards specific functional goals.

Key Words: Decision making, ecological psychology, dynamical systems, cognition, action, representative tasks.

Introduction

In sport psychology, the majority of traditional decision making studies reviewed by Starkes et al. (2001) have adopted a closed systems analysis, typical of the classical scientific method founded on a determinate world view (Glimcher, 2005). In a determinate world, a major aim is the reduction of uncertainty through testing the causal relationship formed by related phenomena in 'closed systems'. In the early decades of the last century, a challenge to a determinate view of the world was raised by quantum physics and taken up later in the social, psychological and neurosciences (Glimcher, 2005). Indeterminacy has begun to figure strongly in many 'open-systems' analyses of brain and behaviour (e.g., Gigerenzer et al., 1999; Hastie, 2001; Schall, 2001, 2004). These developments in the natural sciences raise important questions for sport psychology's traditional 'closed-systems' modeling of rational decision making, founded on classical utility theory used to analyse economic systems (e.g. Bar-Eli, Lurie, & Breivik, 1999). As we consider in this paper, an alternative conceptualisation of perception, cognition, decision making and action in ecological psychology demands an extension from the natural sciences (Turvey & Shaw, 1995, 1999).

Clearly, the traditional rational approach is the result of many years of scholarly activity, and is, by any standard, a major intellectual achievement. Moreover, it has constantly generated new variations and improvements that have reinforced its dominant role in the psychological study of decision making (e.g., Hoffmann, Stoecker & Kunde, 2004; Koch, Keller & Prinz, 2004). Because it is the dominant paradigm on decision-making, challengers are required to offer a great deal before criticisms and alternative views are taken seriously. Nevertheless, alternative ways of understanding decision making processes have arisen in recent years including the ecological approach (e.g., Araújo et al., 2004, 2005) and the aim of this position paper is to elucidate the theoretical basis of this alternative view on decision making in sport. In our analysis we discuss how environmental and task constraints shape decision-making, providing sport psychologists with a theoretical framework for understanding how ecological information provides a basis for knowledge about the world. The ecological constraints of sport are distinguished by constraints of each individual performer and physical characteristics of participation locations for athletic activities, but also by social and cultural factors surrounding performance (Araújo et al., 2004, 2005). We introduce our position paper by highlighting the theoretical basis of an ecological approach to understanding cognition and decision making in sport, followed by a discussion of recent data generated from this alternative theoretical perspective. We conclude by suggesting some consequences for future research.

It has been well documented that an ecological approach stresses the lawful relations (i.e., relations based in the natural sciences) between any individual and the environment in which he or she functions (Turvey et al., 1981; Turvey & Shaw, 1999). Gibson (1979), in his theory of direct perception, emphasised such a functionalist approach by arguing that humans and other animals perceive and act on substances (e.g., water), surfaces (e.g., ground surrounding water), places (e.g., a swimming pool), objects (e.g., a ball) and events (e.g., a water polo competition) in the environment. Such properties provide opportunities for action, defined across the complementary relationship between the environment and person. These opportunities or possibilities for action, known as *affordances* (Gibson, 1966, 1979), are neither phenomenal nor subjective. They are defined by the complementary relations between objective, real and physical properties and are ecological, since they are properties of the environment relative to a performer (Turvey & Shaw, 1999). Affordances, therefore, are the starting point for the ecological study of what humans perceive, what they learn and know, and how they decide and act (Turvey, 1992). This view implies that, for an affordance, what a substance, etc., *is* and what a substance, etc. *means* are not separate. The constraining of behaviour by detected affordances includes, in one unitary activity, the processes of perceiving and conceiving (Turvey & Shaw, 1999).

Laws and symmetry conditions at nature's ecological scale

Ecological psychology assumes a performer-environment mutuality and reciprocity, in which both combine to form a whole ecosystem. Under this synergy, biology and physics come together with psychology to define a science at a new scale – the ecological scale (Turvey & Shaw, 1995). In an emerging ecological physics a major challenge is to understand the ability of each individual to perceive the surrounding layout of the performance environment in the scale of its body and action capabilities (Turvey & Shaw, 1995, 1999). From this perspective, the role of information and intentionality in decision making and action needs to be understood in physical terms (i.e., there is a need for a law-based understanding of discrete and dynamic aspects of human behaviour) (see Shaw, 2001; Shaw & Turvey, 1999).

The empirical studies described later in this paper, clarify that, as a performer moves with respect to his/her surroundings, opportunities for action persist, emerge and dissolve, even though the surroundings analysed as objects, and the relations among them, remain stable. Subtle changes of action can give rise to multiple and marked variations in opportunities for subsequent actions. We show that the dynamic process implied in the perception of affordances provides a basis by which a performer can control his/her behaviour prospectively (Turvey & Shaw, 1995). The studies show that, in investigating cognition, an individual and his/her performance environment constitute two structures that relate in a special way such that understanding of one is, simultaneously, an understanding of the other.

This theoretical interpretation of decision making and action in sport provides an extension of nonlinear dynamics and the developing physics of self-organizing systems to cognitive systems. From this ecological perspective, characteristic cognitive capabilities are what they are by virtue of laws and general principles. Within this approach, dynamics (involving laws of motion and change) and dynamical systems (involving time evolution of observable quantities according to law) can help us to understand decision-making in sport in line with the work initiated by Kugler, Kelso and Turvey (1980, 1982) (see also, Turvey & Carello, 1995). The dynamical approach that emerged from this work emphasized the physics of nonlinear dissipative systems as the basic explanatory tool for movement control and coordination in neurobiological systems. One of their major goals was "to explain the *characteristic quantities* (their emphasis) of a rhythmic behaviour - for example, its period, amplitude and energy per cycle [which] cannot be rationalized by neural considerations alone" (Kugler & Turvey, 1987, p.4). For example, in the study of intralimb coordination (e.g., locomotion), Kugler and Turvey's (1987) model represented the joint effects of gravity's tendency to return the limbs to its equilibrium position and the spring's stiffness or restoring torque. This theoretical modelling fitted the data obtained by other researchers measuring different animals' locomotion in different contexts, showing that there is a universality to the design of locomotion, a particular exploitation of nature's laws (Turvey, 1990). In a number of other scientific disciplines, including physics, biology and economics, 'universality' has been found to ubiquitous to the modelling of complex systems' behaviour (Stanley, et al., 2000).

This ecological dynamics approach provides a powerful theoretical framework for interpreting recent advances in the psychological, social and neurosciences, shaped by understanding of indeterminacy in brain and behaviour, and with clear implications for understanding decision making behaviour in sport. The term 'ecological dynamics' signifies an approach using concepts and tools of dynamical systems theory to understand phenomena that occur at an ecological scale - the scale where the relationship between individuals and their environments is defined. Decision making from this perspective is considered a complex temporally extended process which does not characterise an individual as having made a decision prior to its behavioural expression (Beer, 2003). Indeed, if decisions are expressed by actions (Turvey & Shaw, 1995), the ecological analysis of human movement is the grounded way to understand decision-making. Rather, decision-making behaviour is considered at the level of the performer-environment relationship and is viewed as emerging from the interactions of individuals with environmental constraints over time towards specific goals. This functional analysis of decision making contrasts with traditional information processing approaches to decision-making in which humans have been modelled as ‘closed systems’ i.e. rational decision makers computing and selecting options from those represented in mental or neural models designed to maximize utility for performance (Mellers et al., 1998). The dominant tendency is to equate knowledge with concepts and to inquire about their form and about the inferential processes (explicit when cognition is defined as symbol manipulation and implicit when it is defined as connected subsymbols) that operate upon them. The grounding of the concepts (i.e., how they can refer to the environment of the performer) and the origins of the constraints on the inference mechanisms (i.e., the reasons that these mechanisms should function in just that way that renders their consequences sensible, meaning that one could, in principle, act upon them) are not of paramount concern.

Cognition and Dynamics: The Role of Qualitative and Heuristic Modelling

From an ecological point of view, cognition, should be understood in direct and deep connection with (thermo)dynamic principles (Barab et al., 1999; Swenson & Turvey, 1991; Turvey & Shaw, 1995). The investigation of the evolution of the Earth as a system, has affirmed the hypothesis of the reciprocal fit between living things and their terrestrial surroundings (see Swenson & Turvey, 1991). Living things and their ecosystems are not logically independent of each other. Together, they constitute a unitary system abiding by a single and directed evolutionary strategy that opportunistically produces – in progressively more varied and intense ways – the means for the global unit to dynamically generate entropy. The global dynamic relation of Life and Earth is foundational to an ecological inquiry into the local relations of organisms and their niches that constitute the subject matter of cognition in neurobiological systems (Turvey & Shaw, 1995). Nervous system, body, and environment are all continuously evolving and simultaneously influencing one another; All aspects of the cognitive system are undergoing change over time (Van Gelder & Port, 1995).

Dynamics is a large and diverse set of concepts and methods, and consequently there are many different ways that cognitive phenomena can be understood dynamically. Yet they all have certain key elements (Van Gelder & Port, 1995). A central one is 'time', when looking at behaviour that unfolds over time, the aim is to describe and explain the temporal course of this behaviour. Another important concept is 'total state', where it is assumed that all aspects of a (neurobiological) system are changing simultaneously. Thus it is possible to think about the behaviour of the system as a matter of how the total state of a system is changing from one occasion to the next. Because dynamicists focus on how a system changes from one total state to another, this change is seen as a matter of movements in the 'space' of all possible total states of the system; and since the phase spaces of their systems are numerical, natural notions of 'distance' apply.

Another key notion is the 'phase' of a system. Pikovsky, Rosenblum and Kurths (2001) define phase as a quantity that increases by a maximum (e.g., 2π) within one (oscillatory) cycle, proportional to the fraction of the period. The phase parameterizes the waveform within the cycle. The phase seems to provide no new information about the system, but its advantage becomes evident if we consider the difference of the phases in two systems, or 'phase transitions' in one system. This helps researchers distinguish between different regimes. A phase may possess 'symmetry' in both space and time (e.g., relative phase in

Haken et al.'s 1985 model). Symmetry is simply a transformation that leaves the system the same afterward as it was before (Kugler & Shaw, 1990). Symmetry identifies the basic patterns of coordination to be captured theoretically, and it imposes restriction on the dynamics (only certain solutions of the equations of motion are stable). However, there can be transitions in the patterns of coordination of a dynamic system, these transitions take the form of 'symmetry-breaking' bifurcations (Kelso, 1995).

Quantitative modelling of some aspects of cognitive performance has been one of the ultimate goals of a dynamical analysis. The modelling process is a matter of distilling out the phenomenon to be understood, obtaining the time-series data, developing a model, and interpreting whether the model has captured a significant proportion of the data. When carried out successfully, the modelling process yields not only precise descriptions of the existing data but also predictions which can be used in evaluating the model (see Haken, Kelso & Buntz, 1985). However, every human behaves in a different way, and is embedded in a rich, constantly changing environment, making it challenging for science to apply to cognition the kinds of explanatory techniques that have worked so successfully in studying other natural dynamical systems (Van Gelder & Port, 1995, Tschacher & Dauwalder, 2003).

This is why qualitative and heuristic modelling are so useful in the study of adaptive behaviour in neurobiological systems. Even without elaborate time series data, researchers can study a mathematical model which exhibits behaviour that is at least qualitatively similar to the natural phenomena being studied (see the sailing and the boxing examples later in this article). Alternatively, in the absence of precise mathematical models, a dynamical analysis can be used to develop qualitative dynamical descriptions of phenomena that may have been recorded in a precise data time series (exemplified by the basketball example later in this article). Often the system one wants to understand can be observed to exhibit any variety of highly distinctive dynamical properties including: criticality, universality, sudden jumps, fluctuations, hysteresis, multistability, qualitative change, and so on. Such properties can be observed even without knowing the precise equations which govern the evolution of the system. They can still be understood, however, as a particularly rich source of constraints for the process of qualitative dynamical modelling, for they narrow down considerably the classes of equations that can exhibit qualitatively similar behaviour (see Van Gelder & Port, 1995).

On the basis of this conceptualisation from an ecological viewpoint, in the rest of this paper we present theory and data exploring the merits of more ‘open’ and dynamic, indeterminate models of decision making incorporating the contextual constraints within which human movement systems interact (see Davids et al., 1994, 2001).

Decision-making is rooted on perception and action capabilities

From an ecological perspective, traditional notions of representation are subordinate, with greater significance attached to specification (i.e., specificity of information to environment; specificity of perception to information, Turvey & Shaw, 1999). Environmental properties structure ambient energy fields in such a way that the structure of these fields specifies, i.e. is uniquely related to the generative environmental properties. The lawful relations that exist between environmental properties and ambient energy give rise to what Gibson (1979) called specification. Perception of environmental properties is supported by light in the case of seeing, sound for hearing, chemicals in the air or water for smelling and tasting, and mechanical forces during touch. For example, the established starting point of traditional approaches of visual perception is the inability of light to specify the facts of the environment. This lack of specificity means that the light available to eyes, whatever their design, is intractable. The mechanisms typically proposed of associative memory, inference engines, concepts, and organizational dispositions are special mediators. Their role is to provide the link between the individual and its environment, the link that is missing, in large part, because of the assumed non-specificity of light distributions. As an alternative, the ecological approach holds that ambient energy distributions are necessarily specific to the environment and to a performer's movements relative to the environment. Perceivers are actively engaged in dynamical transactions with their functionally defined environments. Gibson (1966) argued that in all instances in which affordances are perceived, no matter how complex the property to be cognized, our awareness of it is necessarily rooted in perception (viewed as exploratory activity).Without decisions being realized through action, cognition would remain forever locked in a black box.

For Gibson (1966) this was the best way to understand how perception could regulate action: by detecting informational constraints specific to goal-paths (Shaw & Turvey, 1999). Goal constraints, as compared to physical constraints, can be considered extraordinary (Kugler & Turvey, 1987), for they take the form of a rule that prescribes how one should act if some outcome is intended. More to the point, the prescriptive rule asserts that one should act so as to change current information, non-specific to an intended outcome, into information that is specific. Such intentional 'rules' for action are not computational, they are more in the nature of laws at the ecological scale. Their effect may be observed whether or not an animal is aware of them (Shaw & Turvey, 1999).

The answer to Bernstein's (1967) well-known question about the control of motor system degrees of freedom, considered from a Gibsonian perspective is that a system with many degrees of freedom can act as if it were a simpler system only if sufficient constraints, or linkages, are established among its components by coupling them into a synergy (Shaw & Turvey, 1999). According to Shaw and Turvey (1999), three sources of freedom (the removal of constraints) and constraint (the limiting of degrees of freedom) can be identified: (i) external force fields of physical origin; (ii) internal force fields of biological origin; and (iii), information fields of psychological origin – in the ecological sense. The coupling of external, environment-based force fields with internal, performer-based force fields by means of information fields (Kugler & Turvey, 1987) forms the basis of a theory of cognition for goal-directed behaviour (e.g. showing an interaction of choosing goals, authoring intentions, using information, and controlling actions).

Ecological information

In information theory (Shannon & Weaver, 1949), information refers to the amount of uncertainty that has been reduced by the appearance of a signal. Information theory has typically been applied to the study of human discrimination capacity, where information processes are viewed as selection processes that must be made from among a specific set of alternatives (e.g., Schmidt & Lee, 2005)[1]. However, for these approaches the set of choices must be known in advance. Discrimination among elements of a set presupposes that the elements are perceptible, meaning that the capacity to discriminate is derivate. But, perception of environmental properties is more fundamental than the perception of differences among stimuli (Turvey & Shaw, 1995). Unsurprisingly, knowing in advance the environmental entities to be met is incompatible with the idea that information detection should be the basis for adapting behaviour to novel situations. Decision making requires environmental properties that, when perceived, convey information (i.e., information that permits the perception of something) rather than discrimination among things (Gibson, 1979). During the act of perceiving, the hands, ears or eyes of an actor can explore the available stimulation in an environment, searching the complex, structured energy fields. These fields of ambient,

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[1] It should be noted that traditional notions of information also characterises some schools of thought in ecological psychology (e.g. the Brunswikian school, see Gigerenzer et al., 1999; see also Johnson & Raab, 2003, for applications of theories of ecological rationality, emphasising the relations between internal and external sampling of information, in sport). This emphasis demonstrates that these other ecological approaches study environment and individual as if they could be independent.

structured energy are an environmental resource to be exploited by active persons (Reed, 1996).

Shaw and Turvey (1999) argued that informable systems may be of two kinds: those which are externally informed or self-informed. Ordinary physical systems are externally informed systems; when acted upon by a force, an immediate reactive force tempers their response (in accordance with Newton's law of action and reaction). However, neurobiological systems are self-informable, in the sense of being self-motivating and self-controlling. They are capable of a delayed reaction in addition to the immediate reaction to external forces which they can modulate by self-generation of counter-forces. To interact meaningfully with the environment, biological movement systems must have complex interiors, an on-board (metabolic) potential capable of biogenic forces that may be used to cancel, modulate, or delay their immediate reaction to an external force (Kugler & Turvey, 1987; Kugler et al., 1990). Systems that are more dependent on information fields, with information defined in the specificational sense, may be driven by specific intentions towards a goal (Shaw & Turvey, 1999). Systems that interact with the environment through information are said to be transactional rather than simply self-actional (Turvey & Shaw, 1999).

Being information-driven and adaptive does not preclude a fit transactional system from being driven by external force fields. Biological movement systems have available extra degrees of freedom that may or may not be, used to modulate external forces by internal forces. Voluntary movements of a performer may intend consequences at some later time and place beyond the context in which the movements were initiated. Actions (construed as goal-directed behaviours), like perceptions, are intentional because their meaning and significance lie elsewhere than in their causal origins. Furthermore, "actions are inherently forms of true choice behaviour" (Shaw, 2001; p.283); at each subsequent moment, a person must select from among all available affordances that particular affordance deemed most worthy to be targeted as the next intended goal.

Ecological dynamics of decision making in sport

From an operational viewpoint, the dynamics of perception, action, and cognition can be described at two levels of analysis. The first level characterizes agent-environment interactions, with performer actions detecting information. Reciprocally, this information is used to regulate further actions according to control laws (Warren, 1998). The problem at this level is to identify the informational variables that are used to guide behaviour and to formalize the control laws by which they regulate actions (e.g., Warren, Kay, Zosh, Duchon, & Sahuc, 2001).

When an agent interacts with a structured environment over time, functional patterns of behaviour emerge (Fajen & Warren, 2003). The second level of analysis characterises the temporal evolution of this behaviour, which Fajen and Warren called ‘behavioural dynamics’. Briefly, functional behaviour can often be described by changes in a few key variables. Observed behaviour corresponds to trajectories in the state space of behavioral variables (i.e., the hypothetical totality of all the possible states of order which are achievable by an action system). Goals correspond to attractors or regions in state space toward which trajectories converge. Conversely, states to be avoided correspond to repellers, regions from which trajectories diverge. Sudden changes in the number or type of these fixed points are known as bifurcations, which correspond to qualitative transitions in behaviour. In other words, they express decisions. Thus, the challenge at the second level of analysis is to identify a system of differential equations (i.e. a dynamical system) whose solutions capture observed system behaviour. These two levels are linked because behaviour at the second level is a consequence of control laws interacting with the biomechanics of the body and physics of the environment at the first level. Nervous systems or internal representations cannot simply prescribe functional behaviours as if they operate in a vacuum; they must adopt control laws that give rise to attractors and repellers in the behavioural dynamics corresponding to the intended behaviour.

In this approach, steering during agent-environment interactions, for example, could be based on current information about heading with respect to nearby objects, with steering paths emerging on-line from the interaction between an agent and the environment. Fajen and Warren (e.g., 2003; Warren & Fajen, 2004) investigated dynamics of steering and obstacle avoidance, with the aim of predicting routes through complex environments. In a succession of experiments their participants walked toward a target and around an obstacle whose initial angle and distance varied. Observed behaviour was modelled as a dynamical system in which angular acceleration was a function of target position and obstacle angle and distance. The simplest case involved selecting one of two possible routes around an obstacle to the target – the most direct route on an "inside" path, or the long way around on an "outside" path. Such a choice appeared as a bifurcation in the model dynamics, and the branch that was taken depended on an agent's initial conditions. Fajen and Warren (2003) found that participants switched from an outside to an inside path when the initial angle between the goal and the obstacle increased to 2° to 4°and as the distance of the goal decreased. There was a switch to an inside path when the initial target-obstacle angle increased to 2˚-4˚, as the goal got closer. Such a choice appeared as a bifurcation in model dynamics. Route switching behaviour resulted from competition between the attractiveness of the target, which increased with angle and nearness of the target location, and the repulsion of the obstacle, which decreased with angle. If the obstacle was positioned between the agent and the target, the model was bistable, with both outside and inside heading directions being attractive; the route that was selected depended on the agent's initial conditions.

Warren and Fajen's (2004) model captured the qualitative structure of locomotor paths and route switching in terms of the dynamics of attractors, repellors, and bifurcations. It demonstrated that human route selection can be understood as a form of emergent behaviour, resulting from an agent with certain steering dynamics interacting with a structured environment. Nonlinear behaviour, such as route decisions, emerged from the interactions of attractors and repellers at bifurcation points. The results demonstrated that the on-line steering dynamics were sufficient to account for human locomotor paths, even in fairly complex environments, rendering explicit path planning and an internal world model unnecessary.

These findings exemplified the complex interactions between intentional and information constraints during emergent decision making. It showed that to intend a behavioural goal (i.e., a final condition) involves the performer selecting the initial condition that permits attainment of the final condition under the existing (physical) law domain. With each step closer to the goal the information detected and used for action must become ever more specific, narrowing the possible action paths available for the movement system, until ultimately, at the moment of goal accomplishment, the emergent path becomes uniquely defined (Kugler et al., 1990; Shaw, 2001). Given this view, decision-making is viewed as a functional and emergent process in which a selection is made among converging paths for an intended goal. Choices are made at bifurcation points where more specific information becomes available, constraining the environment-athlete system to switch to the most functional path. When deciding, the performer uses internal energy sources to influence contextual interactions to define a path towards a specific goal. In summary, the capacity to be sensitive and attuned to ecological constraints underpins the emergence of order in a dynamical movement system and underpins successful decision-making in complex environments (Araújo et al., 2004).

Ecological dynamics can provide an alternative explanation for results obtained from other studies. For example, Johnson and Raab (2003) demonstrated that a decision-making heuristic that produce fewer generated options, rather than exhaustively generating all possible options and subsequently processing them deliberatively, result in better and more consistent decisions in “familiar yet ill-defined tasks” for a handball player. The decision to be made by these players acting as attackers, was to name as quickly as possible the first decision that intuitively came to mind after a video scene of a game was stopped.

Their explanation assumes that simple strategies linked with the current environment determine which options are generated by an associative memory network, and the initial resulting options will be beneficial to the performer. Following Gigerenzer et al., (1999), Johnson and Raab (2003) used as an explanation an inference mechanism with three steps[2] which defines the initially-activated memory node, and the criteria for determining the similarity rules that guide the spreading activation, whereas the associative network provides the structure that determines which options are generated. They adopt the principle of sequential (serial) search through an associative network based on the options’ with higher validity to meet the goal.

However an alternative explanation is that a decision is made by relaxing the performer-environment system to the most attractive state in the potential landscape. This happens without referring to any additional inference mechanisms or mediating rules. The order of validity for searching the option is an attractor landscape with various depths (“validities”) of attractors. The first option that can be selected is the strongest attractor, which can be conceived in terms of an affordance. If the task is "familiar" that means that there are already some affordances that turn some options into attractors (the “valid” ones) and other options into repellers. The selected option is the affordance (i.e., the action

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[2] They call it “take-the-first” heuristic: 1st step *Search rule:* Generate options in the order of validity; 2nd step *Stopping rule:* Stop after the first option is generated that can be implemented, ignore all the rest; 3rd step *Decision rule*: Take this option.

possibility that drives the system towards the goal). Ignoring the other options is a dynamical consequence, since if the system relaxes to one attractor it “concomitantly ignores” the remaining options (attractors). The fact that there is a stronger attractor does not eliminate other attractors. Under certain conditions these other attractors (e.g., options 2 and 3) exert their attraction. Moreover, they belong to the landscape of this dynamical system, indicating that they are still exerting influence, depending on how the system evolves. That is these attractors are metastable. The system can jump from one decision to another (metastability), because these jumps are on a faster time scale than the change of the control parameters (constraints), like time constraints. In sport situations under severe time constraints (one to few seconds) the jumps under fluctuations are smaller at an order scale of magnitude (few hundreds of milliseconds; see Haken et al., 1986). Thus, if few attractors are present, the system will jump several times from one attractor to another, dwelling mostly in the deepest of them and the time constraint will actualize the attractor which was last inhabited. Thus, for several measurements the most probable decision is the deepest attractor exerting the strongest constraint on a neurobiological system. With equal probabilities, the attractors have the same depth and strength. When measurement of the influence of attractors occurs sequentially under the same conditions, with the statistics of the reports it is possible to calculate the probability of the system falling into one of those attractors. This probability value is equal to their depths.

Performance correspondence between experimental task constraints and behaviour settings

An important environmental feature that shapes decision making involves task constraints. Neisser (1976) argued that laboratory settings with contrived, and often trivial tasks, can lead to artificial decisions and behaviour. Examples abound in sport psychology research and may be best exemplified in studies where film and video presentations have been used to simulate sport performance (see Williams et al., 1999 for a complete description). Behavioural settings (as defined by Barker, 1968, and refined by Heft, 2001) rarely have ‘all-or-none’ discrete stimulus onset points which parallel stimulus onset conditions in the laboratory (Abernethy, 1991). Contrary to this tendency, Brunswik’s (1956) ecological approach suggests an emphasis on experimental designs that specify those conditions toward which a generalization is intended. The essential characteristic of “representative design”, as he called it, is that the experimenter carefully specifies what generalizations can be made from an experiment and then sets it up to examine those generalizations (Hammond & Stewart, 2001). According to Gibsonian theorising, ecological decision-making is typically based on a continuous and active process of exploration and selection of relevant information to support choices. This means that, actions by which cognition is expressed require that information about environmental constraints be referential to the energy for behaving with respect to those constraints.

Although some machines need a stimulus to get them going, sport performers are always active in competition and practice and continuously engaged in functional behaviours constrained by individual and environmental entities. For an attacker in team ball games trying to pass a defender, “to see the distance-to-contact is to see the work required, to see the time-to-contact is to see the impulse forces required, to see the direction to-contact is to see the torques required” (Turvey & Shaw, 1995, p.158). The implication is that, in studies of decision-making, experimental tasks should be designed to ensure correspondence between phenomena of interest (e.g., decisional behaviour) manifested by the individual in a performance setting and in the experimental task (Araújo, Davids & Passos, in press). As noted in discussions of Milner and Goodale’s (1995) model of cortical activation during different types of perception, passive perception, typically encouraged by task design in traditional decision-making research, may be misleading when studying perception for action in dynamic sports performance environments (see Van der Kamp et al., 2003).

In sum, the ecological approach suggests that cognition can be studied by attending to settings in which it is actually observed and to establish how it is organized and recognized to meet the needs of different situations and intentions. To explain the complex, contextually varying phenomena of cognition requires a theory that is rich enough to explain how patterns of coherence emerge from ranges of variation (Reed, 1996). These theoretical ideas have been examined in a programme involving several experiments using sport-related tasks. This programme is still in its infancy, and it is clear that much work needs to be done. It requires considerable technical sophistication and the patience to develop rigorous descriptions of apparently simple phenomena. However, it promises to deliver an understanding of cognitive capacities which is mathematically well-founded and fundamentally continuous with the natural sciences. In the following section, we refer to data from three such studies to empirically substantiate the conceptual arguments proposed in the first part of this paper. The first study focused on the ecological dynamics of decision making process in an ongoing dribbling task in basketball. The second study showed empirical support for the dynamics of a categorical decision in sailing, and the third study provided data for categorical decisions in a continuous handstriking task in boxing. These three experiments were selected to illustrate three different performance context phenomena. The basketball study illustrates a task where individual and environment are both changing over time, with a concatenation of interdependent decisions over time. The sailing study illustrates a task where each decision is discrete but the sequence of these categorical decisions is embedded in the overall ecological dynamics of the system, thus showing the properties of a dynamical system. Finally, the boxing task demands continuous decisions in an environment that does not change, providing a contrast with the basketball study,

Experimental observations of embodied and embedded decisions in sport

Decision making in a continuous task in basketball

The relative positioning of an attacker with the ball and a marking defender near an important target area (e.g., a goal/try-line/basket) is a typical one-on-one situation in team games such as football, rugby and basketball. According to Araújo et al. (2002, 2004; Davids et al., 2006) it is informative to model this sub-phase of team ball sports as a dyad. The dyad formed by an attacker and defender, plus the basket, comprises a complex system for the purpose of analysing decision-making behaviour. The aim of the attacker is to disrupt the stability of this micro-system. When a defender matches the movements of his/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/she creates a break in the symmetry of the system, as the previous stable interpersonal state transits to a new dynamic state (Kugler & Turvey, 1987). According to Araújo et al. (2002), due to the dynamics of competitive ball games, there is typically not enough information to specify a goal path completely in advance for attackers; Goal path selection, or decision-making in de-stabilising dyads formed with defenders, was revealed as an emergent process for attackers.

Analysis of coaching literature reveals that, for this exploratory study, a candidate order parameter (i.e., a collective variable that synthesizes the relevant coordinated parts of the system as a whole) to describe the organization of an attacker-defender system could be the distance between the basket and the attacker or the defender during a 1 v 1 sub-phase of the game (e.g., Bain et al., 1978). A specific control parameter could be the interpersonal distance between attacker and defender. Inspired by the modelling of interpersonal dynamics by R.C. Schmidt and colleagues (1999), Araújo et al. (2002) examined whether the distance from the attacker-defender dyad to the basket would become less stable (i.e., not maintaining a similar distance from the dyad to the basket) until some critical value of interpersonal distance was reached. The investigation considered whether changes in interpersonal distance were associated with dribbling success by attackers, and a specific issue of interest was whether the attacker-defender dyad became more frequently de-stabilised at critical values of interpersonal distance.

INSERT FIGURE 1 ABOUT HERE

In Figure 1, we decomposed the collective variable (distance between the medium point of the dyad to the basket) showing each player's distance to the basket. It can be observed that, during the initial part of the dyadic entrainment there was a stable state of the collective variables, followed by an abrupt change (symmetry breaking) in the state of the system due to an attacker's success in de-stabilizing the dyad. These dynamical properties were clarified with the use of a running correlation[3] (Meador et al., 2002). After starting uncoupled, the players formed a system which exhibited symmetry (coupling with $r > .80$) , changes to uncorrelated states, and antisymmetric states (coupling with $r < -.80$). Finally the coupling was broken during transition to a new state (attacker's advantage) at a critical value of the control parameter. The data showed that the attacker was trying to dribble past the defender, but the defender was attempting to maintain the initial steady state. The attacker persisted with dribbling actions in order to force the emergence of a system transition (decision when to 'go'). Suddenly (when the symmetry was broken), the decision emerged. In summary, the data suggested that it is possible to describe the attacker-defender dyad as a dynamical system (Van Gelder & Port, 1995) and to interpret the dynamics of player interactions in dribbling as emergent properties under constraints.

The dynamics of a categorical decision making in sailing

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[3] The running correlation curve RC(t) is the time course of correlation coefficients obtained from a sliding rectangular window of waveform data centred at t. The correlation coefficient at each instant is the normalized sample covariance of the windowed waveforms $x'(t)$ e $y'(t)$: $\mathrm{RC}(t) = <(x'-m_{x'})(y'-m_{y'})>/(s_{x'}s_{y'})$
where m and s are the amplitude mean and standard deviation across the duration of each windowed waveform (see Meador et al., 2002).

In sailing, Araújo et al. (2003) showed how the local environment plays a large role in selecting functional behaviours. The purpose of a sailing regatta can be described as obtaining the best use of the available wind to arrive at the finish line as quickly as possible. This goal must be achieved through manoeuvres that aim to control the direction and the speed of the boat. According to regatta rules, five minutes before the start, sailors initiate starting procedures in order to be in a favourable position at the starting line (at the "second zero"). This position is selected during the start period according to wind shifts tendencies and the actions of other boats.

In this study we manipulated the angle between the wind direction and the starting line and observed discontinuities in the decision "where to start" in twenty-three consecutive regattas. The control parameter was designated as the angle between the wind direction and the starting line (which we manipulate in steps of 10º), and the order parameter was the position of the boat on the starting line at second zero, based on experiential and coaching knowledge (e.g., Dahon, 1997).

We found that the boats' start positions tended to be located at the extremities of the start line with higher |angle| values (> +10º or < - 10º). In fact, when the wind favoured one of the extremities of the starting line, the nearer to that extremity the boat was positioned, the more direct was the required trajectory (to the 1st mark of a regatta). Interestingly, the start position in one of the extremities (near the committee boat) tended to be undervalued because of the starboard priority (see left side of Figure 2). However, in the zone where the wind was neutral (between–10º and +10º) there was higher variability in start location (i.e., enhanced fluctuations), because there was no advantage from boat positioning for the required trajectory. Araújo et al.'s (2003) interpretation identified the presence of a phase transition in the decision "where to start" (Figure 2).

INSERT FIGURE 2 ABOUT HERE

A region of instability was identified, characterised by enhanced fluctuations, as well as other hallmark properties of dynamical systems (e.g., qualitative change, abrupt jump, hysteresis effects).

This dynamical behaviour is captured in the canonical form4 used in modelling the categorical decision making proposed by Tuller and colleagues (e.g., Tuller et al., 1994). This model accounted for behaviour with two attractor states: $V(x) = kx - x^2/2 + x^4/4$, in which $V(x)$ represents a potential function with at most two minima, which might correspond in our sailing study to the "left side of the starting line" and "right side of starting line". Here x is the decision (i.e., expressed by the place of the starting line where the sailor was on 'second zero'), and k is the control parameter specifying the direction of the wind.

In line with the modeling predictions of Kelso and Schöner (1988) we observed a qualitative change since the tactical requirements of starting on one side (e.g., the left side) were qualitatively different than starting on the other side. The qualitative change is based on the fact that, for example, regatta rules differ according to the position of the boat - starboard or portboard - and each side – left or right - implies predominantly different positions. Moreover, in a regatta setting each side has different micro-meteorological conditions. The abrupt change is evident in Figure 2, occurring in line with the progression of the control parameter. In the angles between -50º and -10º the start position was never below 45% (M = 60.33; SD = 12.65) of the starting line; in the angles above 10º the start position was never above 20% (M = 8.55; SD = 6.31). These two clusters of start positions were significantly different (z (12) = -2.88; $p<.004$). Critical fluctuations are evident in the figure, but only in a range of 20º (between -10º and +10º) was there much higher variability (M= 30.08; SD=30.58) than in the two attractors which included 40º each ($F(2, 34) = 15.58$; $p < .001$.

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4 Canonical form refers to a general mathematical form (e.g., the polynomial form of the potential of order 4) to which a different set of mathematical forms could be reduced by a redefinition of the coordinates.

Another hallmark characteristic of dynamical systems, multistability, was also observed. At the same values of the control parameter it was possible to observe two different values of the order parameter since in the transition zone (between -10º and +10º) it was simultaneously possible to start both on the right or left side. This dynamical model exemplified how decision making in sport can be emergent depending on how the task and environmental constraints change instantaneously. Thus, by manipulating a key task constraint, wind-starting line angle (the control parameter), we changed the dynamics of decision making of these sailors (the place chosen to start).

As can be seen from the data presented, due to the dynamic instability of this metastable region, the starting positions possessed a significant amount of variability especially in the region around $k = 0$. To explain how the decisions were a juxtaposition of deterministic and stochastic influences which produced the variability, it has to be emphasized that dynamical systems are essentially nonlinear systems typically containing deterministic and stochastic components. The stochastic influences on the system dynamics are represented by the diffusion coefficient Q. The larger the value of Q, the larger the fluctuations arising from the microprocesses acting on the macroscopic system dynamics (e.g. the decision dynamics). The Fokker-Planck equation (for details see Haken, 1987, Sugakov, 1998) takes into account: (i) the deterministic component contained in the first derivative of potential function $V(\mathrm{x})$ with respect to x; and (ii), the strength of the fluctuations represented by the value of Q.

The solution of the Fokker – Planck equation determines the probabilities of finding the decision system in some of the possible states. It has a general form:

$$P(x) = C \exp(-2V_k(x)/\mathrm{Q}) \qquad (1)$$

Where C is a constant obtained by the use of normalization condition.

The key point to note is that equation (1) on the right hand side contains a deterministic component given by the potential $V_k(x)$, where the index k signifies that the deterministic influences depend on the control parameter k, and a stochastic component given by the strength of the diffusion coefficient Q. Hence the behaviour of this nonlinear system (in this case, the decision-making dynamics), given by $P(x)$, is probabilistic and subject to deterministic flow influences which are controlled through changing the parameter k as well as stochastic fluctuations dependent on Q.

Our sailing experiment aimed to empirically verify the general self-organizing characteristics of competing deterministic and stochastic forces in the metastable region, and thus we varied the control parameter k (the wind angle), and kept constant the fluctuating forces given by Q. In this case we took $Q = 1.5$. If $k = 0$ (see Figure 3a and b) then both (left and right) starting positions that is: $x = -1$ and $x =1$ are equally attractive and the variability of decisions in the system is at its highest. Note that the local minimum of the probability located around $x = 0$ has very close values with those of the maxima (Figure 3b). That is, in this region of metastability, stochastic forces have a much larger effect than the deterministic flow found in the experiment. In other words, the data confirm that stochastic events dominantly influence the decision where to start. Regions around $x = 0$ are almost equally likely to be observed as starting positions compared to those of the attracting points (i.e. $x = -1$ and $x = 1$). However, if the absolute value of the control parameter $|k| >0$, stochastic force effects loosen their grip and much more probable decisions are those close to the deterministic attractors on the right side: $x = 1.5$ for $k = - 2$; (Figure 3 c and d) or on the left side: $x = -1.5$ for $k = 2$; (Figure 3 e and f). In other words, the larger the $|k|$, the easier it is to predict which decision will be made (see Figure 2). Thus the interplay (i.e. competition) between the deterministic and stochastic forces shapes the actual decision landscape of the competitors as formalised in the equation and reinforced in the experimentation.

The dynamics of categorical decisions in a continuous handstriking task in boxing

In martial arts such as boxing, athletes need to become attuned to relevant properties that produce unique patterns of information flows (e.g., optical information from a punch bag or opponent's body). Such flow patterns are specific to particular environmental properties and can act as information sources to be picked by boxers to constrain decision-making on the type of attack to be made (e.g., uppercut, jab or hook). In line with this, Hristovski, Davids and Araújo (2006) studied how distance-to-target information constrained the actions of fighters in a typical training task. In other words, we were interested in the problem of formation and dissolution of the set of alternative action choices which is missing in the traditional decision – making approach (e.g., Schmidt & Lee, 2005). Boxers aged 21-23 years were required to select appropriate action patterns to ensure shots of efficient collision magnitude to a black leather hanging heavy-bag fixed to the wall with its bottom 95 cm from the floor. A conventional procedure of a gradual change of the hypothesized control parameter (Kelso, 1995), operationalized as the" boxer – target distance", was used to observe the distances at which new actions emerged as well as changes in the associated perceived efficiencies of each boxer. The scaled boxer - target distance "D" was estimated as a ratio between the physical boxer – target distance and the boxer's arm length. The degree of attraction of the boxing action modes was measured by the probabilities of occurrence of the action modes for each distance from the target. The unpredictability (information content) of the boxer's decisions was measured as a Boltzmann - Gibbs-Shannon entropy. The diversity of behavioral decisions was measured through distribution symmetry measures.

INSERT FIGURE 4 ABOUT HERE

The systematic change of the scaled boxer - target distance (i.e. the candidate control parameter) brought about a cascade of abrupt changes in the number of possible motor solutions (i.e. bifurcations)[5] to the hitting task (see Figure 4 A). The abrupt changes of the number of stable choices perceived as attainable efficient solutions to the task signified that a nonlinear control law existed between the perceived scaled distance and the movement variable (i.e. action modes operationally defined as angles of hand-striking attack on the target). A significant distance main effect, obtained for a one-way repeated measures analysis of variance, between the scaled distances for first time emergence ($F(5.35) = 44.58$; $p < 0.01$) and dissolutions ($F(3. 21) = 2467.93$; $p < 0.01$) of actions indicated the existence of affordances specific to the boxing action patterns used by participants. Results of our study revealed the existence of critical values of scaled distances of first time emergence and dissolution of a diverse range of boxing actions. In other words, participants selected specific strokes at distances that fitted the effective length of their arms, meaning that they exploited a kind of body-scaled distance information to decide on the specific hand-strike to be used.

The cascade of bifurcations in the motor solution space produced by a gradual change of the scaled boxer-target distance (i.e. the control parameter) generated changes in the entropy and diversity of boxers' actions (see Figure 4 B). Thus, the unpredictability (or conversely, the information content[6]) of boxers' actions was created by nonlinear dynamical effects (bifurcations) which in turn were generated by the gradual change of the body - scaled distance perceptual information. The context dependent creation and change of the information content of the boxer's decisions was a result of the variation of the body scaled ecological information (i.e. the strikability affordance) which controlled the nonlinear dynamical effects in the motor solution space of the boxers. Hence, the nonlinear dynamical effects (i.e. bifurcations) were responsible for creating and dissolving the number of possible

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[5] The abrupt change of the number of the possible behaviors of the state variable as a consequence of a gradual change of some other variable is called a bifurcation. It is a purely nonlinear effect. Thus, it can be detected only in systems whose generic behavior is nonlinear.

[6] The meaning of the information content that is created at bifurcation points is elaborated in Haken (2000). In this example, we have shown how the ecological information (i.e. the perception of the body-scaled distance from the target) enables the boxer to create macroscopic information in a form of a behavioural decision. Both kinds of information are connected through a nonlinear perception – action coupling.

decisions and consequently of creating and changing their information content. In this example we showed how an affordance can dynamically create information for decision-making. This information was only created through exploiting nonlinear perception - action processes. Thus, by analysing the environment-performer relation in boxing we showed how the set of possible choices was dynamically formed and dissolved by changing key contextual variables such as body-scaled distance to target. We also showed how information not provided in advance can be created and dissolved through nonlinear dynamical effects (i.e. bifurcations).

Consequences for future research

To summarise the findings from this developing programme of work on decision making in sport, based on the indeterminacy of brain and behaviour, empirical studies have highlighted the emergent nature of decision making dependent on the interaction of each individual performer with the specific constraints of each performance context. The implications are that athletes cannot completely plan their specific actions in advance (plans represent only one way of constraining the emergence of actions). Nor can they merely react to information in the environment and perform actions, based on the interaction of local constraints. The decision making behaviour of successful athletes must be eminently anticipatory and cyclical, based on perception of key information sources from their actions and the external environment. Through the search for relevant information to achieve specific competition goals, athletes can induce the occurrence of certain interactions with the environment that facilitate goal achievement. For this to happen, the performance context needs to offer affordances or possibilities for athletes' actions (Araújo et al., 2004). Specific perception-action couplings are selected over others primarily because of the existence of a specific set of interacting constraints that influence the emergence of certain decisions.

From this point of view, to make decisions is to direct a course of personal interactions with the environment towards a goal. It is from this cyclical process of searching for information to act and acting to acquire information that decisions emerge. The effectiveness of decisions is, therefore, clearly constrained by the level of attunement of each athlete to the relevant information and the respective calibration of his/her movements to that information (Jacobs & Michaels, 2002).

In this position paper we have clarified how decision-making processes could be understood as an integral part of goal-directed behaviour that is influenced by bodily constraints at the scale of the environment-athlete relationship. In line with this standpoint, an ecological model of decision-making proposes that: i) decision-making is strongly influenced by the detection and use of contextual information; ii) the acquisition of decision making skill is characterized by the narrowing of the variability of actions to achieve a goal and by the progressive attunement to relevant sources of information; iii) it is possible to explain the effects of relevant constraints (e.g., expertise) on decision making as well as the extent of these effects; iv) it is possible to detect (measure) stable patterns of interaction between performers and the environment; and v), the maintenance and the transition between stable patterns of behaviour is the result of the interaction of multiple constraints (not of a single controlling factor) (for relevant discussions see Beek et al, 2003, Runeson et al., 2000; Vicente, 2003). Furthermore, from an ecological perspective, the experimental designs for studies of decision-making should: i) maintain the noisy decision tasks towards which one intends to generalise; ii) have information in the task diagnostic enough to let the performer act on it in a way that supports goal achievement according to his/her expertise level.

Different kinds of activities and different kinds of information produce a number of various cognitive functions, although all of them have their basis in perceptually guided encounters with the environment. Researchers can actually test hypotheses about both action and cognition directly. Investigators can modify ambient information in addition to modifying task demands when they attempt to study cognition. As we noted in the previous section, because behaviour itself is considered part of the cognitive process, it should be possible to look at organizational and functional aspects of behaviour as evidence for and against hypotheses about cognitive aspects of those behaviours (Reed, 1996; see also Beer, 2003).

The ultimate aim of our research program is to model the ecological dynamics of tactical actions in a complex dynamic environment, namely the interactions among multiple performers in particular sports. This programme of work includes several steps such as to model steering towards stationary and moving goals and avoidance of stationary and moving obstacles, such as other players. Of particular interest is to model the interaction of these constraints such as dribbling to a moving target while avoiding stationary or moving players.

The ecological approach to decision-making demonstrates evolutionary plausibility, since individual differences in decision-making are a function of adaptive and random variation (Kenrick, Li & Butner, 2003; Swenson & Turvey, 1992), and demonstrates neurophysiological plausibility, since decisions and action initiation cannot be predicted in advance (Glimcher, 2005; Schall, 2001, 2004). The theoretical analysis of how embedded and embodied cognition can be captured in an ecological dynamics theoretical framework on decision-making in sport is in its infancy. However, it is becoming clear that concepts such as affordances, body-scaling of actions, maintenance and breaking of stability in competition systems, fluctuations in movement through exploration, phase transitions in decisional behaviour are potentially useful ideas that need to be investigated in future research in sport.

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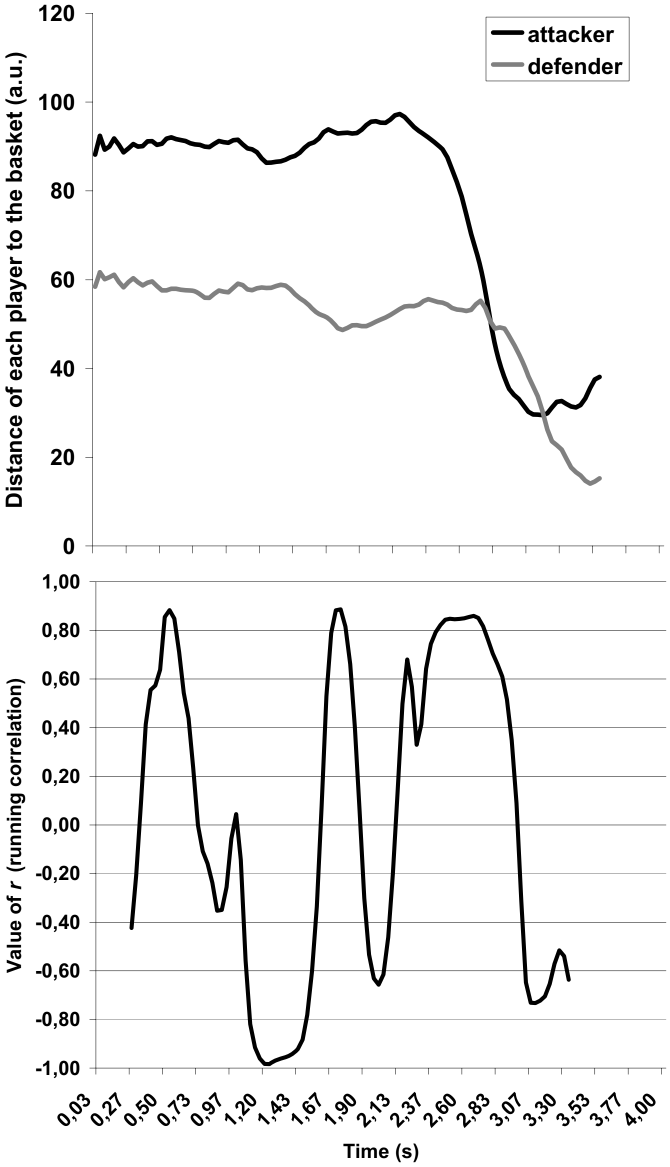
Figure captions

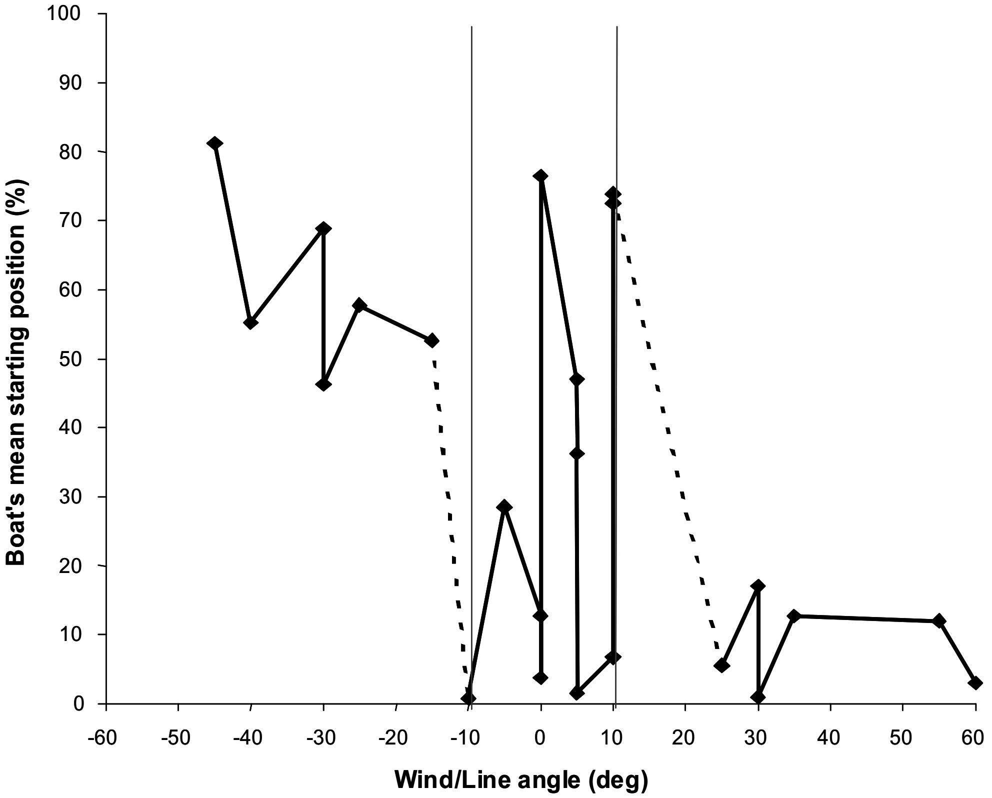
Figure 1. Top graph: Collective variable (order parameter) for attacker and defender describing a situation of 1v1 with advantage for attacker. Bottom graph: Values of *r* in the running correlation of the collective variable for attacker and the defender.

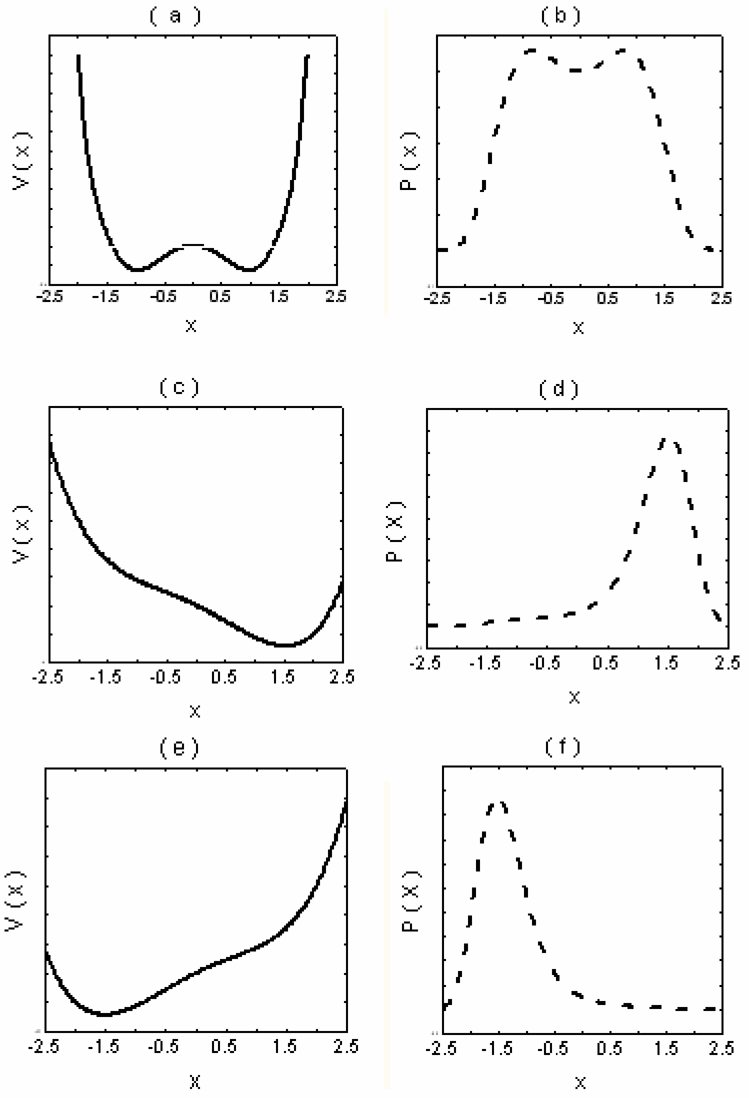
Figure 2. Phase transitions in the decision ‘where to start’ along 23 regatta starts, where the wind direction / starting line angle were manipulated (Data from Araújo et al., 2003).

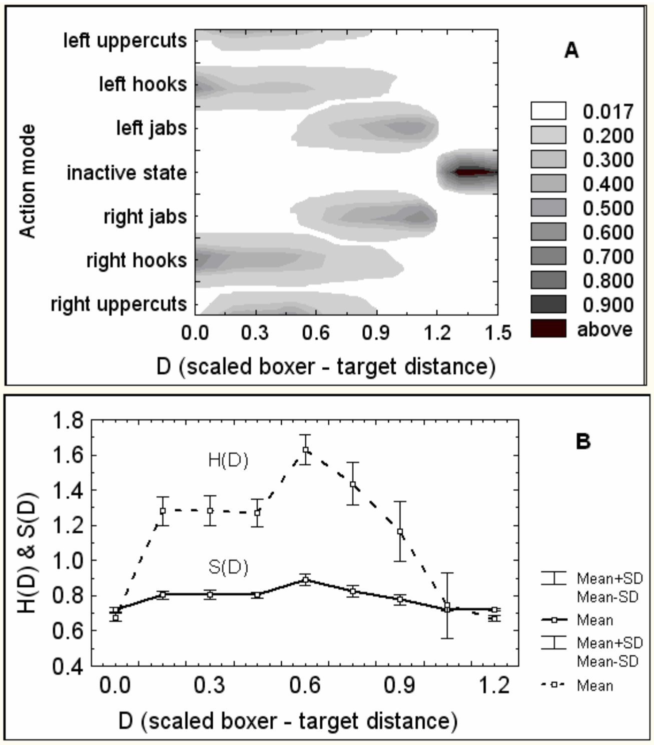
Figure 3 . The interplay of deterministic and stochastic forces in the metastable region of a regatta start. N.B.: a) The potential function V (x) for k = 0; b) The probability density function P (x) for the symmetric case k = 0; c) The potential function V(x) for k = -2; d) The probability density function P (x) for the asymmetric case k = -2; e) The potential function V (x) for k = 2; f) The probability density function P (x) for the asymmetric case k = 2.

Figure 4. Graph A. Bifurcations of action solutions to the hitting task in relation to the scaled “boxer – target distance”. For certain values of the control parameter (the scaled boxer – target distance) the number of possible action solutions to the hitting task changes abruptly. This cascade of bifurcations creates changes and dissolves the set of action choices. The legend refers to the probability of occurrence of action modes as a measure of the degree of their attraction. Graph B. Change in the unpredictability (i.e information content) (H) and in the diversity (S) of the hand-striking behaviour of boxers in relation to the scaled “boxer – target distance” D. As the number of possible decisions increases abruptly through the bifurcation cascade, the information content of the decisions increases. The jab dissolution bifurcation at D = 0.45 brings about a sharp decrease in the information content of the actions of boxers. Nonlinear dynamical effects are the generic processes that enable the creation and change of the information content of decisions (Data from Hristovski et al., 2006).


attacker
defender
Distance of each player to the basket (a.u.)
120
100
80
60
40
20
0
Value of r (running correlation)
1,00
0,80
0,60
0,40
0,20
0,00
-0,20
-0,40
-0,60
-0,80
-1,00
0,03
0,27
0,50
0,73
0,97
1,20
1,43
1,67
1,90
2,13
2,37
2,60
2,83
3,07
3,30
3,53
3,77
4,00
Time (s)


Boat's mean starting position (%)
100
90
80
70
60
50
40
30
20
10
0
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
Wind/Line angle (deg)


(a)
V (x)
-2.5 -1.5 -0.5 0.5 1.5 2.5
x
(b)
P (x)
-2.5 -1.5 -0.5 0.5 1.5 2.5
x
(c)
V (x)
-2.5 -1.5 -0.5 0.5 1.5 2.5
x
(d)
P (X)
-2.5 -1.5 -0.5 0.5 1.5 2.5
x
(e)
V (x)
-2.5 -1.5 -0.5 0.5 1.5 2.5
x
(f)
P (X)
-2.5 -1.5 -0.5 0.5 1.5 2.5
x


A
Action mode
left uppercuts
left hooks
left jabs
inactive state
right jabs
right hooks
right uppercuts
0.0
0.3
0.6
0.9
1.2
1.5
D (scaled boxer - target distance)
0.017
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
above
B
H(D) & S(D)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
H(D)
S(D)
0.0
0.3
0.6
0.9
1.2
D (scaled boxer - target distance)
Mean+SD
Mean-SD
Mean
Mean+SD
Mean-SD
Mean