

## Insights from Ecological Psychology and Dynamical Systems. Theory can underpin a philosophy of coaching

IAN RENSHAW\*, KEITH DAVIDS\*, RICK SHUTTLEWORTH\*\*, and  
JIA YI CHOW\*\*\*

(\*) *School of Human Movement Studies, Queensland University of Technology, Australia*

(\*\*) *Australian Institute of Sport, Canberra, Australia*

(\*\*\*) *Department of Physical Education and Sports Science, National Institute of Education, Nanyang Technological University, Singapore*

*The aim of this paper is to show how principles of ecological psychology and dynamical systems theory can underpin a philosophy of coaching practice in a nonlinear pedagogy. Nonlinear pedagogy is based on a view of the human movement system as a nonlinear dynamical system and has been basically defined as the application of concepts and tools of nonlinear dynamics to coaching practice. A systems orientation is adopted to show how nonlinear dynamical movement systems demonstrate an openness to environmental information flows, use inherent degeneracy to adapt movements to dynamic environments, show capacity for self-organisation, and fluctuate between stability and instability as changes in constraints on performance shape transitions in system organisation. We demonstrate how this perspective of the human movement system can aid understanding of motor learning processes and underpin practice for sports coaches. We provide a description of nonlinear pedagogy followed by a consideration of some of the fundamental principles of ecological psychology and dynamical systems theory that underpin it as a coaching philosophy. We illustrate how each principle impacts on nonlinear pedagogical coaching practice, demonstrating how they can substantiate a framework for the coaching process.*

KEY WORDS: Coaching practice, Dynamical systems, Ecological psychology, Non linear pedagogy. Task constraints.

Although physical education is a well established profession with a sound tradition of formal training and established pedagogical practices, there has been some criticism that practice is often not based on a theoretical model of how learners actually learn (Newell & Rovegno, 1990). The need to

---

*For correspondence: Ian Renshaw, School of Human Movement Studies, Faculty of Health, Queensland University of Technology, Kelvin Grove, Queensland 4059, Australia (e-mail: i.renshaw@qut.edu.au).*

ing

ralia  
ication,

biology and  
e in a non-  
movement  
: the appli-  
A systems  
it systems  
ent degen-  
elf-organi-  
straints on  
how this  
tor learn-  
ription of  
tal princi-  
in it as a  
lear peda-  
ework for

ogy, Non

with a  
actices,  
oretical  
need to

f Health,  
(e-mail:

base pedagogical practice on a sound theoretical model of the learner and of the learning process has been previously emphasized (Renshaw, Davids, Chow, & Hammond, in press). In contrast, sports coaching is less well established as a profession and the majority of practitioners at participation level are volunteers who are often ex-performers and who have learned their craft via practitioner experience (Lyle, 2002). In this more performance-oriented learning environment, coaching practice is even less likely to be based on theory.

It has also been argued that the development of coaching as a profession has been hindered by the cult of 'big' personalities (Carter, 2006), leading to an emphasis on 'qualities' of individual coaches and 'coaching style' rather than on the coaching processes that ultimately determine the effectiveness of coaching practice. Lyle (2002) argued that there is currently little evidence to suggest that one coaching style is more efficacious than another and that a 'style' still has to have 'substance'. It has been suggested that all coaches need to base their practice on a philosophy of coaching otherwise they will lack direction and succumb to external pressures (Lyle, 2002; Martens, 2004). The quest for a guiding theoretical framework will provide a philosophical approach that is evidence-based, focusing on mechanism and not just operational issues such as practice, competition and programme management (Lyle, 2002). A coaching philosophy should provide a set of guiding principles for coaching practice, while at the same time identifying the major beliefs or principles that help achieve coaching objectives (Lyle, 2002; Martens, 2004). A theory-based coaching philosophy is also likely to impact on coach education programmes. Since coaches rely on their education and experience to be effective (Feltz, Chase, Moritz, & Sullivan, 1999), it is essential that coach education provides a principled theoretical base on which coaching practitioners can build their own underpinning philosophy.

In other papers we have outlined a rationale for motor learning specialists and pedagogues to develop a much closer relationship. To this end, we provided an overview of motor learning processes emanating from a *constraints-led perspective*, demonstrating how it can substantiate a platform for a new pedagogical framework: nonlinear pedagogy (e.g., Chow et al., 2006, Chow et al., 2007; Davids, Button & Bennett, 2008; Renshaw et al., in review). In this previous work we showed how a nonlinear pedagogical framework, emanating from concepts in ecological psychology and dynamical systems theory, provides a sound conceptualization for teaching games. These papers built on numerous published studies that have elucidated the theoretical basis of the constraints-led approach and its roots in ecological psychology and dynamical systems theory (Araújo, Bennett, Button, & Chap-

man, 2004; Davids, Button, Araéapman, 2004; Davids, Button, Araújo, Renshaw, & Hristovski, 2006). The application of insights from a constraints-led perspective is ongoing and there is a need for further understanding of how the key theoretical concepts might help coaching practitioners enhance their pedagogical practice. The aim of this paper is to show how key principles of ecological psychology and dynamical systems theory might underpin a philosophy of coaching practice based on nonlinear pedagogical principles. To achieve this aim a brief description of nonlinear pedagogy will be provided followed by a consideration of some of the fundamental principles of ecological psychology and dynamical systems theory that underpin its application. We propose how these overarching principles can act as the cement holding together the building blocks of the coaching process (Lyle, 2002).

In simple terms, nonlinear pedagogy is 'application of the concepts and tools of nonlinear dynamics' to coaching practice, (Chow et al., 2006, p.72). Nonlinear pedagogy is predicated on a view of the learner as a human movement system which is inherently nonlinear in character. It seeks to establish the practical relevance of adopting such a view of the learner as well as identifying implications for understanding learning processes. In this respect, nonlinear dynamical movement systems are considered to exhibit key characteristics observed in other nonlinear dynamical systems in nature e.g., openness to surrounding information flows, capacity for self-organisation, stabilities and instabilities, capacity for transitions in states of order, especially in the metastable region of criticality (an area of system organization which provides a foundation for the emergence of creative and adaptive behaviours (Davids, Bennett, & Newell, 2006). An important task is to identify key constraints that impinge on any specialized nonlinear dynamical system in nature in order to understand emergent properties of such systems (Newell, 1986). In nature, different nonlinear dynamical systems satisfy a range of constraints as behaviour emerges from them (Davids et al., 2007). The basis of nonlinear pedagogy, therefore, involves the manipulation of key (personal, task and environmental) constraints impinging on learners leading them to satisfy these interacting constraints. In this way, constraints manipulation facilitates the emergence of functional movement patterns and decision-making behaviours in different sports and physical activities (Chow et al., 2006). In the following sections of this paper we elucidate a number of key concepts of dynamical systems theory and ecological psychology that will help a coach implement a constraint-led approach in a nonlinear pedagogy.

#### *Key Concepts Underpinning Nonlinear Pedagogical Coaching Practice*

### 1. The mutuality of the performer and the environment

One of the established tenets of ecological psychology is the mutuality of the individual and environment: one cannot be considered without careful reference to the other. The environment refers to the surroundings of animals that perceive and behave (Gibson, 1986), and behaviours of individuals cannot be understood without reference to their specific environments (Araújo et al., 2004). In team sports, the environment consists of team mates and opponents, as well as playing surfaces and inanimate objects that define specific performance contexts (such as an ice rink in skating, a bicycle in the triathlon, parallel bars in gymnastics or goalposts and pitch markings in the football codes). For an individual to engage effectively with other individuals, events, surfaces and objects in the performance environment their affordances for action need to be detected. An affordance refers to a property of the environment which can be detected as information to support an action, and which is related to an individual's ability to use it (Gibson & Pick, 2000). For example, an unmarked team mate affords the option for a pass for a player with the ball in team sports, while the surface of the ice in a rink affords sliding across on the blades of a skate. For the rock climber, a narrow fissure between two pieces of rock affords a two-finger hand hold that can be used to grip the surface. Although these affordances are always available for actions by any individual athlete, the detection and learning of affordances is not an automatic process. The role of the learner is to learn to pick up the affordances that these specific environments offers them (Gibson & Pick, 2000). Some affordances will require significant periods of exploration, practice and time to enable detection for action (Gibson & Pick, 2000). To exemplify, infant perceptual development occurs through active exploratory behaviour resulting in an increase in discrimination and detection of meaningful properties of affordances in the environment (Pick, 1992). This finding implies that affordances are specific to each individual and relate to his/her action capabilities. In athletes, these capabilities may change as a result of growth and development of body sub-systems across the lifespan or by the application of principled training programmes that develop movement system variables such as strength, speed or range of flexibility.

The importance of exploratory behaviour for facilitating perceptual learning has important implications for coaches attempting to develop athletic performance. It highlights the need to accurately identify the key perceptual information sources in the performance environment (Davids et al., 2006) so that practice opportunities can enable learners to become attuned to specifying information sources available in specific performance environ-

ments (Beek, Jacobs, Daffertshoffer, & Huys, 2003). Specifying information can be classified as useful information that constrains movements, whereas non-specifying information is information that is less useful for action (Jacobs & Michaels, 2002). For example, in a series of studies, Jacobs and colleagues (Jacobs, Michaels, & Runeson, 2001; Jacobs, Runeson, & Michaels, 2001) required observers to judge the relative mass of two colliding balls. Initially, participants' judgments correlated highly with the speed difference of the balls after the moment of impact, information which was not useful in specifying relative mass. After feedback was provided, further exploration led to the use of specifying information - the relative amount of motion change. The shift from non-specifying to specifying information has been described as a process of 'education of attention' in which performers learn to pick up specifying information for action (Jacobs & Michaels, 2002).

In sports, performers may initially use non-specifying information when they are not attuned to specifying information sources. For example, skilled cricket batters determine differences between a wristspin bowler's standard legspinner (clockwise spin) from the googly (anti-clockwise spin) by picking up specifying information from the hand position at ball release. Less skilled batters learn that the trajectory of a ball aimed outside off-stump will be a googly while a ball aimed at leg stump will be a legspinner (Philpott, 1995). Although this information may have some saliency it is based on non-specifying (less useful) information and the learner will often make incorrect decisions. With experience batters become attuned to the bowler's action and he/she learns to differentiate between the two ball types by using the specifying information that is available from observing the bowler's action (Renshaw & Fairweather, 2000). So, it is clear that non-specifying information for action may be relatively less useful for the performer. An interesting observation of Jacobs and colleagues was that, if initial use of non-specifying variables led to a reasonable level of success, subsequent convergence on the specifying variables was slowed (Jacobs et al., 2001).

These results suggest that performance environments need to be carefully replicated during practice so that athletes can engage in exploratory behaviour and learn to detect affordances for action. Jacobs et al. (2001) emphasized that some of the less successful participants in their investigation did not engage in further exploratory behaviour that could have led them to become better attuned to the specifying information. To help athletes pick up specifying information, it is important for coaches to understand whether practice sessions are representative of the performance environment. In ecological psychology, 'representative task design' underpins successful identification of information for action in the Brunswikian tradition. For Egon

Br  
co  
ex  
co  
th  
en  
m  
pr  
be  
pe

2.

th  
ca  
o  
ir  
E  
ti  
n  
T  
t  
v  
s  
E  
t  
k  
t  
f  
i  
:  
l

Brunswick (e.g., 1956), representativeness referred to the generality of task constraints in a specific research context to the perceptual variables outside experimental settings (Davids, Araújo, Button, & Renshaw, 2007). For coaches experimental settings equate to practice environments, implying that they need to accurately sample the environmental conditions of practice to ensure congruence with the performance environment in which the movements will be implemented (Davids et al., 2007). Designing representative practice tasks requires the coach to have an understanding of the interaction between key individual, task and environmental constraints of specific sports performances (Davids, Chow, & Shuttleworth, 2005).

## 2. Perception and action are coupled

A key implication of the concept of performer-environment mutuality is that perception and action sub-systems have the capacity to become inextricably linked through practice and learning. In ecological psychology the theory of direct perception signifies how the perception and action systems in individuals can become tightly coupled (see Gibson, 1979; Savelsbergh, Davids, Van Der Kamp, & Bennett, 2003). Gibson's theory of direct perception (1979) suggests how information drives movements, but also how movements influence what information can be picked up by performers/learners. The principle of perception-action coupling has meaningful implications for the design of coaching practice. During practice, athletes need to be provided with opportunities to learn to perceive the key specifying information sources to enable the emergence of functional movement solutions. This point can be illustrated by observing what happens under practice conditions that do not include specifying information sources. In a study of cricket batting, we demonstrated that batting against bowling machines compared to real bowlers led to a re-organisation of the timing and co-ordination of a forward defensive shot (Renshaw, Oldham, Davids, & Golds, 2007). The former task constraints did not facilitate opportunities for batters to pick up specifying information from the bowler's actions—a key component of expert batting performance (Müller, Abernethy, & Farrow, 2006). These findings support the principle of perception-action coupling and suggest that coaches should design practice tasks that keep specifying information sources and actions together. This principle might be violated in practice tasks such as batting against a bowling machine or when long jumpers practice run-throughs without jumping (see Glize & Laurent, 1997). In this regard it is important for coaches to use a strategy of 'task simplification' rather than

'task decomposition' when designing practice sessions (Davids et al., 2007). Task simplification signifies that information-movement couplings utilised during performance are preserved by requiring learners to practice in simulated performance conditions. In task simplification key performance variables such as velocity of balls and opponents, number of players in the game and size of playing areas are maintained and managed to simplify the task. To illustrate, in long jumping, the athlete might run up and jump from a shorter run up, rather than using a decomposition strategy of practicing the run-up separately to the jump. In team games, tasks can be simplified by reducing the numbers in teams or by reducing the size of the playing area (i.e. playing attack vs. defence in half the normal area). This approach contrasts with the traditional strategy of breaking up actions into arbitrary units by reducing skills to practice in static drill activities where no decision making opportunities are required of the participants, and hence the drill is not particularly relevant to a game situation. In summary, the key point of task simplification is that it enables learners to practice in a managed environment with all key information sources present.

### **3. Self Organisation under constraints**

It has been well established that dynamical systems in nature contain inherent processes of self organization (Davids, et al., 2008). Dynamical systems in sport have the capacity to utilize environmental energy enabling them to spontaneously achieve states of organisation shaped by the interacting constraints of the individual, task and environment. Changes in constraints lead to instabilities in learners and result in new patterns of behaviour emerging due to system re-organisation. Because coaching involves the emergence of new, functional patterns of behaviour in learners, instabilities are an important part of the learning process. In sport, the coach is faced with constantly changing constraints due to lifespan development (e.g., growth and maturation, ageing, changes in fitness, psychological variations), dynamic task constraints (e.g., performing a task under a variety of conditions due to differences in locations, weather, and performance environments) and environmental conditions (e.g., altitude, travel, social and cultural contexts of performance). Some individual functional constraints changes may be within the control of the coach (e.g., fitness levels), whereas others are structural, more uncontrolled processes (e.g., height and leg length of individual athletes). Coaches need an understanding of how structural or functional constraints might shape the behaviours of learn-

ers/performers. For example, when coaching children the structural constraints of the size a child's hand and grip strength rather than poor technique may be a determining factor in the quality of a pass in basketball. Similarly, at a different level of development, an ageing adult's muscle stiffness rather than lack of skill may be responsible for the manner in which a flic-flac is performed towards the end of a gymnastic routine. A key to understanding the impact of structural constraints on performance is identifying how specific sub-systems can act as rate limiters on the emergence of specific movement solutions. As sub-systems of the body do not develop at the same rate, the slow development of one sub-system can act as a rate limiter meaning that skills may only emerge when all the relevant sub-systems have reached a critical level of development (Thelen, 1995). For example, in child development, muscle strength is a rate limiter for the emergence of walking (Haywood & Getchell, 2005). Clearly, the contemporaneous rate limiters of individuals need to be understood as they will determine the potential emergence of specific movements or game strategies. Additionally, it should be understood that rate limiters can change as constraints change. For example, a poor throw by an older performer may be due to poor mobility around the shoulder joint, while a similar poor throw from a younger less experienced player, may be due to a limited tactical knowledge base acting as a rate limiter on decision-making (Haywood & Getchell, 2005). It is important to note that rate limiters are not exclusive to individual constraints and an interesting idea for future research could be to examine how cultural and physical environments can act as rate limiters on performance development.

More generally, the concept of self organisation has important implications for coaching practice and supports the use of a more 'hands-off' coaching style where coaches can shape behaviour by designing practice tasks constraints that facilitate the emergence of functional movement solutions (Davids, et al., 2008).

To illustrate this point, it is worth considering how gymnastics coaches might use task constraints to shape behaviour to support more effective performance in a floor activity (the cartwheel) and a pommel horse activity (double leg circles). A common error in performing the cartwheel is for the gymnast to 'pike' at the hips, so that the performer fails to keep a linear shape between the hands and the toes during rotation. A common approach to solve this problem is to point out the error and use instructions to correct it. An alternative approach is to exploit self-organisation processes in learners by introducing a constraint on performance. For example, two crash mats could be placed in parallel, requiring the gymnast to cartwheel between them without touching each surface. Performers can gain feedback from the legs



touching the mats and as they become better at keeping the straight line body position, the mats are brought closer together. A strength of this approach is that it reduces the need for the coach to constantly monitor practice and intervene with verbal instructions to the performer since task-related feedback is constantly available during performance from the mat positions relative to the learner's legs. In our second task, the young gymnast who struggles to perform two legged circles can be helped to overcome this problem by placing both feet in a bucket which is suspended by a rope hanging from a beam placed above the pommel horse. The use of equipment in both examples forces learners to adapt to temporary practice task constraints, showing how coaches might introduce physical constraints on learners to harness inherent self-organisation processes in human movement systems.

#### **4. Performance development is a nonlinear process.**

In traditional neural-maturation approaches to development, achievements in motor behaviour were believed to occur at predetermined ages, with movement patterns emerging as a result of cerebral maturation in an orderly genetic sequence (Savelsbergh et al., 2003). The key contribution of this approach was the idea of motor milestones which were used to monitor an individual's developmental progress. Although this approach has lost favour in the field due to its uni-dimensionality, its influence can still be seen in linear models of talent development. Traditional models of talent identification are biased towards chronological age leading to those children born earlier in the calendar year, and who are consequently biologically more mature than their counterparts, being favoured in selection for elite representative squads in many sports (Côté, Baker, & Abernethy, 2007).

Recent research has demonstrated that talent development is a nonlinear process that exhibits many features of open dynamical systems such as (i) non linear changes in performance; (ii) increased performance variability and instability as individuals are exposed to new levels of competition (changes in constraints); (iii) unique differences in the interactions of the individual and the environment leading to many different developmental trajectories (Abbott, Button, Pepping, & Collins, 2005); (iv) shifts in performance occur in a discontinuous manner as a result of the different rates of development of body sub-systems (Thelen, 1989); and (v), the emergence of expertise being a dynamic, multidimensional and multiplicative developmental process (Simonton, 1999). The model presented by Simonton (1999) highlighted that interaction of key components (which are domain specific) underpinning

skilled performance is essential to the development of expertise. In the model it appears that the late emergence of any one factor might act as a rate limiter on performance. Theoretically, Simonton's (1999) ideas on talent identification provide a strong link with contemporary thinking in motor development and highlight that behaviour is an emergent property of a confluence of constraints (Thelen, 1995). Simonton's (1999) model suggests that talent is not stable over time, which might help explain the development rates of early and late bloomers as well as the loss of talent. The model may prove useful in further research on talent development to explore the role of non-linearities in expertise development (e.g. hot streaks, slumps, form reversals, plateaux).

The nonlinear nature of performance development has a number of practical implications for coaches. First, it highlights the need to recognise that children grow at different rates at different ages and different children also develop at different rates (Aldridge, 1993). Second, individual sub-system development needs to be monitored, including factors such as the onset of growth spurts and changes in body proportions. Sudden changes incurred by growth spurts may require re-scaling of equipment used by learners or of practice environments (e.g., practice fields or court dimensions). Finally, the coach needs to identify the rate-limiting constraints on performance and learn how to carefully manipulate them by creating instabilities in the learner to assist system re-organisation.

### 5. A focus on the individual

In nonlinear pedagogy the individual is at the centre of the learning process supported by an individualised coaching practice. However, many coaches in charge of large squads of athletes can find this requirement challenging and often resort to recipe-book coaching (Lyle, 2002). How might coaches individualise the design of practice sessions? The first requirement is to identify the intrinsic dynamics of each individual learner in the squad or team. Intrinsic dynamics refer to the set of movement capabilities that each individual brings with him/her when learning a new skill (Thelen, 1995). A person's intrinsic dynamics are unique and shaped by genetic factors, previous experiences and both physical and cultural environmental influences (Davids, Glazier, Araujo, & Bartlett, 2003). Consequently, the coach needs to identify previous sport specific experiences for learners and their participation in tasks that may facilitate skill acquisition due to cooperation between intrinsic and task dynamics (e.g., throwing balls and overhead shots in bad-

minton). Coaches also could consider where previous task experiences might hinder development due to competition between intrinsic and task dynamics (e.g., playing tennis shots after initially playing squash). More detailed assessment of a performer's intrinsic dynamics should identify the emergent (contemporaneous) constraints on current performance for each individual. When coaching large groups, individuals may form sub-groups with similar intrinsic dynamics to provide learning experiences that are optimal for all individuals in the group. To achieve this aim, coaches could categorise athletes according to Newell's (1985) model of motor learning (e.g. co-ordination, control and skill). An individual at the co-ordination level is challenged to assemble a functional co-ordination pattern. For example, in learning to kick a football the individual needs to organise the relative motions of legs, hips, trunk and arms to produce a basic kicking action. Gradually a reasonable level of success will be achieved, but the kicking action will be much more rigid with less hip extension and knee flexion than seen in expert kickers (Anderson & Sidaway, 1994). To simplify and solve the complex co-ordination problem of kicking a ball, the beginner freezes the mechanical degrees of freedom of the body (Bernstein, 1967). At the control level, performers have developed a co-ordinated pattern and need to develop a tighter fit between the assembled co-ordinated structure and the environment (Davids, et al., 2008). This is often typified by a greater release of the degrees of freedom enabling more efficient movement patterns (kicking with a greater range of hip extension and knee flexion). An individual at stage three in Newell's model is able to optimize performance by exploiting the degrees of freedom demonstrating instantaneous adaptability in their movements to satisfy changing task constraints (Davids, et al., 2008). Our kicker would be able to pass the ball with the inside, instep, outside or the heel of the foot, by lifting the ball over defenders or driving it along the ground. In summary, it seems that one size does not fit all in terms of practice activities and understanding intrinsic dynamics of each individual provides the basis for programmes that truly individualise the coaching process even in team or squad coaching.

#### 6. Co-adaptive moves and the team as an open dynamical system: Implications for practice

Research has demonstrated how ideas and principles of ecological psychology and dynamical systems theory can help enhance understanding of sport performance at an individual level e.g., squash (McGarry & Franks,

19  
K  
sp  
H  
Sc  
pl  
ic  
fr  
ou  
be  
&  
in  
tic  
ob  
Be  
foi  
tio  
mc  
the  
de  
att  
tio  
sh  
ov  
  
ma  
cor  
ma  
(e.g  
the  
Ka  
ner  
cou  
exa  
wh  
bet  
atta  
an  
terr  
the

1994; McGarry & Franks, 1996a; McGarry & Franks, 1996b; McGarry, Khan, & Franks, 1999) and tennis (Palut & Zanone, 2005), as well as in team sports (Araújo et al., 2004; McGarry, 2006; McGarry, Anderson, Wallace, Hughes, & Franks, 2002; Passos, Araújo, Davids, Gouveia, & Serpa, 2006; Schmidt, O'Brien, & Sysko, 1999). From this perspective an individual player, a team or a complete team game could each be described as a dynamical system because each system is "one in which regularity self-organises from within as a result of information exchanges that occur both inside and outside the system (i.e. among the parts that comprise the system, and between the system and its surrounding constraints, respectively) (McGarry & Franks, 2007, p. 48). This tendency is facilitated by many complex systems in nature displaying *self-similarity* at different levels, with *fractal* characteristics to features which look similar even when there is a change in scale of observation (Passos, Araújo, Davids, Gouveia, Serpa, & Milho, in press). Behaviour emerges in such complex systems as spontaneous patterns are formed from the interactions of individuals in the team game. These interactions can occur between team mates or with opponents. The actions and movements of team mates/opponents provide information that constrains the actions of other individuals. For example, in doubles badminton a high defensive lift from one player will lead the partner standing at the net (in an attacking formation) to drop back to adopt a side-by-side defensive formation. In hockey, a winger who dribbles the ball infield towards the inside shoulder of a full back creates space on the outside for exploitation by an overlapping full-back.

Actions of opponents also provide important information that players may use to influence decision making and nonlinear pedagogy advocates the concept of co-adaptation in learning in sport. Co-adaptation is a feature of many evolutionary complex systems in nature in which co-evolving agents (e.g., predator and prey) compete to modify the landscape characterizing their 'fitness' (e.g., success in populating the region) (Kauffmann, 1993). Kauffmann noted that co-evolving adaptive behaviours of system components within critical regions are typically emergent because of the evolved coupling between system components. These ideas can be understood by examining behaviours in complex social systems such as team sports, in which behaviours can emerge out of fluctuations created by interactions between interdependent constituents of the system (e.g., the moves of an attacker and defender in a 1 v 1 dyad). For example, in the dyad formed by an attacker and closest defender in team invasion games, their actions are systematically related through specific rules and tactical principles. Because of these task constraints, attackers and defenders form a system and their inten-

tions do not make sense if separated from each other's actions (Passos, Araújo, Davids, & Shuttleworth, 2008; Passos, Araújo, Davids, Gouveia, et al., 2008). Actions and decisions made by protagonists in this dyadic system are externally regulated by constraints that include performance area dimensions, inter-personal distance between players (and rate of change of this distance), position on field, and rules of the game. Changes in interactions between the two individuals in the system can lead to the de-stabilising of current system order (defender between a target area and the attacker) and the emergence of a new state of order (e.g., the attacker dribbles past the defender towards the target).

Although empirical work is just beginning to emerge in this area (e.g. Passos, Araújo, Davids, Gouveia, et al., 2008), the ideas of co-adaptation may be useful for understanding how multiple interactions between attackers and defenders influence the emergence of tactical decisions. For example, providing opportunities for players to learn to become attuned to the affordances offered by the spacing between defenders could be important for developing tactical performance. In field hockey, a widely spaced defensive line affords opportunities to exploit gaps between defenders, while a narrowly spaced line, may provide opportunities to pass the ball wide and exploit the spaces around the outside of the defence. However, the combined intrinsic dynamics of teams will also determine their own action possibilities. In the hockey example, it may only be possible to exploit the space outside the opposing full-back if (a) the attacking full back is attuned to the affordance, i.e., he can see the space that has been created and (b) has the fitness (speed and endurance) to move into that space. It should also be noted that the decision to make the overlap or not, may also be influenced by the state of the game. Passos, Araújo, Davids, Gouveia, et al. (2008) explored these issues in rugby union, and demonstrated that an important consideration when assessing the decisions made by defenders and attackers is to take into account the initial conditions of interpersonal interactions, since slight differences in performance contexts can lead to substantial differences in outcomes. For example in hockey, the position on the field, state of the game as well as positions of other attackers and defenders might have a significant impact that determines whether a defender attempts to win the ball back by pressuring the winger or tries to conserve system stability by moving backwards and maintaining the current inter-personal distance between him/her and the winger.

In complex adaptive systems such as team games, due to the emergent nature of the information constraining decision-making and action there is no single optimal decision that can be determined in advance, since it may be difficult to predict or prescribe large sequences of play (Passos, Araújo,

Dauids, Gouveia, et al., 2008; Passos, Araújo, Davids, & Shuttleworth, 2008). Coaches might avoid attempting to 'control the uncontrollable' by not designing 'reductionist' drills that limit decision making and actions of performers. Training programmes based on a sound understanding of the constraints that shape system attractors in performance contexts are likely to be more helpful to learners. Additionally, high levels of variability in task demands should be encouraged enabling individuals to become more adaptable performers because they can learn to make decisions in representative practice tasks. Coaches could aim to help players to become attuned to the key specifying information within the performance environment, especially the actions of 'significant other' players by providing practice tasks that are contextualized from the principles of the team game (Passos et al., 2006). Decision-making skills can be facilitated by manipulating task constraints to provide practice that incorporates 'repetition without repetition' (Bernstein, 1967). This aim could be achieved by creating an environment in which the learning system (the team) does not repeatedly practice the same solution to a problem but instead is continually forced to search for new solutions to the same problem. A simple way to operationalise these ideas would be to change the instructional constraints on defenders. For example, in helping players in invasion games to understand how to break down different types of defences, defenders could be asked to defend specific zones (which can be changed in size over a series of practice attempts), or by using a close marking defence. This approach would help both defending and attacking players to understand the strengths and weaknesses of the two approaches and facilitate opportunities to search for appropriate solutions.

### **7. Coaching is a balance between maintaining stability versus creating instabilities**

Coaching is a balance between protecting the confidence of athletes by providing environments that enable them to be successful and risking the loss of existing confidence levels by exposing them to more demanding practice tasks. This dilemma is one of maintaining performance stability by allowing athletes to exploit their current information-movement couplings or of creating instabilities that force learners to explore the perceptual-motor workspace for additional information to guide actions (Gibson, 1986). In dynamical systems theory, instabilities are useful since they could lead to system re-organisation and development. From a coaching perspective, deliberately creating instability is useful to prevent performance plateaux due to

individual movement systems being trapped in deep, stable attractor states (Davids, et al., 2008). Similarly, perturbing a system is a useful strategy for modifying the technique of experienced performers who have well-established co-ordination patterns. When deliberately creating instabilities, coaches need to understand the effects that this might have on performers. Creating a phase transition will lead to high levels of non-functional variability that will initially lead to lower levels of performance as learners adapt to the new task constraints. Creating instabilities require understanding and support of the potential psychological impact on the athlete such as loss of confidence which might impact on motivation and performance.

In summary, coaches should consider whether providing too much stability in the coaching progress might lead to a reliance on non-specifying information sources that limit future success. For example, in junior singles badminton a high serve that only reaches the back double service line may afford the strong player the opportunity to smash to win the rally. However, if playing against an older, bigger opponent who can cover more of the court, the same serve may result in the opponent picking off the smash return with an easy block at the net. Practically, coaches need to provide learning opportunities that expose individuals to a lot of variety forcing 'learning movement systems' to explore their boundaries. For example, in tennis, coaches might seek players to practice and compete on indoor surfaces, clay, synthetic or grass, and against left handed and right handed opponents who adopt various tactical approaches such as serve and volleying or baseline rallying. However, it is important to understand when instabilities might be implemented and coaches might provide more stability in the immediate lead-up to major competition events in order to maintain or build the confidence of performers.

#### **8. Variability is an essential component of performance development**

Variability within individual movement patterns has traditionally been viewed negatively, since a common goal for many coaches is the acquisition of an 'ideal' technique as a template for performance success. In fact, much traditional practice is based around the need for performers to have acquired a 'correct' technique before being exposed to the *real* game. However, there is now a large body of research that demonstrates that individual learners can achieve similar task outcomes by using different co-ordination patterns and that experts often display more variability within their movement patterns than less skilled individuals (Bootsma, Houbiers, Whiting, & van Wieringham, 1991; Brisson & Alain, 1996; Davids et al., 2006; Davids, et al., 2008;

Renshaw & Davids, 2004; Schöllhorn & Bauer, 1998). The concept of degeneracy, which refers to the capability of structurally distinct parts of complex movement systems to achieve different outcomes in varying contexts (Davids, et al., 2008) supports the efficacy of performers developing more functionally variable movement patterns. Functional variability is essential so that skilled performers can adapt to subtle changes in initial conditions at the start of the movement or to ongoing changes in the performance environment. For example, long jump competitions take place in environments that require the jumper to undertake 6 maximal efforts in environmental conditions that may vary over the time frame of the competition. Despite this many coaches require athletes to practice in sterile conditions and undertake decomposed practice tasks such as run-throughs in order to provide what they believe is the best chance for their athletes to standardise their run-up. However, it is now well established that Olympic standard long jumpers are not capable of placing their feet in the same place for every run-up and actually adjust their step patterns as they approach the take-off board (Hay, 1988; Montagne, Cornus, Glize, Quaine, & Laurent, 2000). During a competition the jumper may need to make adjustments for changes in individual constraints such as fatigue and psychological stress as well as changes in environmental conditions such as run-up surfaces and changes in wind speed or direction. The implication is that while maintaining the essential specifying information for actions, rather than reduce variability, the coach might seek to increase variability in practice conditions so that the athlete develops adaptability and flexibility to cope with changing task constraints (Davids et al., 2007).

### 9. Encouraging creativity in learning and performance.

Extensive practice is essential to realise performance potential in any domain (Ericsson, Krampe, & Tesch-Römer, 1993). Ericsson et al. (1993) built their 'expert-performance approach' on the concept of deliberate practice, defined as engagement in relevant activities that require great effort, lots of repetition and opportunities to acquire feedback and is not inherently enjoyable (Ericsson, 2003; Ward, Hodges, Williams, & Starkes, 2004). Even in later work, Ericsson (2007) described practice as deliberate 'when individuals engage in a practice activity (usually designed by their teachers), with full concentration on improving some aspect of performance' (p.14). This view of practice proposed by Ericsson might be interpreted as emphasizing the need for early specialisation and the need to practise using highly repeti-



tive drills-the concept of perfect practice. However, given the importance of developing performers with adaptive variability, it could be argued (as Ericsson did in later work (Ericsson, 2003) that this type of practice is far from perfect and can lead to performance that lacks flexibility to adapt in the ways demonstrated by highly skilled individuals.

In contrast to deliberate practice, nonlinear pedagogy advocates the need for practice that adopts the principle of 'repetition without repetition' (Bernstein, 1967). In this approach, coaches design representative practice tasks that allow individuals time and space to explore and discover co-ordination patterns and make decisions that are most appropriate for their unique constraints (Davids, et al., 2008). In contrast to the deliberate practice framework, coaching based on a nonlinear pedagogy would not reject unstructured learning environments and would promote informal learning opportunities, including having children design their own games and activities (Chappell, 2004; Kidman, 2001, 2005). The importance of designing practice that is not over structured is supported by the counter-intuitive findings of Schöllhorn et al. (2009) who demonstrated how adding noise in the form of random movement variability to a target movement can enhance learning. Schöllhorn et al.'s (1999, 2000) differential learning approach requires the design of practice tasks which lead individuals to explore many possible movement solutions. The premise is that this exploration leads to participants becoming more adaptable performers with greater levels of functional variability within their movement patterns. Differential learning has been shown to be a better training method than the traditional training method in sports such as shot putt, handball, hurdles, football, volleyball and tennis. It would appear that creating unavoidable movement variance enhances performance and learning by requiring performers to continuously change movement execution and to scan the high dimensional space of their nonlinear movement system for emergent solutions in a stochastic manner. In this way, the learner is confronted with larger (in comparison to repetitive practice constraints) differences between two consecutive trials that, through the process of differential learning, encourages exploration and pick up of information about the stability of the perceptual-motor landscape (Schöllhorn et al., 2009). In summary, providing opportunities to learn by playing modified tasks or games that are inherently enjoyable and intrinsically motivating for the performer will have the dual effect of helping to create 'love' for the sport while at the same time developing the integrated physical, technical, tactical and psychological skills needed for competitive success (Bloom, 1985; Chappell, 2004; Côté et al., 2007; Ericsson, 2007; Janelle & Hillman, 2003).

## 10. What do we mean by natural (implicit) learning?

Traditional coaching models tend to emphasise high levels of explicit verbal instruction and augmented feedback (Williams & Hodges, 2005). This approach is described as highly conscious and is based on cognitive views of motor learning as typified by Fitts and Posner's (1967) stages of learning model. Verbal instruction is justified as early efforts by beginners in sport are said to be based on conscious control processes (Masters & Maxwell, 2004). However, recent research has highlighted that implicit learning may be more appropriate for some skill learning tasks. First, explicit learning appears to lead to skill failure under stress as performers 'reinvest' in conscious, cognitive processing in an attempt to control their co-ordination patterns (Jackson & Farrow 2005; Masters & Maxwell, 2004). Second, research in neuroscience has highlighted that visual information for action is picked up learners in sport through the dorsal pathway and remains subconscious to the perceiver, while information for object recognition is picked up by the ventral system using conscious awareness (Milner & Goodale, 1995). Finally, explicit learning may not always be the most appropriate strategy for practice in sport because, according to Bernstein (1967), typically movements are not controlled by higher levels of the central nervous system, drawing heavily on lower levels of control which regulate movement behaviour subconsciously (Davids, et al., 2008). Therefore, because movement is driven by subconscious processes, explicit instructions directed at conscious control processes do not direct the learner to the information flows during action. It is no surprise that forcing learners to switch to more conscious levels of control, through providing explicit instructions and feedback, will lead to performance disruption and de-automisation (Beek, 2000). These ideas do not imply that explicit learning has no place in skill development. In fact, the theories of both Milner and Goodale (1995) and Bernstein (1967) highlight that both approaches may have a place alongside implicit approaches underpinning the development of actions such as a golf swing, while explicit learning may be the most appropriate strategy for developing performance in complicated cultural skills like dancing or gymnastics floor routines (Savelsbergh & van der Kamp, 2009).

Given the interest in developing implicit learning methods, a number of techniques, such as incidental and analogy learning have been developed by sport psychologists (see Jackson and Farrow (2005) for a comprehensive list) to try and promote this 'new' approach to learning by 'preventing' conscious rule making by learners during the acquisition process. By using these approaches coaches might be going 'back to the future' and promoting nat-

ural implicit learning by creating environments that typify the exploratory behaviour of young children who learn to crawl, walk and run without recourse to verbal instruction (e.g., see Laurentino, 2008). In nonlinear pedagogy, the link with approaches such as Teaching Games for Understanding (Bunker & Thorpe, 1982) and Inner Game coaching (Gallwey, 1979) emphasizes how they can be used by coaches to provide discovery learning opportunities that minimise potential disruption to performance by overemphasising explicit instruction (see Chow et al., 2007).

### Summary

In this paper we suggested that coaches need to base their practice on a philosophy that is underpinned by sound theory. We demonstrated that nonlinear pedagogy, underpinned by ecological psychology and dynamical systems theory, is one such theoretical approach that provides the coach with a foundation for developing programmes predicated on empirical evidence from motor learning studies. Key concepts that can underpin practice include designing practice tasks to facilitate the development of appropriate perception-action couplings in learners which are representative of specific performance environments. Representative task design ensures that these practice environments contain specifying information sources for performers to make successful decisions and actions. We proposed how individual, task and environmental constraints shape the performance of individuals and teams and that coaches might seek to identify the key rate limiters on performance so they are able to manipulate constraints to facilitate changes in performance. Essential to this process is understanding that principled manipulation of constraints can be used by coaches to create system instability, forcing the search for new more effective strategies. A good way to create more adaptable performers is for coaches to use their detailed understanding of sports to be creative in designing practice activities with high levels of variability to facilitate 'repetition without repetition'. We considered how coaches need to consider the task goals to underpin when they should use implicit and explicit learning strategies. In summary, we showed that basing practice on nonlinear pedagogy need not result in highly structured practice based on reductionist perspectives of the learner; rather, individualised skill development should be understood from a systems orientation based on an integrative, inter-disciplinary approach leading to coaching that is more hands-off than traditional coaching models.

Al  
Al  
Ar  
Ar  
Be  
Be  
Be  
Bl  
Bc  
Br  
Br  
Br  
Bu  
Ca  
Cl  
Cl  
Cl  
Cl  
Cl  
Co  
D  
D  
D

## REFERENCES

- Abbott, A., Button, C., Pepping, G.-J., & Collins, D. (2005). Unnatural Selection: Talent Identification and Development in Sport. *Nonlinear Dynamics, Psychology, and Life Sciences*, 9, 61-68.
- Aldridge, J. (Ed.). (1993). *Skeletal growth and development*. London: Spon Press.
- Anderson, D. I., & Sidaway, B. (1994). Coordination changes associated with practice of a soccer kick. *Research Quarterly for Exercise & Sport*, 65, 3-99.
- Araújo, D., Bennett, S. J., Button, C., & Chapman, G. (2004). Emergence of sport skill under constraints. In A. M. Williams, Hodges, N., Scott, M. A., & Court, M. (Eds.), *Skill acquisition in sport: research, theory and practice*. London: Routledge.
- Beek, P. J. (2000). Toward a theory of implicit learning in the perceptual motor domain. *International Journal of Sport Psychology*, 31, 547-554.
- Beek, P. J., Jacobs, D. M., Daffertshoffer, A., & Huys, R. (2003). Expert performance in sport: Views from the joint perspectives of ecological psychology and dynamical systems theory. In J. L. Starkes & K. A. Ericsson (Eds.), *Expert performance in sports: Advances in research on sport expertise* (pp. 321-344). Champaign: Human Kinetics.
- Bernstein, N. A. (1967). *The control and regulation of movements*. London: Pergamon Press.
- Bloom, B. S. (1985). *Developing talent in young people*. New York: Ballentine.
- Bootsma, R. J., Houbiers, M., Whiting, H. T. A., & van Wieringham, P. C. W. (1991). Acquiring an Attacking Forehand Drive: The Effects of Static and Dynamic Environmental Conditions. *Research Quarterly for Exercise and Sport*, 16, 21-29.
- Brisson, T. A., & Alain, C. (1996). Should common optimal movement patterns be identified as the criterion to be achieved? *Journal of Motor Behavior*, 28, 211-223.
- Brunswik, E. (1956). *Perception and the representative design of psychological experiments* (2nd ed.). Berkeley: University of California Press.
- Bunker, D., & Thorpe, R. (1982). A model for the teaching of games in the secondary schools. *The Bulletin of Physical Education*, 5-8.
- Carter, N. (2006). *The football manager: A history*. London: Routledge.
- Chappell, G. (2004). *Cricket: The making of champions*. Melbourne: Lothian Books.
- Chow, J. Y., Davids, K., Button, C., Shuttleworth, R., Renshaw, I., & Araújo, D. (2006). Non-linear pedagogy: A constraints-led framework to understanding emergence of game play and skills. *Nonlinear Dynamics, Psychology, and Life Sciences*, 10, 71-103.
- Chow, J.-Y., Davids, K., Button, C., Shuttleworth, R., Renshaw, I., & Araújo, D. (2007). The Role of Nonlinear Pedagogy in Physical Education. *Review of Educational Research* 71, 251-278.
- Côté, J., Baker, J., & Abernethy, B. (2007). Practice and play in the development of sport expertise. In G. Tenenbaum & R. C. Eklund (Eds.), *Handbook of sport psychology*. New Jersey: John Wiley & Sons.
- Davids, K., Araújo, D., Button, C., & Renshaw, I. (2007). Degenerate brains, indeterminate behaviour; and representative tasks. In G. Tenenbaum & R. C. Eklund (Eds.), *Handbook of sport psychology*. London: John Wiley & Sons.
- Davids, K., Bennett, S. J., & Newell, K. (Eds.). (2006). *Movement system variability*. Champaign: Human Kinetics.
- Davids, K., Button, C., Araújo, D., Renshaw, I., & Hristovski, R. (2006). Movement models from sports provide representative task constraints for studying adaptive behavior in human movement systems. *Adaptive Behavior*, 14, 73-95.

- Davids, K., Button, C., & Bennett, S. J. (2008). *Dynamics of skill acquisition: A constraints-led approach*. Champaign: Human Kinetics.
- Davids, K., Chow, J. Y., & Shuttleworth, R. (2005). A constraints-led framework for non-linear pedagogy in physical education. *Journal of Physical Education, New Zealand*, 38, 17-29.
- Davids, K., Glazier, P., Araujo, D., & Bartlett, R. M. (2003). Movement systems as dynamical systems: The functional role of variability and its implications for Sports Medicine. *Sports Medicine*, 33, 245-260.
- Ericsson, K. A., Krampe, R. T., & Tesch-Römer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review*, 100, 363-406.
- Ericsson, K. A. (2003). Development of elite performance and deliberate practice. In J. L. Starkes & K. A. Ericsson (Eds.), *Expert performance in sports: Advances in research on sport expertise*. Champaign: Human Kinetics.
- Ericsson, K. A. (2007). Deliberate practice and the modifiability of body and mind: toward a science of the structure and acquisition of expert and elite performance. *International Journal of Sport Psychology*, 38(1), 4-34.
- Feltz, D. L., Chase, M. A., Moritz, S. E., & Sullivan, P. J. (1999). A conceptual model of coaching efficacy: Preliminary investigation and instrument development. *Journal of Educational Psychology*, 91, 765-776.
- Fitts, P. M., & Posner, M. I. (1967). *Human performance*. Belmont: Brooks/Cole.
- Gallwey, T. W. (1979). *The inner game of golf*. London: Jonathan Cape Limited.
- Gibson, E. J., & Pick, A. D. (2000). *An Ecological Approach to Perceptual Learning and Development*. Oxford: Oxford University Press.
- Gibson, J. J. (1986). *The Ecological Approach to Visual Perception*. Boston: Houghton Mifflin.
- Glize, D., & Laurent, M. (1997). Controlling locomotion during the acceleration phase in sprinting and long jumping. *Journal of Sports Sciences*, 15, 181-189.
- Hay, J. G. (1988). Approach strategies in the long jump. *International Journal of Sport Biomechanics*, 4, 114-129.
- Haywood, K. M., & Getchell, N. (2005). *Life span motor development* (4th ed.). Champaign: Human Kinetics.
- Jackson, R. C., & Farrow, D. (2005). Implicit perceptual training: How, when, and why? *Human Movement Science*, 24, 308-325.
- Jacobs, D. M., & Michaels, C. F. (2002). On the paradox of learning and realism. *Ecological Psychology*, 14, 127-140.
- Jacobs, D. M., Michaels, C. F., & Runeson, S. (2001). Learning to perceive the relative mass of colliding balls: The effects of ratio-scaling and feedback. *Perception & Psychophysics*, 62, 1332-1340.
- Jacobs, D. M., Runeson, S., & Michaels, C. F. (2001). Learning to visually perceive the relative mass of colliding balls in locally and globally constrained task ecologies. *Journal of Experimental Psychology: Human Perception and Performance*, 27, 1019-1038.
- Janelle, C., & Hillman, C. H. (2003). Expert performance in sport: Current perspectives and critical issues. In J. L. Starkes & K. A. Ericsson (Eds.), *Expert performance in sports: Advances in research on sport expertise*. Champaign: Human Kinetics.
- Kauffman, S. (1993). *The Origins of Order. Self-organization and selection in evolution*. New York: Oxford University Press.
- Kidman, L. (2001). *Developing decision makers: An empowerment approach to coaching*. Christchurch: Innovative Print Communications.

- Kidman, L. (2005). *Athlete-centred coaching: developing and inspiring people*. Christchurch: Innovative Print Communications Ltd.
- Laurentino, J. (2008). *The Negotiable Golf Swing: How to Improve Your Game Without Picture-Perfect Form*. N.Y.: Negotiable Golf.
- Lyle, J. (2002). *Sports Coaching Concepts: A Framework for Coaches' Behaviour*. London: Routledge.
- Martens, R. (2004). *Successful coaching*. Champaign: Human Kinetics.
- Masters, R. S. W., & Maxwell, J. P. (2004). Implicit learning, reinvestment and movement disruption: What you don't know won't hurt you. In A. M. Williams & N. Hodges (Eds.), *Skill acquisition in sport: research, theory and practice*. London: Routledge.
- McGarry, T. (2006). Identifying patterns in squash contests using dynamical analysis and human perception. *International Journal of Performance Analysis in Sport*, 6, 134-147.
- McGarry, T., Anderson, D. I., Wallace, S. A., Hughes, M. D., & Franks, I. M. (2002). Sport competition as a dynamical self-organizing system. *Journal of Sports Sciences*, 20, 771-781.
- McGarry, T., & Franks, I. M. (1994). A stochastic approach to predicting competition squash match-play. *Journal of Sports Sciences*, 12, 573-584.
- McGarry, T., & Franks, I. M. (1996a). In search of invariant athletic behaviour in competitive sport systems: An example from championship squash match-play. *Sports Sciences*, 14, 445-456.
- McGarry, T., & Franks, I. M. (1996b). Development, application and limitation of a stochastic Markov model in explaining championship squash match-play. *Research Quarterly for Exercise and Sport*, 67, 406-415.
- McGarry, T., & Franks, I. (2007). System approach to games and competitive playing: Reply to Lebed (2006). *European Journal of Sport Science*, 7, 47-53.
- McGarry, T., Khan, M. A., & Franks, I. M. (1999). On the presence and absence of behavioural traits in sport: An example of championship squash match-play. *Journal of Sports Sciences*, 17, 297-311.
- Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action*. Oxford: Oxford University Press.
- Montagne, G., Cornus, S., Glize, D., Quaine, F., & Laurent, M. (2000). A perception-action coupling type of control in long jumping. *Journal of Motor Behavior*, 32, 37-43.
- Müller, S., Abernethy, B., & Farrow, D. (2006). How do world class cricket batsmen anticipate a bowler's intention? *Quarterly Journal of Experimental Psychology*, 59, 2162-2168.
- Newell, K. M. (1985). Co-ordination, control and skill. In D. Goodman, R. B. Wilburg & I. M. Franks (Eds.), *Differing perspectives in motor learning, memory, and control* (pp. 295-317). Amsterdam: Elsevier Science.
- Newell, K. M. (1986). Constraints on the development of co-ordination. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor development in children: Aspects of co-ordination and control* (pp. 341-360). Dordrecht: Martinus Nijhoff.
- Newell, K. M., & Rovegno, I. (1990). Commentary-Motor Learning: Theory and Practice. *Quest*, 42, 184-192.
- Palut, Y., & Zanone, P.-G. (2005). A dynamical analysis of tennis: Concepts and data. *Journal of Sports Sciences*, 23, 1021-1032.
- Passos, P., Araújo, D., Davids, K., Gouveia, L., & Serpa, S. (2006). Interpersonal Dynamics in Sport: The Role of Artificial Neural Networks and Three-dimensional Analysis. *Behavior and Research Methods*, 38, 683-691.
- Passos, P., Araújo, D., Davids, K., & Shuttleworth, R. (2008). Manipulating Constraints to Train Decision Making in Rugby Union. *International Journal of Sport Science & Coaching*, 3, 125-140.

- Passos, P., Araújo, D., Davids, K., Gouveia, L. Serpa, S. & Milho, J. (2008). Information governing dynamics of attacker-defender interactions in youth level rugby union. *Journal of Sports Sciences*.
- Philpott, P. (1995). *The Art of Wrist-spin Bowling*. Ramsbury: The Crowood Press.
- Pick, H. L. (1992). Eleanor J. Gibson: Learning to perceive and perceiving to learn. *Developmental Psychology*, 28, 787-794.
- Renshaw, I., & Davids, K. (2004). Nested task constraints shape continuous perception-action coupling control during human locomotor pointing. *Neuroscience Letters*, 369, 93-98.
- Renshaw, I., Davids, K., Chow, J. W., & Hammond, J. (in press). A constraints-led perspective to understanding skill acquisition and game play: A basis for integration of motor learning theory and physical education praxis? *P.E. & Sport Pedagogy*.
- Renshaw, I., & Fairweather, M. M. (2000). Cricket bowling deliveries and the discrimination ability of professional and amateur batters. *Journal of Sports Sciences*, 18, 951-957.
- Renshaw, I., Oldham, T., Davids, K., & Golds, T. (2007). Changing ecological constraints of practice alters coordination of dynamic interceptive actions. *European Journal of Sports Sciences*, 7, 157-167.
- Savelsbergh, G. J. P., Davids, K., Van Der Kamp, J., & Bennett, S. J. (Eds.). (2003). *Development of movement co-ordination in children: Applications in the fields of Ergonomics, Health Sciences and Sport*. London: Routledge.
- Savelsbergh, G. J. P., & van der Kamp, J. (2009). Catching two visual systems at once: Ventral and dorsal system contributions in the visual regulation of catching. In D. Araújo, H. Ripoll & M. Raab (Eds.), *Perspectives on cognition and action in sport*.
- Schmidt, R. C., O'Brien, B., & Sysko, R. (1999). Self-organisation of between-person cooperative trials and possible applications to sport. *International Journal of Sport Psychology*, 30, 558-579.
- Schöllhorn, W. I., & Bauer, H. U. (1998, July 7-12). *Identifying individual movement styles in high performance sport by means of self-organizing kohonen maps*. Paper presented at the Proceedings of the XVI Annual Conference of the International Society of Biomechanics in Sport, Konstanz, Germany.
- Schöllhorn, W. I. (1999). Individualität - ein vernachlässigter parameter? *Leistungssport*, 29, 7-11.
- Schöllhorn, W. I. (2000). Applications of systems dynamic principles to technique and strength training. *Acda Academiae Olympiquae estoniae*, 8, 67-85.
- Schöllhorn, W., Michelbrink, M., Welminski, D., & Davids, K. (2009). Increasing stochastic perturbations enhances acquisition and learning of complex sport movements. In D. Araújo, H. Ripoll & M. Raab (Eds.), *Perspectives on Cognition and Action in Sport*, (pp. 59-73). New York: Nova Science Publishers, Inc.
- Simonton, D. K. (1999). Talent and Its Development: An Emergent and Epigenetic Model. *Psychological Review*, 106, 435-457.
- Thelen, E. (1995). Motor development: A new synthesis. *American Psychologist*, 50, 79-95.
- Thelen, E. (Ed.). (1989). *Self-organization in developmental processes; Can systems approaches work?* (Vol. 22). London: LEA.
- Ward, P., Hodges, N. J., Williams, A. M., & Starkes, J. L. (2004). Deliberate practice and expert performance. In A. M. Williams & N. J. Hodges (Eds.), *Skill acquisition in sport: research, theory and practice*. London: Routledge.
- Williams, A. M., & Hodges, N. J. (2005). Practice, instruction and skill acquisition in soccer: Challenging tradition. *Journal of Sports Sciences*, 23, 637-650.