Movement Models from Sports Provide Representative Task Constraints for Studying Adaptive Behavior in Human Movement Systems

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Researchers studying adaptive behavior in human movement systems have traditionally employed simplified, laboratory-based movement models in an effort to conserve experimental rigor. Brunswikian psychology raises questions over the representativeness of many of these popular experimental models for studying how movements are coordinated with events, objects, and surfaces of dynamic environments. In this article we argue that sports provide rich ecological constraints for representative task design in modeling the complex interactions of human performers with their environments. Adopting a functionalist perspective enriched by ideas from ecological psychology and nonlinear dynamics, we consider data from exemplar movement models in basketball and boxing to support this contention. We show that this preference for movement models from sports, although not completely novel, has accelerated over recent years, mainly due to the theoretical re-emphasis on studying the interaction of individual and task constraints. The implications of using such applied models of movement behavior in studying the design of natural and artificial systems are also discussed.

Keywords movement coordination and control · constraints · representative design · perception and action · degrees of freedom

1 Introduction

As Seth and Edelman (2004) have argued, in order to understand adaptive behavior, it has become increasingly clear that the interactions between complex organisms, task constraints, and environments need to be studied. For this reason, sub-disciplines such as robotics and artificial intelligence are drawing inspiration from research on how biological movement systems interact with complex environments. Traditional models of robotic design, based on “sense, model, plan, act” principles, are being complemented by “behavior-based control” approaches with the goal of engineering machines to operate in unpredictable and challenging environments, such as during space exploration or playing in robocup soccer competitions (Matarić, 1998). Alterna-
tive design principles, including “situated robotics,” are informed by research on how biological movement systems search for and pick up information to support sophisticated interactions with their environments (e.g., Di Paolo, 2002; Paine & Tani, 2005).

However, as Robert Rosen (1978) has proposed, the question of design in complex biological systems is of a different order of magnitude compared to machine engineering. Unlike artificial devices, there are non-trivial differences between biological structure and function and the challenge of capturing adaptive functional behaviors makes designing a complex biological system from a multitude of individual components an impossible task. According to Mikulecky (2000) evolutionary design principles target functional components of organisms, which are not permanent static features of biological systems but dynamically constrained by context. This view is harmonious with some “behavior-based” robotic implementations that have been founded on ecological principles in which an agent and environment are viewed as an inseparable system studied at an ecological scale of analysis. In “ecological robotics,” adaptive behavior is specified by information in the environment which does not need to be represented internally in explicit detail (Fajen, Warren, Temizer, & Kaelbling, 2003), and there have been attempts to forego a central planner for behaviors and to map sensory systems directly to actuators (Duchon & Warren, 2002).

1.1 The Role of Movement Models from Sport in Studying Adaptive Behavior

The problem of understanding how robots can adapt their behaviors to interact with dynamically changing conditions has parallels in the study of how humans assemble functional, goal-directed movement behaviors such as prehension, locomotion and interceptive actions. In this position paper we discuss how the study of human movement systems can provide meaningful theoretical insights into how behaviors can be adapted to relevant constraints on action during interactions with complex environments. In particular, we note how, increasingly, the experimental models used by many psychologists and movement scientists to study adaptive behavior of complex movement systems are being provided by a rich range of sports and physical activities (e.g., Davids, Savelbergh, Bennett, & Van der Kamp, 2002). Accordingly, we explore the proposition that sports provide an important performance context with relevant experimental movement models for studying a wide range of constraints on human movement systems. We argue that movement models in sports readily lend themselves to the “representative design” of tasks for studying key processes in adaptive behavior such as perception, decision-making, intentionality and action.

Although technological advances have also impacted on the selection of movement models for studying coordination and control, complex movement models from sports are gaining in popularity because of the powerful influence of a theoretical framework suggesting that movement coordination is best viewed as adaptive, emergent behavior which self-organizes under constraints, particularly informational and cognitive constraints. Preference by movement scientists and psychologists for more complex experimental models from sports has accelerated rapidly in recent years and insights into the adaptive nature of movement behavior have been provided by activities such as playground swinging (Post, Peper, & Beek, 2003), pole-balancing (DeGuzman, 2004), hula-hooping (Balasubramaniam & Turvey, 2003), sit-ups (Cordo & Gurfinke, 2004), basketball free-throw shooting (Oudejans, et al., 1996), javelin and discus throwing (Schöllhorn, 2003), rowing (Daffertshofer, Huys, & Beek, 2004; Shuttleworth, 2004), sailing (Araújo, Davids, & Serpa, 2005), cascade juggling (Post, Daffertshofer, & Beek, 2000; Huys, Daffertshofer, & Beek, 2004; Haibach, Daniels, & Newell, 2004), pistol shooting (Scholz, Schoner, & Latash, 2000), volleyball serving (Handford, 2002), long jumping run-ups (Montagne, Cornus, Glize, Quaine, & Laurent, 2000), ball catching and hitting (Bennett, van der Kamp, Savelbergh, & Davids, 2000; Scott, van der Kamp, Savelbergh, Oudejans, & Davids, 2004), soccer juggling (Tlili, Mottet, Dupuy, & Pavis, 2004), basketball ball bouncing (Broderick, Pavis & Newell, 2000), ball-racket bouncing (Sternad & Dijkstra, 2004), golf driving (Knight, 2004), pedalo paddle boating (Chen, Liu, Mayer-Kress, & Newell, 2005), and front crawl swimming (Satkunskiene, Schega, Kunze, Birzinyte, & Daly, 2005).

Traditionally, selection of movement models to investigate motor system functioning has been biased away from dynamic, multijoint, functional actions prevalent in sports because of the reductionist view that experimental rigor could be better maintained in laboratory studies of simple movements. Experimental movement models created in laboratory settings tend
to involve fewer motor system degrees of freedom than sports movements, have a limited range of scaling for key variables such as spatial and temporal constraints, include a lower level of intentional constraint on behavior and typically have a reduced amount of perceptual information needed to regulate action (Newell, 1989; Davids, Kingsbury, Bennett, & Handford, 2001; Wulf & Shea, 2002). The distinction between experimental rigor and field research is now being recognized as a false dichotomy, at least in part due to the influence of a functionalist theoretical paradigm on movement coordination, dominated by ecological psychology (e.g., Brunswik, 1956; Gibson, 1979) and nonlinear dynamics (e.g., Jirsa & Kelso, 2004). This theoretical paradigm has been characterized as a “constraints-based framework” emphasizing the study of movement behavior as an emergent property of the continuous interactions of a biological movement system and its environment (Newell, 1986; Davids, Araújo, Shuttleworth, & Button, 2003). Whilst it is clearly possible to explain adaptive movements from a variety of theoretical standpoints, including representational accounts (e.g., Rieger, Knoblich, & Prinz, 2005), a constraints-based perspective is a popular biologically inspired approach which is harmonious with the tenets of “situated” and “ecological” robotics and their emphasis on enhancing our understanding of the constraints of natural law on cognition (Duchon & Warren, 2002).

1.2 Representative Task Design: Insights of Egon Brunswik

Egon Brunswik’s (1956) theoretical insights in ecological psychology on the adaptive nature of human psychological processes also provide a case for rejecting the view of laboratory tasks as diametrically opposed to field based research designs for studying human movement systems. The issue of task constraints and their effect on behavior has often been mistakenly presented in the psychology literature as an issue of differences in ecological validity (misconceived as experimental design realism) involving contrived, laboratory tasks versus natural tasks. Brunswik (1956) showed how this interpretation of scientific methodology was a false dichotomy, based on a misunderstanding of the concept of task “representativeness.” He defended the view that perceptual variables should be sampled from an organism’s natural environment so as to be representative of the typical environmental stimulation to which it had adapted and which formed the focus of an experimenter’s generalisation. Brunswik’s (1956) contribution to understanding of functional movement behavior has been immense in many respects including: (i) promoting idiographic analyses of how individuals solve motor problems (i.e., examining unique functional adaptations of individuals to the environment); and (ii), stressing design of specialized experimental contexts with a high level of representativeness of a biological movement system’s niche habitat. The generalization of findings outside of specific experimental contexts is still recognized as problematic in many different areas of psychology, including educational, social, developmental and experimental fields. These issues are also significant in understanding how artificial and biological systems adapt to dynamic environments.

To support our theoretical analysis, we highlight extant data from our program of research in the sports of basketball and boxing. In these experiments we studied adaptation of human movement systems to other individuals and important objects in the environment during tasks such as dribbling a ball and hitting a target, respectively (for recent examples see Araújo et al., 2005b; Hristovski, Davids, & Araújo, in press). We start by briefly overviewing key concepts from nonlinear dynamics and ecological psychology for studying movement coordination and control. In particular, we discuss in more detail the idea of task representativeness, defined earlier, which provides a strong rationale for selection and design of experimental task constraints based on sport movements.

1.3 The Theoretical Impetus of Nonlinear Dynamics and Ecological Psychology

Prominent ideas in nonlinear dynamics and ecological psychology have been integrated into a constraints-based framework for developing understanding of how movements are coordinated with respect to complex and dynamical environments (for detailed overviews see Araújo, Davids, Bennett, Button, & Chapman, 2004; Davids et al., 2001; Williams, Davids, & Williams, 1999). A functionalist perspective in both areas has characterized biological movement systems as complex, adaptive systems. A key focus concerns how the many interacting system components, or motor system degrees of freedom, are coordinated and control-
led during goal-directed movements (see Bernstein, 1967; Berthouze & Lungarella, 2004). Research has revealed that patterns emerge between parts of dynamical movement systems through processes of self-organization ubiquitous to physical and biological systems in nature (for reviews see Davids et al., 2003; Guerin & Kunkle, 2004). It has been revealed how dynamical movement systems exploit surrounding constraints to shape the functional, self-sustaining patterns of behavior that emerge in specific performance contexts. In dynamical movement systems, information plays an important role in constraining the number of biomechanical degrees of freedom of the motor system that the central nervous system (CNS) needs to regulate during functional behavior. Rather than controlling each degree of freedom separately during goal-directed movement, the CNS exploits self-organization in movement systems to form temporarily-assembled muscle complexes called coordinative structures. Coordinative structures are functional synergies that emerge between parts of the body used to achieve movement goals such as locomotion, reaching and grasping, and hitting. Adaptive behavior in dynamical movement systems has been studied by focusing on “phase transitions” (movements of system components into a different macro-state of organization). Phase transitions between patterns of coordination in biological movement systems are considered highly relevant for study because they exemplify the emergent nature of behavior.

Ecological psychologists have also addressed the problem of how perceptual information guides actions in natural environments, by emphasizing how biological movement systems are surrounded by huge banks of energy (e.g., light reflected from objects and surfaces or emitted sound waves from an event or another individual). These energy arrays are highly structured and can act as information constraints to support decision making, planning, and organization of action. Gibson (e.g., 1979) argued that specific movements of a performer and/or environmental objects to be acted upon led to the pick up of these key information sources for adapting actions. Movements cause changes to energy flows that provide specific information to organisms on the properties of a dynamic environment leading to lawful relations between a kinetic property of a movement and the kinematic property of the surrounding perceptual flow. Because flow patterns are specific to particular environmental properties, they can act as invariant information variables to be picked by individual performers to constrain their actions within specific contexts.

Ecological constraints regulate movement coordination and it has become evident that task constraints interact with informational constraints, sometimes overriding the influence of important structural constraints in human movement systems. For example, a number of studies of rhythmic finger movements have reported that neuroanatomical constraints of muscles involved in coordination have a strong influence on stability observed (for reviews see Carson, 2004; Carson & Kelso, 2004). In these studies the basic movement model required participants to flex and extend an index finger either synchronous or syncopated with acoustic information provided by a metronome. Finger flexions synchronous with the acoustic beat were found to be more stable than extension movements syncopated with the beat. It was proposed that evolutionary constraints on the neuroanatomical system had a profound influence on differential stability of flexors compared to extensors (Carson, 2004). Flexor muscles originated phylogenetically as anti-gravity muscles and have evolved to produce relatively stronger forces from similar numbers of motor units. However, these effects of neuroanatomical constraints can be overridden by the addition of informational constraints so that neither flexion nor extension phases of the rhythmic oscillatory finger movements are more stable. In one study a small padded plastic stop was inserted into the typical rhythmic finger movement experimental protocol to interrupt the trajectory of participants’ index fingers as they were rhythmically syncopated or synchronized to a metronomic beat. The stop provided additional haptic information to constrain flexion and extension movements (Kelso, Fink, Delaplain, & Carson, 2001). Data suggested that afferent information from contact of the finger with the haptic stop device overrode the neuroanatomical design constraints of the metacarpophalangeal joints during rhythmic finger flexion and extension movements. These findings show how constraints interact during many natural activities and underline why movement models from sports could provide rich task vehicles for studying adaptive behaviors, exemplifying how coordinative structures are soft-assembled and tuned to prevailing task conditions (Kugler & Turvey, 1987).

The constraints-led perspective has considerable implications for understanding variability, traditionally thought of as noise or error in biological movement.
systems. Rather, instances of variability in movement patterns, exemplified by fluctuations in stability, may more accurately reflect flexible and adaptive motor system behavior during exploration of performance contexts. This theoretical position is in line with recent attempts to decompose observed movement system variability into separate components which are functional and stochastic (e.g., Riley & Turvey, 2002; Button, McLeod, Sanders, & Coleman, 2003; Rosengren, Savelsbergh, & Van der Kamp, 2003; Müller & Sternad, 2004). This paradox between stability and variability explains why skilled individuals are capable of both persistence and change in motor output during performance (Davids et al., 2003). The radical implication of these ideas is that perceptions, memories, intentions, decisions or actions may be conceived of as emergent, self-organizing, macroscopic patterns formed as individuals adapt to the ecological constraints of their environments (see van Rooij, Bongers, & Haselager, 2002; Williams et al., 1999). These ideas have some parallels in the theoretical views of Egon Brunswik (1956) who viewed psychological processes as adaptations to complex environments, effectively opening the window on to movement models from sports and exemplifying why they have gained such rapid popularity in recent years.

1.4 Task Representativeness and a Constraints-Led Perspective

Brunswik (1956) drew attention to some major concepts—representative design and intra-ecological correlation—which can be understood with reference to the emergence of movement coordination and control under constraints. Representativeness refers to the generalization of task constraints in specific research settings to performance constraints outside the experiment. Brunswik (1956) noted the need for congruence between experimental conditions for controlled study of a particular aspect of behavior and the environmental conditions of performance. The principle of task representativeness is predicated on the accurate sampling of environmental conditions for the design of a research study on a specific characteristic of behavior. Brunswik (1956) also suggested that, to be representative, environmental constraints of a “to-be-studied behavior” need to interact, as they do in many contexts of performance. He labeled this feature of experimental design ecological intercorrelation. His ideas on sampling environmental conditions pre-empted the popularization of the current strategy of focusing on the relationship or intercorrelations between key variables in a behavioral task. The more extensive the sample of constraints, the more representative was the experimental task design. As in other areas of ecological psychology, Brunswik’s (1956) attention to the concept of task representativeness was focused on enhancing the study of the organismic behavior relative to environmental constraints. The critical role of experimental task constraints, exemplified in the earlier discussion on interaction with flexion/extension phases of finger movements, points to the significance of the principle of ecological intercorrelation in task representativeness.

In this way, Brunswik (1956) contributed the strong conceptualization of representative task design to the traditional dichotomization of empirical work as “laboratory versus field-based.” Clearly, understanding of the interaction between key organismic, task, and environmental constraints for the emergence of adaptive behavior provides a powerful theoretical framework for designing representative tasks, regardless of whether they are located in a laboratory or field setting.

So, what are the key principles of a constraints-led perspective which could inform the design of representative tasks? How are these principles highlighted in sports tasks? First, a constraints-led perspective emphasizes understanding of the ecological constraints on behavior and rejects any attempt to provide unilateral explanations of mind, body, and environment. As in the implementation of ecological robotics a systems-based relationship between an organism and its environment is advocated. An important implication of this theoretical commitment for empirical research on processes of perception, decision-making, and action, is that representative task designs are needed to examine the role of ecological constraints during active task exploration, i.e., functional adaptive behaviors need to be investigated at the level of the organism–environment relationship. Second, the primacy of perception is recognized in a functionalist view of knowledge. Task design needs to ensure that perceptual systems are allowed to function as they were designed in order to pick up information for movement. Use of movement models from sports is a powerful method for achieving this goal of research. Third, the adaptation of organisms to their environments needs to be explained through the complex interactions between perception,
intentions, and actions. Fourth, information and movement become functionally coupled to support adaptive behaviors, an important principle for designing representative tasks for experimentation and training.

These principles receive support from recent trends in ecological psychology aimed at exploring the integration of ideas from two founding figures: Egon Brunswik and James J. Gibson (Vicente, 2003; Davids, Bennett, & Newell, 2006; Araújo, Davids, & Passos, 2005a). A broad ecological psychology begins by analyzing the ecological constraints on behavior, before addressing the organism's adaptation (Vicente, 2003). The main aim of a broader ecological psychology is to sample environmental variables in range and distribution to be "representative of a carefully defined set of conditions" (Brunswik, 1956, page 53). Gibson (1979) demonstrated that a serious analysis of perception as an adaptive process requires a simultaneous analysis of the environment and the information that it affords or invites in the form of actions. An object affords what it does because it has certain specific properties, which are not intrinsic to that object. On the contrary, object properties are taken with reference to agents who will perceive information about the object or intend to use it for action. To realize these affordance properties requires that an agent regulates its activity according to information concerning both the object and itself. Many of the affordances that an agent uses in adapting to its ecology require extensive practice and learning to be perceived or to be used. Representative experimental design is likely to vary, based on participant, task, and environmental constraints (Kugler, Kelso, & Turvey, 1980; Newell, 1986). For this reason the constraints-based framework provides a way of measuring the degree of adaptation between an organism's behavior and the structure of its environment. The interaction of key task and environment constraints provides a referent for evaluating the fitness of behavior in individual performers. The empirical data reviewed in this paper demonstrate that relatively simple changes in task constraints can provide powerful insights into the adaptive coordinative structures that emerge as individuals find functional coordination solutions. They also show that sports abound with a variety of unique task constraints and that analysis of movement coordination solutions after manipulating task constraints provide particularly useful windows on the role of specific intentions and perceptual information sources in constraining movements.

1.5 Representativeness of Task Constraints and Research on Perception and Action

An integration of Gibsonian and Brunswikian ideas in a broader ecological psychology also alerts us to the idea that in order to be representative, an experimental task should be set up in such a way that the actor can perceive in order to act, but also can act in order to perceive (Gibson, 1979). Gibson (1957) deplored the design of experimental contexts that were convenient for investigators, but relatively alien for participants who typically use exploratory actions to seek and use perceptual information to guide goal-directed behavior. This is necessary because actions by which cognition is expressed require that information about environmental facts be referential to the energy for behaving with respect to those facts (Turvey & Shaw, 1995). A clear finding in the literature on expertise and in anticipation and decision making in sport is that unrepresentative experimental task constraints tend to undermine the expert’s performance advantage in comparison with less skilled performers (Abernethy, Thomas, & Thomas, 1993). There are a number of reasons for this observation in the literature, with perhaps the most important relating to experimental designs which restrict access of experts to key information sources which are normally available during performance (Williams et al., 1999). For example, Oudejans, Michaels, Bakker, & Dolné, (1996) found that expert baseball outfielders could only be distinguished from non-baseball players when the experimental task of catching allowed them to act on ball-flight information, and not just react to the sudden appearance of ball-flight information. Additionally, experimental task constraints designed to elicit movement responses rather than verbal responses are better able to distinguish expert performers from novices in sport (Williams et al., 1999).

To exemplify these arguments, in this section we discuss research on dynamic interceptive actions illustrating how subtle alterations in task constraints can lead to adaptive behavior by participants and underlining how sports tasks can enhance representativeness in studying adaptive movement behaviors. There are a number of key differences between traditional laboratory methodologies for studying processes of perception and movement, and the task constraints of natural interceptive movements such as catching, batting or running towards a target area (Davids et al., 2002).
Some traditional experimental contexts for studying perception have been characterized by “informational-minimalism” because of a reductionist belief that holding a huge number of variables constant could allow investigators to produce laws of perception (Harris & Jenkin, 1998). For example, an inordinate emphasis on use of simulated motion has led to the popularity of coincident timing tasks in which participants have to typically predict when a (suddenly occluded) object/image will arrive at a designated target point in space. The task constraints of motion prediction paradigms emphasize the significance of perceptual anticipation processes in studying how predictive visual timing processes are used for interception. The assumption is that participants can “represent” part of the approach trajectory of an object image in short term memory to predict its time to arrival at a target location (e.g., see Todd, 1981). This traditional emphasis in designing studies to investigate predictive visual processes fitted well with theories of hierarchically organized perceptual and movement systems (see Poulton, 1957; Williams et al., 1999). From this theoretical standpoint, the performer is highly dependent on accurate perception of spatio-temporal characteristics of projectile motion in order to program the movement of an effector towards a predicted future contact point.

However, it has been argued that this type of design may not be representative of many natural interceptive actions which emphasize receptor anticipation processes (Poulton, 1957; Davids et al., 2001). Under the constraints of natural interceptive tasks like ball catching or hitting, participants are usually able to continuously regulate movements by viewing the ball until it arrives at the location of the hands or the bat. They do not need to perceptually construct the ball’s trajectory from earlier remembered information from ball flight. This view of the task constraints of natural interceptive actions fits well with the concept of information–movement coupling in ecological psychology, promoting a strategy of prospective movement control, rather than predictive visual timing (Beek, Jacobs, Daffertshoffer, & Huys, 2003b). Prospection exemplifies a heterarchical view of the performer, and a highly integrated, functional relationship between movement and perceptual systems (for other examples of heterarchical control models see Hill & Raab, 2005). In ecological psychology, it involves a close and continuous coupling of movement and perceptual systems based on the relationship between the instantaneous states of the performer and environment during task performance (Montagne, Laurent, Durey, & Bootsma, 1999).

1.6 Coupling Perception and Action in Experiments on Interceptive Actions

The different constraints of motion prediction and natural interceptive tasks have signalled the existence of different control mechanisms for successful completion of each type of task, exemplifying the relevance of Brunswik’s (1956) concept of task representativeness. For example, slower velocities are typically used in perceptual anticipation tasks (>1 s) which might afford the perceptual construction of the stimulus trajectory for prediction of future contact points. In most natural interceptive actions, however, movement execution times are usually more brief [e.g., 300 ms for catching balls traveling at 10 m/s velocity with one hand (Alderson, Sully, & Sully, 1974)], facilitating the development of strategies of continuous regulation or perception-movement coupling (Tresilian, 1995).

Extant data on movement outcome variability also suggest that performers find the task constraints of natural interceptive actions more functionally relevant than psychophysically based experiments (in line with Woodworth, 1938). For example, in some studies involving computer simulations, participants underestimated time to arrival of a stimulus object at a designated location point on monitor screens. The amount of underestimation increased with increasing time to arrival (e.g., see data from Schiff & Detwiler, 1979; Schiff & Oldak, 1990). Tresilian (1994) has calculated that the average underestimate of reported time to arrival in these tasks is around 60% of actual time to arrival at the point of execution of the button press, with the SD (standard deviation) of the estimates being 50%. These error margins and levels of outcome variability suggest that participants do not find these task constraints functionally relevant. In contrast, data on timing behavior in adults and infants suggest that the large amount of variability in estimated time to arrival is often not observed in performance of natural tasks such as fast interceptive actions (see section below on spatio-temporal constraints of interceptive movements documenting the results of several studies of interceptive actions in sport). Tresilian (1995) highlighted the fact that “... the variability (standard deviation of response times) of responses in CA [coincidence anticipation] tasks is some five or six times greater
than that observed in IAs [interceptive actions] performed under the same stimulus conditions....

This observation demonstrates Bootsma’s (1989) criticism of the “unprincipled” way in which processes of perception and movement have sometimes been studied separately. Bootsma (1989) examined effects on performance of de-coupling information and movement under three different types of task constraints. Participants in his study were presented with squash balls dropped through a plastic tube (length = 50 cm, diameter = 4.3 cm) from a height of 270 cm above a table surface. They attempted to intercept the ball in one of three different conditions: (i) using their own arm and a bat; (ii) pressing a button to release a 55-cm mechanical arm to hit the ball just before it landed on the table top; and (iii) pressing a button when the ball was judged to be level with the table-top surface (equivalent to motion prediction task constraints).

These conditions represented a successive degradation in information–movement coupling, and percentage accuracy data on hitting performance under natural-arm task constraints (82.4%) and artificial-arm constraints (49.5%) were significantly different. Further, movement times were more variable for the artificial-arm task constraints (14.6 ms) than the natural-arm task constraints (5.0 ms). These findings supported the ecological notion of information as “specificational” in regulating the behavior under the natural task constraints of interceptive actions. Variability in timing initiation of striking movements was lower under natural-arm constraints (SD = 16.3 ms) compared to artificial arm task constraints (SD = 34.0 ms). When only perceptual judgements of interception points were required by participants, variability was significantly higher (SD = 61.8 ms) than under both arm conditions.

These findings implied that structuring experimental tasks to keep key sources of perceptual information and actions together seems to be a principle for designing representative tasks to study interceptive actions. Interestingly, these findings cannot be attributed to transient effects due to lack of familiarity with task constraints by participants. Even after a 100-trial learning period (including 20 familiarization trials), although mean movement initiation time (MIT) in the motion prediction conditions was higher than the natural-arm conditions, these observed differences were not statistically significant (Davids et al., 2001). In line with Bootsma’s (1989) original findings, statistically significant differences were obtained for the variability of MIT (operationalized as the SD around the mean) between the two conditions. Variability of MIT was greater in the motion prediction conditions compared to the natural-arm condition.

Bootsma’s (1989) data illustrated the effects of decoupling perception and movement in studies of interceptive actions and highlight the significance of sports tasks as one important means of designing representative tasks for studying adaptive behavior. When the number of trials in the perceptual judgement (i.e., CA) task was quintupled, performance was still significantly better in the natural-arm striking condition, as evidenced by variability of movement initiation time. It seems that information-movement coupling is a robust principle of constraints-led perspective, and there is some merit in the proposal of Bootsma (1989) for recognizing “a movement-dependent use of perceptual information, emphasising the inseparability [of perception and movement]” (Bootsma, 1989, page 498). The task constraints of striking a ball set up the saliency of various sources of perceptual information involved in timing the movement (Davids et al., 2001). Under these specific task and informational constraints, the performer develops a coupling of movement to relevant sources of perceptual information. As evident from the data from the motion prediction task, the developed coupling cannot easily be transferred to different task constraints (Bootsma, 1989), highlighting the importance of task representativeness for studying adaptive movement behavior.

To summarize, these findings indicate the extensive insights into adaptive behavior that might be available from studying movement models under the enriched ecological constraints found in sports. The constraints-led perspective signals the need to carefully distinguish variability in movement organization, a healthy sign of adaptive behavior in biological movement systems, from variability in movement output which is less functional (Davids, Shuttleworth, Button, Renshaw, & Glazier, 2004). The latter is often caused by the use of task constraints which are unrepresentative, as data reported from studies of hitting actions have shown. Compelling arguments exist for empirical work to adequately reflect “enriched action environments” based on a broad range of task constraints, to ensure that movement model selection does not occur to confirm a priori theorizing (Newell, 1991; Cordo & Gurfinkel, 2004). In the following section we show how the sports of basketball and boxing provide a rich backdrop for the study of emergent functional behaviors.
Movement Models in Basketball and Boxing: Windows on Adaptive Movement Behavior

2.1 Dribbling in Basketball

Spontaneous movement variability can play an important role in allowing performers to create different solutions to fit different situations. In a dynamic sport such as basketball, one can get a good impression of how skilled players utilize a range of coordination patterns to achieve individual and team goals. Araújo et al. (2002, 2004) recently examined the agent–agent interactions in a dyad formed by competing players in basketball dribbling. In spite of the enormous variability and complexity of team ball game situations, theoretical and experimental evidence points to the existence of patterned interpersonal interactions (Schmidt, Carello, & Turvey, 1990). In physical terms, these processes are expressed in the emergence of organized structures in phase-space describing the interpersonal interactions in a dribbling dyad. Interpersonal coordination can be studied in the emergence and regulation of coordinated states through inherently perceptual processes, based on the dynamics between individuals in a dyad or group (Kugler & Turvey, 1987).

From the theoretical perspective of nonlinear dynamics, the behavior of interacting players could be interpreted as an emergent process resulting from the spatio-temporal relations established during game situations. Two individuals in a dribbling dyad may be considered as a single system with dyadic synergy (Schmidt et al., 1990). A dyadic synergy can show nonlinear properties, namely entrainment and sustained periodic behavior, and specific modes of interpersonal coordination emerge from contextual, personal, and task constraints. Team ball sports can be described as a series of sub-goals, each constraining the coordination of different players to different extents (Schmidt, O’Brien, & Sysko, 1999). In basketball, the interaction of a dribbler and a defender in a one-on-one situation can result in a relatively stable interactive dynamic structure, since the defender may counteract any movement towards the basket by an attacker. According to coaching knowledge it is this stable balance between attackers and defenders that characterizes the one-on-one situation in basketball (e.g., Bain, Hayes, & Quance, 1978). In this classic game situation the attacker needs to de-stabilize or perturb the stable state of this momentary dyad. If this system is successfully de-stabilized, the attacker can dribble past the defender towards the basket. This de-stabilization corresponds to a symmetry-breaking process where the previous stable interpersonal state transits to a new dynamic state (Kugler & Turvey, 1987). This transition from one ordered state where the defender has the advantage, to another where the attacker has the advantage (after dribbling past the defender) provides an alternative, biologically inspired explanation, to the information processing approach (e.g., Schmidt & Lee, 2005). In dynamic environments there is typically not one stimulus to set the player going (such as when a sprinter reacts to the starter’s gun), but a constant flux of stimulation available to be picked up from the environment in support of action (Reed, 1996; Whiting, 1991). Therefore, although possible, an explanation for a particular aspect of a complex dyad interaction, such as a fake move by one player, cannot easily be explained by relationships like Hick’s law (the relation between the number of stimulus–response alternatives and reaction time), stimulus–response compatibility, or the psychological refractory period. Also, the fact that both players in interaction exhibit symmetry indicates that one player is not merely responding to the other, but there is a coupling effect as an emergent property, as predicted by the dynamical systems approach, a more parsimonious explanation. A dynamical systems analysis of the just-described transition process (i.e., coupling and decoupling of the dyad) needs to begin with a measure of order in the stable interpersonal pattern formed by the position of the attacker and defender with respect to the ball and the basket.

2.2 A Description of a Methodology for Investigating Interpersonal Dynamics in Team Games

Analysis of coaching literature reveals that an 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 dyad (i.e., medium point of the distance between the attacker and defender) during a 1 v 1 sub-phase of
A specific control parameter could be the interpersonal distance between attacker and defender. Araújo, Davids, Sainhas, & Fernandes, (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. This investigation considered whether changes in interpersonal distance were associated with dribbling success by attackers. A specific issue of interest was whether the attacker–defender dyad became more frequently destabilized at critical values of interpersonal distance.

Ten players (regional level, 15–16 year-old males) participated in the experiment after recommendation by their coaches and informed consent. They were paired to form 5 dyads. Each dyad started in the free throw line, with the other members of both teams placed on field based on the “attack system 1:2:2” (see Figure 1). The horizontal plane trajectory (two-dimensional) of the mass center of each player in the dyad was recorded by one digital camera. Body mass center was calculated with 6 markers (2 ankles, 2 hips, and 2 shoulders). Task instructions were for the attacker to score and the defender to prevent a score, within the rules of basketball. The eight other players started to participate in the play five seconds after the beginning of the task (temporal task constraints), after having been placed in valid positions based on typical basketball match strategy (spatial task constraints). The action sequence started when the defender passed the ball to the attacker, after a signal from experimenters. The action sequence was completed when the attacker shot the ball at the basket or when the defender took it away from the attacker.

From Figures 2a and 3a, it can be observed that during the initial part of the dyadic entrainment there is a stable state of the order parameter, followed by an abrupt change in the state of the system due to an attacker’s success in de-stabilizing the dyad.

In interpersonal equilibrium, one stable state of the dyadic system is maintained during the whole situation, as in Figures 2c and 3c, where the defender has managed to constantly counter-balance the symmetry-breaking actions of the attacker. On the other hand, when the attacker is very successful there is almost no equilibrium. Figures 2b and 3b show that the transition to a new state started immediately after the beginning of the interaction. The transition is seen in Figure 3b when the initial order characterized by a defender’s advantage transits to a new order characterized by the attacker’s advantage. Interestingly, the symmetry was broken exactly during the shortest values of the control parameter: i.e., interpersonal distance (right side of the figure). This is the transition phase from dyad equilibrium to a new system order (attacker’s supremacy). In general, the attacker–defender system exhibited initial symmetry (showed in Figures 2a and c), which was broken during transition to a new state at a critical value of the control parameter (as shown in Figures 2a and b). Further insights were provided when we decomposed our collective variable (distance from the medium point of the dyad to the basket) showing each player’s distance to the basket. In Figure 3 we present the same situations as depicted in Figure 2 and we can clearly observe the nature of symmetry-breaking processes (Figures 3a and b), and how symmetry was maintained (graph c).

The attacker–defender system exhibited initial symmetry, which was broken during transition to a new state at a certain value of the control parameter. In other words, the attacker was trying to dribble past the defender, but the defender was attempting to maintain the initial steady state. The attacker increased the variability of 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 the “intending–perceiving–acting cycle.” Considering the characteristics of the figures showing the distance from the basket to the attacker and defender plotted together, it is possible to consider that the positions above its diagonal represent attacker supremacy, and the positions of the system below the diagonal represent defender supremacy. In
Figure 2  Three examples of order parameters (distance of dyad from basket) in the left column and control parameters (interpersonal distance) in the right column: first row equilibrium situation with a slight attacker advantage; second row attacker’s advantage; third row defender’s advantage. Note that these figures cannot be superimposed because the variables have different scaled magnitudes; distances are measured in arbitrary units (a.u.).
Figure 3  Order parameter data from Figure 2 presented in decomposed format: distance of each player from basket in the left column and distance from the basket of each individual plotted together in the right column: first row equilibrium situation with a slight attacker advantage; second row attacker’s advantage; third row defender’s advantage. Distances are measured in arbitrary units (a.u.).
summary, the data suggest that it is possible to interpret the dynamics of player interactions in dribbling as emergent properties under constraints.

2.3 Affordance Regulated Hitting Behavior in a Boxing Training Task

The nature of agent–agent and agent–environment interactions (Guerin & Kunkle, 2004), are useful for understanding how creation, maintenance, and decay of key constraints affects the interactions of perceptual, cognitive, and action sub-systems during sport performance (Araújo et al., 2005b; Chow et al., 2006). Hand-striking movements in martial arts such as boxing are representative movement models in this respect because (i) they exemplify classes of short lived, multi-joint interceptive action patterns formed from the abundance of upper limb motor system degrees of freedom, which are assembled or dissolved depending on performance constraints, and (ii) they represent time-varying intra- and inter-limb coordinative states with respect to more or less dynamic targets such as opponents or training equipment such as speed bags, hand pads, and heavy bags (Turvey, 1990).

Diversity of handstriking actions plays a crucial role in boxing since it increases uncertainty for opponents and constrains them to depend on probabilistic perceptual judgments for decision making, rather than knowledge of opponent actions. Game theory predicts that unpredictability of an organism’s actions is a requisite feature of efficient adaptive behavior in competitive environments and many organisms show indeterminate behavior when they find it to have survival value (Glimcher, 2005). The diversity of actions is based on motor equivalence, namely the ability of different action patterns to achieve the same goal, suggesting that these properties of the organisms evolved as a consequence of their adaptive value. More generally, this ability of action systems can be viewed as a specific case of the evolutionary stabilized degeneracy inherent to biological systems (Edelman & Gally, 2001).

The possibility of exploiting motor equivalence, and consequently the diversity of actions, depends on the variables to which boxers’ perceptual systems are sensitive. Warren (1984) reported that young adults ranging in stature could, by visual inspection alone, determine which in a series of stairs varying in riser heights afforded bipedal climbing. At a critical point, around 0.88 of leg length, climbers were unable to ascend the stair bipedally and a sudden change in behavior occurred: Climbers ascended quadrupedally. The sensitivity of climbers’ perceptual system to this affordance (i.e., climbability) controlled the behavioral transition between the two climbing modes. In similar vein, reaching towards a target involves detection of affordances for a specific mode of action and requires the pick-up of critical reach distances. These variables are specifically scaled to each individual, around which distinct coordination modes for reaching may be available (Choi & Mark, 2004).

Striking modes of action in martial arts differ from other kinds of reaching modes in a number of biodynamic parameters. In the martial arts, movements such as reaching to hit a target require performers to pick up body-scaled information (e.g., arm length) to judge whether a target is reachable with a specific action (e.g., an uppercut or jab) at a particular distance. Additionally, it is possible that the perception of some biodynamic parameters (Choi & Mark, 2004) (e.g., fist–target energy of collision) might also contribute to constraining striking activity. Therefore, it is theoretically likely that affordances of different hitting actions emerge in martial arts such as boxing, constrained by the scaling of athlete positioning and arm segment dimensions with reference to a target, as well as by their perceived efficiency.

In ecological psychology, perception has been defined as the detection and use of information (Gibson, 1979), and an important experimental approach in researching interceptive actions has been to manipulate properties of environmental information to observe changes in movement behavior, as evident in movement kinematics. The assumption is that observed changes to movement kinematics are likely due to the experimental manipulations of perceptual variables, which act as information specifying or constraining actions such as hitting (Beek, Dessing, Peper, & Bullock, 2003a). Since perception is specific to the environmental properties uniquely constraining each performance situation, it follows that changing the informational constraints during performance can influence emergent action patterns (Beek et al., 2003b).

2.4 A Description of a Methodology for Studying Emergent Decision Making During Boxing Practice

Hitting a heavybag is a key task in the basic training of boxers. By exploring their own perceptual–motor
landscape, boxers can discover areas where their striking diversity is maximal and differences between the efficiency characteristics of their strokes are minimal, which is of utmost importance for adaptation of boxers to stylistic differences in opponents. Hristovski, Davids, and Araújo (in press) examined how the interaction of the repetitive handstriking task, the gradually changing performer–target distance, and efficiency information constrained the decision–action behavior in boxers. Specifically, they were interested in the dynamical interactions between the task and gradual changes in perceptual information from the task solution space of the performers, and effects on the decision–action diversity of the performers. It was predicted that the initial activation of an action, the probability of occurrence, and the dissolution of actions would exhibit dependence on the distance to the target and on perceived striking efficiency by novice boxers. Boxers aged 21–23 years were studied as they selected appropriate action patterns to ensure shots of efficient collision magnitude to a black leather hanging heavybag fixed to the wall with its bottom 95 cm from the floor.

Figure 4A shows how a distance of one meter from the target was calibrated in 10 equal segments of 10 cm so that each boxer could perform 60 shots at each distance. These task constraints were formulated to allow performers to exploit both efficiency and diversity of boxing actions. Six classical boxing actions could be performed during the task: right jab, left jab, right hook, left hook, right uppercut, and left uppercut. A conventional procedure of a gradual change of the hypothesized control parameter (the participant–target distance) was used to observe the distances at which new actions emerged as well as the changes of the associated perceived efficiencies (Kelso, 1995).

Before starting the activity, participants were stringently reminded not to overbalance. This instructional constraint is particularly emphasized in the advice of expert boxers (Walker, 2003). The choice of distance between the lower limbs in the parallel stance and the timing between the shots in the sequence was left to the participants. Participants were also free to apply uppercut strokes to any location of the target. This methodology allowed Hristovski et al. (in press) to
plot the distances of the earliest activation of uppercuts, since due to the specific patterning of this stroke from larger distances, performers could only efficiently strike the lower or middle part of the heavybag. Each boxer was asked about their perceptions of stroke efficiency for each shot selected after they had finished each sequence of activity. Perceived efficiency was scaled by the performers on a 6 point (0–5) continuous scale with 0 reflecting absence of a stroke and 5 signifying a maximally efficient stroke. Modes of performer–target co-ordination patterns were operationally defined as directions of upper limb movements with respect to the central visual line connecting the participant and the target facing him. This procedure allowed a notational strategy to be used in classifying shot frequency as a measure of decision-making stability in the dynamic context of boxing. For example, right jabs have a dominant projection parallel to the central visual axis (z axis) and were numerically classified as 180 degrees. Left jabs, providing a mirror image of right jabs, were classified as −180 deg (see Figure 4b). Notation of hooks was considered to have projections along the sagittal (z) and horizontal (x) axes, with right hooks being classified as 90 deceived and their mirror image left hooks as −90 deceived (see also Figure 4b). Furthermore, upper cut handstrikes were recorded as projections on the sagittal (z) axis, with right and left uppercuts varying along the vertical (y) axis at 90 deceived and −90 deceived, respectively (see Figure 4c).

For the purposes of the analysis the following measures were calculated: (i) Relative scaled distances D determined as a ratio between the physical distance of participants from the target and their arm length; (ii) the absolute probabilities of occurrence of action patterns (relative frequencies) p(k(D)) = k(D)/n, where k(D) is the number of occurrences of a certain type of stroke at distance D and n is the constant length of the sequence (n = 60) for each distance from the target. This variable measured the degree of attraction of the action modes; (iii) the mean group probabilities of each of the three general types of boxing shots (jabs, hooks, and uppercuts) for each distance P(D); (iv) mean group perceived striking efficiencies for each general action mode (jabs, hooks, and uppercuts) at scaled distance D, E(D); (v) unpredictability and diversity of striking activity by the participants assessed by the Shannon entropy H(p(D)) = \sum_{i=1}^{j} p_i(D) \ln p_i(D) ; (j = 6), i.e. as average information over all outcomes in the sequence; and symmetry measures: S(D) = 1 - \frac{1}{N} \sum_{i=1}^{N} |\Delta p(D)|, where N is the number of combinations of class 2 for a set of 6 elements (6 types of strokes), and |\Delta p(D)| is the absolute value of the differences between the probabilities of occurrence of each action pattern. In this study, for 6 possible types of strokes, there were N = 15 probability differences to calculate for each sequence per participant.

Bifurcation points of the action modes were determined by analyzing the behavior of the first derivative of the probability of occurrence of action patterns P'(D) with respect to scaled distance to target (Sugakov, 1998) in order to find the points of discontinuity (non-analyticity) of the performers’ movement patterns. Specifically, the bifurcations of the first-time emergence of action modes were identified by analyzing the behavior of the left and right derivatives, i.e., P'_L(D) and P'_R(D) respectively, in the vicinity of points where the first nonzero values of P(D) were obtained. In similar vein, for detecting the action mode dissolution bifurcations analytical treatments of the behavior of P'(D) in the vicinity of points where P(D) switched to P(D) = const. = 0 were conducted.

Results showed several characteristics of boxing behavior. First, significant differences between the bounded regions of scaled performer–target distances at which specific action modes emerged or were dissolved (i.e., ceased to exist) for the first time were indicative of the existence of affordances specific to the boxing action patterns used by performers (Figure 5a).

Data showed that the performers used these bounded regions of scaled distance as contextual information specifying a change in the number of possible motor solutions to the hitting task. The perceived contextual information was body-scaled distance information (Konczak, 1990; Konczak, Meeuwsen, & Cress, 1992) and depended on the interaction of the environmental constraints (absolute distance from the target) and morphological constraints of performers (effective length of upper limbs specific to each of the action modes).

The data also suggested that strikability is not merely a specific case of the reachability affordance, as indicated by dissolution events of jab and uppercut modes of action. At both these critical points of dissolution the target was reachable, but jabs and uppercuts ceased to exist. It appears that boxers could perceive
the critical distances beyond which jab and uppercut action modes no longer afforded efficient strikes, so a dissolution of these action modes occurred. The implication is that, besides reachability, perception of the strikability affordance incorporated additional biodynamical constraint (Choi & Mark, 2004) probably related to the intended energy of collision between the boxer’s fist and target. Since the first time emergences and dissolutions of the action modes imply that they were not used previously (for a specific scaled distance $D$), the contribution of tactile/muscular proprioceptive information for regulating these events can be excluded. The existence of a visually grounded strikability affordance is indicated instead (for empirical evidence of the existence of neural sensitivity in the visual system with respect to the reachability affordance see Batista, Bruneo, Snyder, & Andersen, 1999).

Emergence of strikeability affordances, brought about by gradual changes in the scaled performer–target distance, led to a cascade of qualitative, discontinuous and topological changes in performers’ decision–action state space. Figure 5b depicts the group mean topological changes (i.e., bifurcations) of the motor solution space of the performers. Whereas for the scaled distances $D > 1.2$ the only available stable state was the inactivity state, the gradual change of $D$ destabilized this state at $D = 1.2$ and a bifurcation occurred presented as a split of the probability mass into two parts of the state space corresponding to the first time formation of the left and right jab action modes. Further gradual changes in body-scaled distance led to two more bifurcations; one for the first time emergence of the right and left hooks at $D = 1.05$, and the other for the first time emergence of the right and left uppercuts at $D = 0.9$. As can be seen from Figure 5B the number of simultaneously available motor solutions to the task increased from 1 during the inactivity state to 6 after the emergence of the uppercut mode of action. The region $0.9 < D < 0.45$ was characterized by the coexistence (simultaneous availability) of all motor solu-
tions to the hitting task with different degrees of attraction as estimated by their probability of occurrence. This is also a region of the full exploitation of the capacity for motor equivalence by performers. The cascade of topological changes in state space characterized by a reduction in the number of co-existent states of action modes started with the dissolution bifurcation of jab actions around \( D = 0.45 \) and ended with the dissolution bifurcation of uppercut actions at \( D = 0.00 \) when only right and left hook action modes remained available. Hence, the perception of affordances at the critical points of the body-scaled distances led to drastic changes in the motor solution manifold of the performers.

Figure 5c depicts the functional discontinuities of the degree of attraction of the uppercut action pattern as measured by the probability of occurrence. The extant discontinuities show that, at critical points, the perceived strikeability affordances led to non-analytical behavior of the action system of performers where it switched into different forms of dependence on the scaled distance \( D \). Hence, the bifurcation cascade events in the motor solution space and the discontinuous changes in behavior of participants at critical points of the scaled distance point strongly to extant affordance-regulated, macroscopic nonlinear dynamics of their perceptual–action systems.

Furthermore, this investigation showed that boxing action modes (i.e., jabs, hooks, and uppercuts) were concurrent to and competing with each other as revealed by the values and signs of partial correlations between the scaled distance dependent perceived efficiencies \( E_i(D) \) and the scaled distance dependent probabilities of occurrence of particular action modes \( P_i(D) \). The strong and positive partial correlations between the jab, hook, and uppercut action modes and their perceived efficiencies (0.968, \( p = 0.004 \); 0.949, \( p = 0.001 \), and 0.962, \( p = 0.0005 \), respectively) showed that perceived efficiencies enhanced the degree of attractiveness of those action modes. In contrast to this finding, strong negative partial correlations between the perceived efficiencies of concurrent action modes and the probabilities of occurrence of other action modes, such as that between the perceived efficiency of hooks and the probability of occurrence of jabs (−0.959, \( p = 0.0007 \)) as well as other highly negative associations, highlight the suppressing influences of concurrent efficiencies on the degree of attractiveness of other actions. In other words, the perceived efficiency of a particular action mode tended to have inhibitory influence on the degree of attractiveness of other concurrent modes and simultaneously an excitatory influence on the associated action mode. These scaled distance-dependent reciprocal enhancing and suppressing influences of the perceived efficiencies shaped the competition effects between the concurrent modes of action.

Perceived efficiencies \( E_i(D) \) also showed a body-scaled performer–target discontinuous, i.e., nonlinear, distance dependence (see Figures 6a–c).

This finding is corroborated by a change in the functional dependence of \( E_i(D) \) at the points when \( E_i(D) = 0 \to E_i(D) \neq 0 \) and at the points when \( E_i(D) \neq 0 \to E_i(D) = 0 \). Hence, the occurrence of action modes at each scaled participant–target distance was a net emergent result of the selective pressure and competition between these interacting enhancing and suppressing contextual constraints. The contextual dependence of the attractiveness of the action modes was represented by a clearly visible distance-dependent polarized structure of the action mode degree of attraction (Figure 7a), where for scaled distances \( 1.2 > D > 0.6 \) jab actions dominated over hooks and uppercuts, and for \( 0.6 > D > 0.00 \) hook and uppercut actions dominated over jabs.

Figure 7b depicts the scaled performer–target distance-dependent changes in the action entropy (unpredictability) and symmetry (diversity) measures. Their maxima lie in the region where the dominance of jab action modes transits to dominance of the hook and uppercut action modes: i.e., In the region of their minimum probability (degree of attraction) difference which is located around \( D = 0.6 \). This region of a maximal dynamic competition of action modes is thus the optimal region of exploitation of the capacity for motor equivalence in performers. The exploitation of motor equivalence, and consequently the diversity and unpredictability of actions, shows a clear contextual dependence. Performers were able to discover the body-scaled perceptual context that afforded them full use of the largest set of available motor system degree of freedom configurations to enhance the diversity and unpredictability of actions which are key determinants of adaptive behavior in boxing. The possibility of exploitation of this one (goal) to many (action modes) mapping depended on the context created by the interaction of the perceptual information such as body-scaled performer–target distances and the perceived efficiencies of actions. In other words, this finding suggests that a basic \( P = P(E(D)) \) nonlinear dynami-
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Figure 6  (a), Change of the perceived efficiency $E$ of the jabs with respect to the scaled performer–target distance $D$ (horizontal axis). (b) and (c), the same for the hook and uppercut action modes.

Figure 7  (a), Change of the probability of occurrence $P$ of the boxing action modes with respect to the scaled performer–target distance $D$. (b), Change of the action entropy (unpredictability) $H(D)$ and symmetry (diversity) $S(D)$ versus the scaled performer–target distance $D$.

cal system governs the macroscopic perceptual-action behavior of the boxers during the performance of the training task studied. Further research is needed to find the detailed structure of these relations.

3 Conclusions and Implications for Future Research

The recent preference for studying movement models from sports and physical activities provides an opportunity for roboticists and design engineers to draw inspiration from the study of adaptive behavior in biological movement systems under task constraints which are high or in representativeness. In this article we discussed how Egon Brunswik’s (1956) modeling of psychological processes as adaptive processes could enhance understanding of experimental design for studying complex agent behavior. To support our analysis, we outlined how representative task design of movement models, from the sports of basketball and boxing, provides rich ecological constraints for understanding how human actions emerge from the interaction of individual anatomical scaling characteristics, specific task goals, and environmental contexts. We emphasized how the trend to study complex task vehicles, avoiding reductionist
The emergence of specific modes of behavior provides insights into the strong influence of task constraints, suggesting the need to carefully consider the nature of tasks used in design laboratories. Designers and engineers of robotic and artificial devices could try to maintain the important perception-action links towards specific goals that characterize performance competition or match play in sports contexts as faithfully as possible. The idea is to design a robot or an artificial device attending to the nature of the external information that should be acted upon in order to achieve a certain goal. By acting upon particular contextual information the agent should be able to adapt its behavior accordingly. This means that behavior is not tailored in advance (internally), but that it is regulated ongoingly by environmental information. The data discussed in this position paper suggest that researchers in robotics, artificial intelligence, and machine design engineering can promote understanding of adaptive behavior of smart agents by continuing to adopt movement models from sports in the future.

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