Sports Med
DOI 10.1007/s40279-012-0001-1

CURRENT OPINION

Self-Organization Processes in Field-Invasion Team Sports

Implications for Leadership

Pedro Passos · Duarte Araújo · Keith Davids

Abstract In nature, the interactions between agents in a complex system (fish schools; colonies of ants) are governed by information that is locally created. Each agent self-organizes (adjusts) its behaviour, not through a central command centre, but based on variables that emerge from the interactions with other system agents in the neighbourhood. Self-organization has been proposed as a mechanism to explain the tendencies for individual performers to interact with each other in field-invasion sports teams, displaying functional co-adaptive behaviours, without the need for central control. The relevance of self-organization as a mechanism that explains pattern-forming dynamics within attacker–defender interactions in field-invasion sports has been sustained in the literature. Nonetheless, other levels of interpersonal coordination, such as intra-team interactions, still raise important questions, particularly with reference to the role of leadership or match strategies that have been prescribed in advance by a coach. The existence of key properties of complex systems, such as system degeneracy, nonlinearity or contextual dependency, suggests that self-organization is a functional mechanism to explain the emergence of interpersonal coordination tendencies within intra-team interactions. In this opinion article we propose how leadership may act as a key constraint on the emergent, self-organizational tendencies of performers in field-invasion sports.

1 Introduction

In this article we argue that field invasion sports can be modelled as complex social systems in which inherent self-organizing coordination tendencies can be exploited to underpin interpersonal interactions between performers. The suggestion is that effective interactions between performers in field invasion sports (both within and between teams) can emerge through spontaneous self-organization processes, under the influence of advanced, prescriptive planning of cooperative actions that operate as umbrella task constraints. This idea has the potential to provide some rich insights for sport scientists and performance analysts. In the study of complex social systems, like sports teams, the mechanisms that support pattern forming dynamics have been analysed for some time. In recent years, researchers have conceptualized field-invasion sports as dynamical systems, proposing that pattern formation processes that occur during subphases of competitive performance are supported by a mechanism of self-organization under task and environmental constraints [1–3]. We also need to recognize, notwithstanding, the influence that pre-set configurations, operating as task constraints, might have on spontaneous formation of group patterns, an issue that we discuss later.

2 Local Interactions to Justify Self-Organization in Social and Biological Systems

Self-organization is an inherent mechanism within complex systems in nature that explains how order emerges due to

P. Passos · D. Araújo
Faculty of Human Kinetics,
Technical University of Lisbon, Lisbon, Portugal

P. Passos (✉)
Faculdade de Motricidade Humana,
Universidade Técnica de Lisboa, Estrada da Costa,
Cruz Quebrada, Dafundo, 1499-002 Lisbon, Portugal
e-mail: ppassos@fmh.utl.pt

K. Davids
School of Human Movement Studies,
Queensland University of Technology,
Brisbane, QLD, Australia

critical fluctuations in a system's intrinsic dynamics[1]. For example, in complex biological systems, it has been observed that individual organisms use relatively simple local behavioural rules to create structures and patterns at a collective level that are more complex than the behaviour of each individual system agent [4–6]. Previous work on schools of fish has revealed that individual agents in complex systems have a tendency to spontaneously organize themselves into coordinated patterns by modifying their behaviours on the basis of local social interactions [4]. Support for this view has also appeared in research examining collective behaviours of mixed groups of cockroaches and socially integrated autonomous robots [7]. Behaviours of agents in these disparate, natural and artificial systems were perceived as equivalent, and it was reported that collective activities (i.e. when the interaction among agents produce a pattern of behaviour at a larger scale than themselves [8]), in both systems, emerged from nonlinear responses over time supported by local interactions rules [7]. An example of self-organizing collective groupings in humans is the traffic jam. To maintain a free flow on a highway the local rule is that each agent must maintain an interpersonal distance from the car ahead, speeding up or slowing down his/her own vehicle [9]. Another example of self-organization under local rules bounded by leadership are military manoeuvres [10] and emergency service rescue operations [11]. These observations exemplify that self-organization is a process whereby patterns at a global system level (i.e. at a group level) emerge solely from interactions at lower levels of the system (e.g. dyadic level). The rules specifying the interactions among the system's components are implemented using only local information, without reference to the global pattern. In field-invasion games, these patterns have been proposed to be caused by continuous attacker–defender interactions bounded by key task constraints [2, 3, 12, 13]. As already noted, pre-set configuration patterns can operate as task constraints, bounding, for instance, players' relative positioning. But the competitive environment within field-invasion sport performance requires that performers continuously co-adapt to the behaviours of other individuals in close proximity on the field of play, and this is where the local interaction rules gain influence on the players' interactive behaviours. This perspective identifies attackers and defenders as components of a self-organizing system (i.e. whose behaviour is guided without an external controller) that are linked by visual and other informational fields (e.g. acoustic). The process of co-adaptation between individuals in invasion team games can lead to the occurrence of spontaneous pattern-forming dynamics. This view of continuous co-adaptations between performers is reinforced by the suggestion that, in any complex system, interactions between individuals are nonlinear [14].

3 Context Dependency as a Critical Feature in Self-Organization

Local interaction rules define the performance task constraints that stabilize agent behaviours in complex social systems (e.g. relative positioning between agents; maintaining proximity to other system agents but avoiding contact; maintaining spatial trajectories towards a target). However, the presence of significant others (i.e. other group members, e.g. predators or opponents) demands continuously adaptive behaviours of system agents, signifying that local interaction rules are not invariant, but rather context dependent [12]. In complex system modelling, the critical feature of context dependency can be captured through analysing the dynamics of interpersonal distances between system agents. This issue has received some attention in sport science in recent years, with numerous investigations analysing the spatial or temporal characteristics of players' movements in field-invasion sports teams [15–18]. For instance, it has been revealed that there are occasions during competitive performance that can be characterized by periods of equilibrium between attackers and defenders (usually when attackers and defenders form a dyadic system and remain a specific distance apart) [19]. During these periods, the players from opposing teams seek to adjust their relative positioning, usually guided by global tactical instructions as an informational constraint that has been previously established during training. Research has shown how these tactical instructions can constrain the intentions of performers during these periods of relative system stability [18]. But during performance in field-invasion sports, the system formed by attackers and defenders can typically evolve far from this zone of balance. It has been observed that decreasing interpersonal distance values between competing players during performance can move an attacker–defender dyadic system to critical performance regions. In these regions, the contextual dependency rules governing performance require constant co-adaptations of performers to the behaviours of immediate opponents [19, 20].

4 In Critical Regions: Is Behaviour Beyond Planned Actions?

The contextual dependency of individuals in field invasion games means that, within some critical regions of

---

[1] Phase transitions do not necessarily need the presence of critical fluctuations, although most typically they can follow the presence of this signature of dynamical systems.

performance, typically characterized by low values of interpersonal distances between attackers and defenders, actions are not (typically) prescribed by pre-planned rules through a coach's instructions but rather emerge from the continuous interactions between players as a game evolves. Importantly, the goals of opposing players are mutually exclusive, since their ongoing interactions can lead to an increasing influence of candidate control parameters (i.e. key variables such as the relative velocity between competing players in an attacker–defender dyad) that can move this type of social system towards a particular performance outcome [20]. When this happens the system achieves a state of criticality, involving changes in a key candidate control parameter, such as the relative velocity between competing performers. This event can lead to a transition in the balance between an attacker and defender, with eventual consequences for performance outcomes in the game [21]. Due to a system's proximity to a threshold region, a difference in circumstances that favours one option over another, for instance, when one opposing player increases speed against an opponent, it can rupture the symmetry of equally poised options, leading to a system state transition. The implication is that a player might gain an advantage over an opponent through continuous, nonlinear interactions between performers and pattern forming dynamics are thus self-organized [20]. Critical fluctuations and self-organization explain that, for example, the performance outcome could be precisely the one that players wanted to avoid, even with strict prescriptive information by the coach to avoid that outcome.

The aims of this opinion article are to (1) discuss evidence from previous research concerning self-organization as a mechanism to explain pattern forming dynamics in invasion team sports; and (2), explain how instructional approaches and strategical planning can influence practice designs, which promote the occurrence of self-organized patterns in practice and performance of field-invasion games.

5 Interpersonal Interactions in Field-Invasion Sports

Previous research has identified properties of dynamical systems in the interactions of attackers and defenders in field-invasion sports like basketball [2], rugby union [20] and association football [22, 23]. These studies have reported that the coupled behaviours of attackers and defenders can be characterized by different coordination states, and that transitions from one state (e.g. where a defender is the closest player to a goal) to another (e.g. where an attacker dribbles past the defender and moves closer to the goal), may have emerged from inherent self-organization processes [24] (Fig. 1). A common feature of these studies is that investigators have tended to use the same coordination variable to accurately capture the behaviours of 1 versus 1 dyads in invasion team sports under a range of different task constraints (i.e. rugby union, basketball and association football). This coordination variable is an angle calculated with a vector from the defender to the attacker with an imaginary horizontal line parallel to the goal line. Data has shown that values of this variable close to 90° signify that the attacker did not pass the defender. A zero crossing point signified the moment when the attacker dribbled past the defender and negative values of the variable have implied that the attacker had become the player closest to the basket, goal or try line, in a position to score (for further details see the work of Passos and colleagues [24]).

Figure 1 displays data from several 1 versus 1 attacker–defender interactions in the team sports of rugby union (Fig. 1a), basketball (Fig. 1b) and association football (Fig. 1c), respectively. It can be observed that the performance variability displayed in these interactions, for instance, the moment that an attacker dribbled past the defender (when the 'x' axis is crossed by the trajectory of the attacker), is unique for each trial. This finding is consistent with a feature of complexity sciences known as system 'degeneracy'. Degeneracy is a property of complex systems in which structurally different components of the system interact to provide distinct ways to achieve the same performance outcome [25]. These data reinforce the idea that nonlinearity is a key feature of interactions between attacker–defender dyadic systems.

In these studies, attackers and defenders were conceptualized as an interpersonal coordination system in invasion team sports suggesting how two elements of a complex, dynamical system can be linked by perceptual informational fields, locally created by the nonlinear interactions of performers. This performance feature in invasion sports means that one cannot predict specific performance outcomes in advance (i.e. whether a defender or attacker will gain an advantage over the other). Small changes in the interactions of opposing players might lead to completely different dyadic system outcomes (e.g. try or tackle; a shot at goal or maintaining ball possession; a dribble past a defender or a loss of ball possession by the attacker). Thus, as displayed in Fig. 1a, b and c, changes in the state of coordination in attacker–defender dyadic systems (i.e. the moment when an attacker becomes the player closest to a goal area) are emergent in time and space, and are self-organized. This empirical observation is consistent with ideas originally proposed by Davids and colleagues [26] and later by McGarry and Perl [27] who provided a description of sport contests as systems with inherent self-organization tendencies. Following their insights, research was needed to analyse the tendencies of such systems to

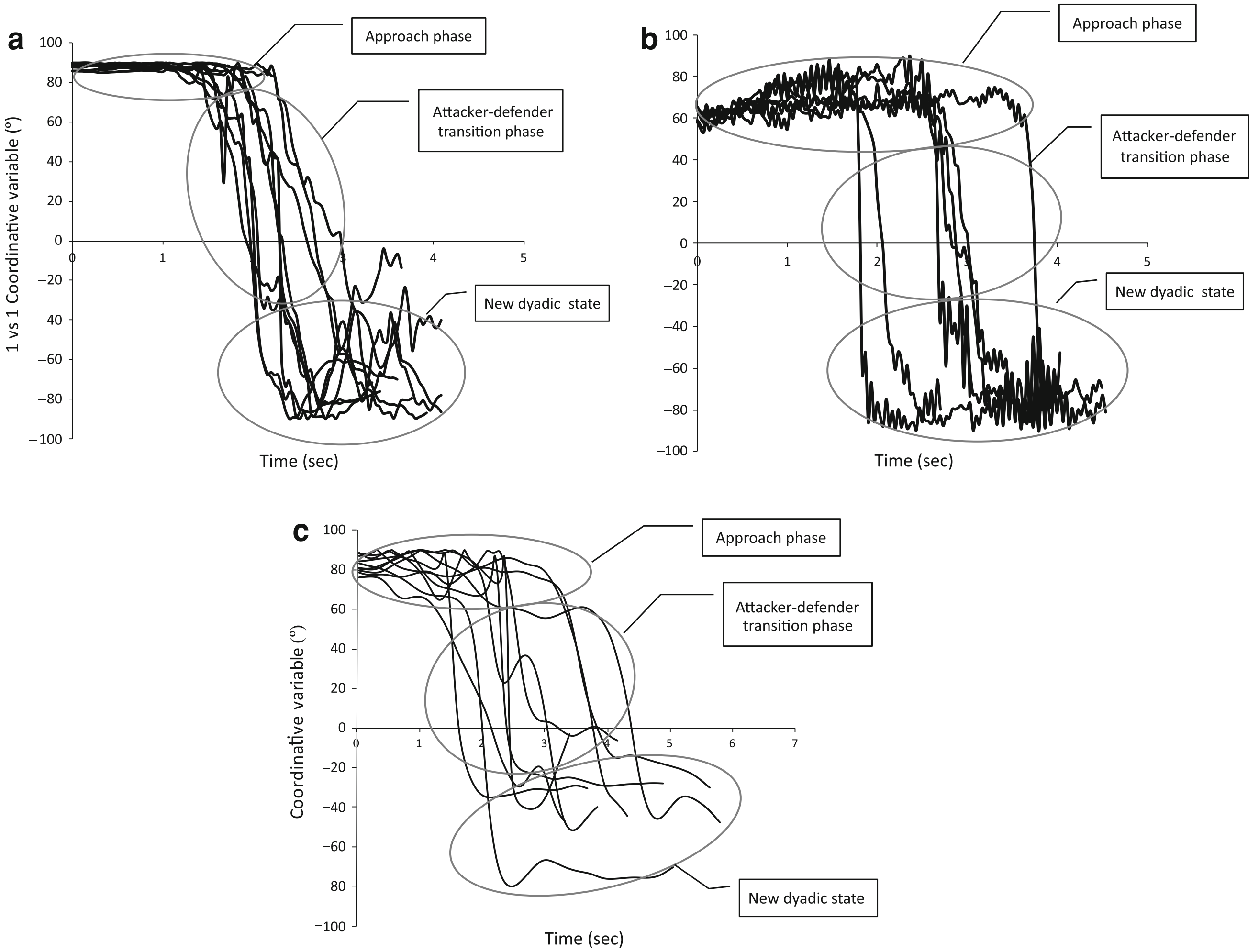

Fig. 1 **a** Rugby union; **b** basketball; **c** association football. The values of the angle are calculated with the vector from the defender to the attacker and an imaginary line parallel to the goal line, suggested as a coordinative variable. Thus, the *black lines* display a coordinative variable that describes attacker–defender interactions in team sports. The 'approach phase', characterized by high values (i.e. close to 90°) of the coordinative variable, shows that the attacker and defender are decreasing interpersonal distance values without changing their running line trajectories. The 'attacker–defender transition phase', characterized by the zero crossing (on the x axis), sets the moment where the attacker moved closer to the goal. The 'new dyadic system state', characterized by a new structural organization, with the attacker the closest player to the goal, shows the coordinative variable assuming negative values

reorganize themselves when they become destabilized under constraints [27].

Advances in conceptualizing attacker–defender interactions as self-organized were provided when studies of performance in the team sport of rugby union identified power law distributions in attacker–defender dyads, as well as collective behaviours in 4 versus 2 performance subphases [12, 19]. The second step was to identify that the mechanism behind the power law distributions observed in field-invasion sports interactions was inherent self-organization processes. Power law distributions observed for the interactions of attackers and defenders signified the presence of many small fluctuations in performer interactions, with occasional large-scale changes to system organization in the form of transitions. These findings signalled how attacker–defender systems evolve towards regions of self-organized criticality. These are regions where attacker–defender interactions are sustained on local rules and where there exists a balance between task constraints with the system poised for a transition. Here, attacker–defender systems can alternate between periods of stability and variability. These ideas were empirically supported by data, showing when the order (i.e. stability) within an attacker–defender system emerged due to the nonlinear interactions between performers. When this occurred, an attacking subunit passed an initial set up of defending players and reorganized to face a second defensive line (Fig. 2).

In accordance with the insights of Per Bak [28], self-organization is a plausible mechanism for the existence of a power law distribution in pattern forming dynamics of

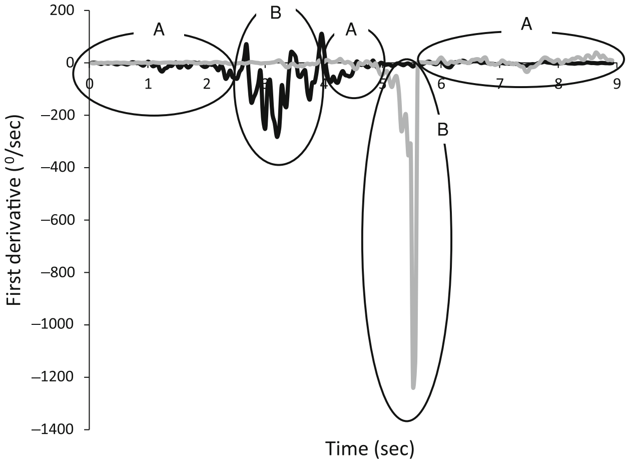

Fig. 2 This figure displays the first derivative of the coordinative variable presented in Fig. 1. The *solid black line* represents the interactive behaviours between the attacking subunit and the first defensive line. The *grey line* signifies the interactive behaviours between the attacking subunit and the second defensive line. *A* identifies the moments of system stability, where there are no changes in the attacker–defender running line trajectories. *B* identifies the volatility periods, meaning that the attacking subunit aimed to cross the defensive line, but the defenders counterbalanced the attackers' movements

field-invasion games. Indeed, a power law distribution might be caused by a range of different mechanisms, such as the highly optimized tolerance system mechanism (i.e. in the 'forest fire' model) [29], the random multiplicative or fragmentation processes (e.g. the distribution of meteor sizes) [30], or self-organized criticality [28, 31]. In the specific case of attacker–defender interactions in field-invasion sports it has been suggested that a power law distribution might be caused by self-organized criticality in the system due to the opposing goals and roles of system agents [19]. Opposing goals and roles constitute important task constraints that create contextual information where an advantage for one player is a disadvantage for an opposing player, sustaining the coadapting, nonlinear behaviours of sport performers. Previously, we discussed the idea that nonlinearity was a general feature of player interactions in field-invasion sports. Agent interactions, as a feature of nonlinearity, induce system perturbations that provoke responses of differing magnitudes, which are at the heart of a power law distribution [32]. These findings, notwithstanding, the existence of power laws to characterize the interactions of performers in field-invasion sports, and the mechanism behind these power laws is an important issue that still requires further research.

During field-invasion games, performance is continuously evolving near critical states (i.e. regions of short interpersonal distances between performers), when actions between team-mates and immediate opponents can become correlated in a type of domino effect, capturing global inter-team coordination tendencies. In these critical regions, due to the presence of criticality in the system, there can be an abrupt change from several potential transitions in system outputs to one (e.g. an abrupt change in the structural organization of a stable attacker–defender system, where suddenly the attacker becomes the closest player to the goal).

6 Leadership and Intra-Team Interactions

Self-organization appears to be a suitable mechanism to explain the emergence of pattern-forming dynamics in inter-team (i.e. attacker–defender) interactions. But what of intra-team interactions under leadership constraints, such as coaching instructions that define specific configurations or patterns of play and tactical strategies for players? This type of informational constraint seems to play a considerable role in bounding behaviours in team sports. For instance, from an overarching perspective, specific coaching instructions bind players to particular tactical behaviours concerning 'what to do in specific situations', wherein each player's positioning on-field is set in advance of a team play emerging. Regardless of such prior planning, during any competitive subphase of invasion team games, the changing proximity of opponents demands ongoing adjustments in player positioning. Such temporal-spatial adjustments are supported by local information, such as the values of interpersonal distances between opposing players, or the distances of players to the goal. This observation was illustrated in a study of collective behaviours in the team sport of rugby union where Passos and colleagues [12, 33] revealed that performers in attacking subunits organized themselves with different mean values of interpersonal distances between themselves, before and after crossing an initial defensive line. Here we discuss how these ongoing adjustments in player behaviours may be mainly influenced by inherent self-organization mechanisms in field-invasion sports teams.

From the study of players' interactions in the team sport of rugby union, it has been established that support players within an attacking subunit need to (re)organize themselves, relative to the ball carrier's position [12]. This attacking subunit behaviour is typically achieved by acquiring a geometric form similar to (but not fixed in) a diamond-shaped structure (i.e. a ball carrier in the front; a left side support player; a right side support player; and an axial support player at the rear). Here, the intentionality of the players can be led by coaching, on-field leadership or performance templates, which all play a role in constraining the (re)organization of players in attacking subunits. However, with decreasing values of interpersonal distances with immediate defenders, the attacking subsystem's organization can be disturbed due to the close presence of the opposing players. Therefore, when considering the dynamics of the attacker–defender interactions in invasion team sports, the ‘when’ (i.e. related to the time that it takes to reorganize), ‘where’ (i.e. the location of the playing field at which the players will reorganize) and ‘how’ (e.g. how many players are involved in the ‘new’ subphase structure) are important. The performance task of adjusting a required diamond shape structure in attack is a mechanism that is strongly influenced by the presence of significant others (especially the ball carrier’s position and running line speed; and the number of opponents, their positions and running line speeds). When a player changes position on-field, the other performers will co-adapt their positioning accordingly. Again, it is contextual dependency that constrains the emergence of a ‘new’ diamond shape (or similar) structure in the available time and space. Therefore, it appears that, under certain boundaries of task constraints, such as the interpersonal distances between opposing players, intra-team collective behaviours also self-organize [12].

Camazine and colleagues [34] have noted that, in biological and social systems, not all patterns arise due to self-organization processes. There are other mechanisms that should be considered in order to understand the influence of self-organization in the pattern forming dynamics of social systems such as field-invasion sports. A primary mechanism is the existence of a leader (e.g. a coach, instructor, captain or the ball carrier in a team sport) acting as an agent who supervises the behaviours of others during performance, providing instructions on ‘what’ actions are required and ‘when’ to perform them, leading to occurrence of pattern formation from this specific instructional constraint. In this case the mechanism responsible for pattern forming dynamics is not inherent self-organization processes [34]. Nevertheless, the influence of the leadership mechanism in pattern forming dynamics within field invasion sports performance is an issue that requires some caution in interpretation. For instance, despite the formal leadership role that a captain or ball carrier has during performance, this leadership influence might lose strength due to the relative proximity of opponent players. Beyond subjective interpretation, it is not possible to accurately identify who is leading whom at every moment of the interactions between opposing players. The system constraint of leadership needs to be investigated carefully in future work since it may be valid as a key constraint on some intra-team pattern forming tendencies (e.g. the initial positions that players adopt on the pitch just before a set play begins). However, it is not implicated in all patterns that spontaneously emerge on-field, and is definitely not valid for interteam (i.e. attacker–defender) pattern-forming dynamics. Other mechanisms for constraining performer behaviours in field-invasion sports include coaches’ instructions, tactical blueprints, templates or performance recipes, which consist of compact or detailed information aiming to prescriptively constrain the players’ behaviours (e.g., tactical instructions). Similar to the leadership mechanism, it is possible that prescriptive blueprints, templates or recipes also provide a constraining influence on pattern forming dynamics under certain limited conditions. Importantly, these kinds of constraints influence, but do not determine, critical fluctuations and self-organization.

7 Conclusions and Implications

In this opinion article, we have argued that, in field invasion sports, the co-adaptation process that governs players’ interactions within specific values of interpersonal distances can lead to fluctuations that can poise an attacker–defender system for sudden transitions. These processes can form a punctuated equilibrium between stability and variability, which can be described with a power law distribution. Data from research on attacker–defender systems in field-invasion sports have displayed features like non-linearity, system degeneracy, state transitions and emergence, which suggest that the mechanism behind the power law is self-organization. A relevant implication is that players need to learn about the adaptive variability needed for performance of specific leadership roles such as how to perform as a ball carrier or as an on-field leader.

These insights create new challenges for coaching, which aim to develop learning environments where players’ behaviours are strongly influenced by proximity to opponents. The implication is that players will learn to adjust to task and environmental constraints during practice under these conditions, rather than solely due to instructional constraints. Importantly, this idea does not contradict traditional views on the role of instructional leadership on a team’s performance. On the contrary, leadership is valid as a specific constraint on some intra-team pattern forming tendencies but not in ‘all’ patterns, and is definitely not valid for interteam pattern-forming dynamics. An important implication to be understood by coaches is that practice tasks outside these critical regions may not expose team players to the demands of competitive performance environments where contextual dependency governs their behaviours.

Acknowledgments The authors have no conflicts of interest to declare that are directly relevant to the content of this article. No funding has been received to assist in the preparation of this article.

References

1. Davids K, Button C, Araujo D, et al. Movement models from sports provide representative task constraints for studying adaptive behavior in human movement systems. Adapt Behav. 2006;14(1):73–95.
2. Araujo D, Davids K, Hristovski R. The ecological dynamics of decision making in sport. Psychol Sport Exerc. 2006;7(6): 653–76.
3. McGarry T, Anderson DI, Wallace SA, et al. Sport competition as a dynamical self-organizing system. J Sports Sci. 2002;20(10): 771–81.
4. Couzin ID, Krause J, Franks NR, et al. Effective leadership and decision-making in animal groups on the move. Nature. 2005; 433(7025):513–6.
5. Grunbaum D. Behavior: align in the sand. Science. 2006; 312(5778):1320–2.
6. Bonabeau E, Theraulaz G, Deneubourg JL, et al. Self-organization in social insects. Trends Ecol Evol. 1997;12(5):188–93.
7. Halloy J, Sempo G, Caprari G, et al. Social integration of robots into groups of cockroaches to control self-organized choices. Science. 2007;318(5853):1155–8.
8. Sumpter DJ. Collective animal behavior. Princeton (NJ): University Press; 2010.
9. Surowiecki J. The wisdom of crowds. New York (NY): Doubleday; 2004.
10. Schmidle RE, Hoffman FG. Commanding the contested zones. US Nav Inst Proc Mag. 2004;130(9):1219.
11. Kulich M, Faigl J, Přeučil L. Cooperative planning for heterogeneous teams in rescue operations. In: IEEE International Workshop on Safety, Security and Rescue Robotics. Kobe: International Rescue System Institute; 2005.
12. Passos P, Milho J, Fonseca S, et al. Interpersonal distance regulates functional grouping tendencies of agents in team sports. J Mot Behav. 2011;43(2):155–63.
13. Kelso S. Dynamic patterns: the self-organization of brain and behavior (complex adaptive systems). Cambridge (MA): Massachusetts Institute of Technology Press; 1995.
14. Strogatz S. Sync: the emerging science of spontaneous order. New York: Penguin Press Science; 2004.
15. Bourbousson J, Seve C, McGarry T. Space-time coordination dynamics in basketball: part 2. The interaction between the two teams. J Sports Sci. 2010;28(3):349–58.
16. Headrick J, Davids K, Renshaw I, et al. Proximity-to-goal as a constraint on patterns of behaviour in attacker–defender dyads in team games. J Sport Sci. 2012;30(3):247–53.
17. Araújo D, Davids K, Sainhas J, et al., editors. Emergent decision-making in sport: a constraints-led approach. In: Proceedings of the International Congress “Movement, Attention & Perception”. Poitiers:Université do Poitiers; 2002.
18. Cordovil R, Araujo D, Davids K, et al. The influence of instructions and body-scaling as constraints on decision-making processes in team sports. Eur J Sport Sci. 2009;9(3):169–79.
19. Passos P, Araújo D, Davids K, et al. Power law distributions in pattern dynamics of attacker–defender dyads in rugby union: phenomena in a region of self-organized criticality. Emerg Complex Organ. 2009;11(2):37–45.
20. Passos P, Araujo D, Davids K, et al. Information-governing dynamics of attacker–defender interactions in youth rugby union. J Sports Sci. 2008;26(13):1421–9.
21. Jensen H. Self-organized criticality: emergent complex behavior in physical and biological systems. Cambridge: Cambridge University Press; 1998.
22. Duarte R, Araujo D, Fernandes O, et al. Capturing complex human behaviors in representative sports contexts with a single camera. Medicina (Kaunas). 2010;46(6):408–14.
23. Passos P, Lopes R, Milho J. Análise de padrões de coordenação interpessoal no um-contra-um no futebol. Revista Portuguesa de Ciências do Desporto. Portuguese J Sport Sci. 2008;8(3):365–76.
24. Passos P, Araujo D, Davids K, et al. Interpersonal pattern dynamics and adaptive behavior in multiagent neurobiological systems: conceptual model and data. J Mot Behav. 2009;41(5): 445–59.
25. Edelman GM, Gally JA. Degeneracy and complexity in biological systems. Proc Natl Acad Sci USA. 2001;98(24):13763–8.
26. Davids K, Handforf C, Williams AM. The natural physical alternative to cognitive theories of motor behaviour: an invitation for interdisciplinary research in sports science? J Sport Sci. 1994;12(6):495–528.
27. McGarry T, Perl J. Models of sports contests: Markov processes, dynamical systems and neural networks. In: Hughes M, Franks I, editors. Notational analysis of sport: systems for better coaching and performance in sport. 2nd ed. London: Routledge; 2004. p. 227–42.
28. Bak P. How nature works: the science of self-organizing criticality. New York (NY): Copernicus, Springer; 1996.
29. Carlson JM, Doyle J. Highly optimized tolerance: a mechanism for power laws in designed systems. Phys Rev E Stat Phys Plasmas Fluids Relat Interdiscip Topics. 1999;60(2 Pt A):1412–27.
30. Newman M. Applied mathematics: the power of design. Nature. 2000;405(6785):412–3.
31. Bak P, Chialvo DR. Adaptive learning by extremal dynamics and negative feedback. Phys Rev E. 2001;6303(3):031912-1–031912-12.
32. Garnett W. The chaos theory tamed: a Joseph Henry Press Book. London: Taylor and Frances; 1997.
33. Passos P, Davids K, Araujo D, et al. Networks as a novel tool for studying team ball sports as complex social systems. J Sci Med Sport. 2011;14(2):170–6.
34. Camazine S, Deneubourg JL, Franks NR, et al. Self-organization in biological systems. Princeton (NJ): Princeton University Press; 2001.