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Performance, learning and expertise in sport: An Ecological Dynamics rationale

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Abstract

Ecological dynamics focuses on self-organization of action and perception under constraints in sport performance and practice. It addresses the socio-material constraints that enhance and diminish the coupling of perception and action directed by athletes and teams towards achieving task goals, proposing and finding that information and constraints are key in regulating the dynamics of behaviour. Performers explore to learn and learn to explore, which finally lead them to better perceive opportunities for action available in the environment and relative to their action capabilities. In this chapter we propose testable hypotheses in accordance with principles of ecological dynamics along three timescales: (1) Behaviour and performance; (2) Learning, transfer and expertise; (3) ‘Talent’ being developed in sport. Finally, we conclude the chapter by providing implications of these ideas for movement practitioners.

Keywords

Complex systems, affordances, representative design, self-organization, constraints, individual-environment system, perception-action coupling

1. Introduction

Since the 2000s, a large body of research has investigated dynamical properties of human movement systems in different contexts (for an overview, see Button et al., 2020). The ecological dynamics approach is a multidisciplinary framework rooted in dynamical system theory (physics), ecological psychology (psychology) and the neurobiology of complex adaptive systems. This chapter traces how these roots helped to jointly conceptualise the key theoretical pillars of ecological dynamics. Ecological dynamics focuses on movement coordination, considering individuals and groups as complex adaptive systems—a network of highly integrated, interacting sub-components (e.g., parts of the body or members of a team). As complex adaptive systems, humans exploit inherent self-organization tendencies to form functional synergies (coherent groupings of system components) under surrounding constraints. They learn to use cognition, perception, and action to regulate performance in practice and competition. These ideas imply the need to examine performance of individuals and groups at different time scales such as: (1) Behaviour during performance, discussing the key question: how to record performance behaviours. (2) Learning, transfer and expertise, considering how to analyse changes in behaviour across time and different contexts. (3) Developing ‘talent’ in sport: How to investigate inter-individual variability and performance profiling to help each athlete develop their potential over a longer timescale.

2. Behaviour and Performance

2.1. The fundamental unit of analysis of behaviour is the performer-environment system

The performer-environment relationship is essential for understanding behaviour in sport contexts (Araújo & Davids, 2018; Seifert et al., 2017). Whenever we move our bodies, performers and environment function in a *relational, synergistic* way, rather than operating independently from each other. Both form integral parts of a complex dynamic system, with each individual’s actions requiring adaptation with respect to changing circumstances. This idea implies that behaviour can only be studied and understood within the context of a

performance environment (Davids & Araújo, 2010; Seifert et al., 2023). Although this idea may appear obvious, it is a misconception to view the performer as the sole active agent, with the environment merely serving as a passive backdrop to individual actions (Araújo & Davids, 2011b). The epistemological separation of person and environment has historically led to theorizing in which the most significant explanatory factors in behaviour are located within the individual. Attending to the performer-environment relationship emphasises that researchers and practitioners need to understand the biases involved in considering individual performance separately from key constraints of the performance environment (e.g., a swimmer's capacities out of the water, a climber's actions away from a surface such as an icefall or a team games player's performance in isolated test drills outside a game context). There are similar limitations in considering environmental influences in isolation, without regard for an athlete's individual skills (personal characteristics, and capabilities) in interacting with key environmental properties.

In ecological dynamics, goal-directed behaviour can be modelled by *eco-physical variables* (Araújo et al., 2017; Araujo & Davids, 2018; Seifert et al., 2023). These variables express the fit between the physics of the environment and organismic adaptations of sport performers. A misconception that might arise from the emphasis on eco-physical variables, is that they cannot elucidate the psychological processes involved in regulating performance. However, psychological measures of goal-directed behaviour can be obtained by analysing physical variables that capture emergent ecological interactions of a performer with key objects, events, and others in a performance environment (Araújo et al., 2020). The emphasis on eco-physical variables avoids a cognitivist tendency to search for variables inside of the organism believed to 'cause' behaviour (i.e., in the mind as reflected in self-reported data, or in the brain as captured by neural activity). Additionally, this emphasis avoids a behaviourist tendency to search for explanatory variables in the environment (e.g., the contingencies of reinforcement of behaviour), ignoring the continuous (re)organization of behaviour itself (Warren, 2006).

Eco-physical variables are especially important for investigating how physical properties of performance environments may help performers and groups re-organise different stable system states during performance. For instance, 3D kinematics are often computed with an egocentric reference (e.g., hand propulsion is often expressed in relation to shoulder position and in reference to the centre of mass) to investigate inter-limb coordination and control in swimming. But, this perspective has limited capacity to capture how swimmers interact with the aquatic environment. Guignard et al. (2017) recommended including the water plan of the swimming pool or the swimming axis to investigate how swimmers coordinate and control their actions in context. For instance, the angle between the trunk and the water level, or between the arm and gravitational direction indicated when swimmers are streamlined and how hydrodynamics may be disturbed.

2.2. Perception is of action possibilities, i.e. affordances

Ecological dynamics emphasizes laws and symmetry conditions at nature's ecological scale, implying the detection of environmental information used to guide performance. Gibson (1979) investigated the relationship between the structured energy distributions (information) of the environment available to a perceptual system and the environmental properties causally responsible for that structure. For Gibson, detection of environmental information is carried out by a functional system distributed throughout an active organism. Adjustments of peripheral organs, such as re-orienting the eyes and head or the locomotion system, play a

most significant role in direct perception of the environment: action is used for perception as well as perception for acting. Perception of the environment reveals functional properties (e.g., 'reach-ability' or 'grasp-ability' of climbing holds that are behaviourally relevant); Boschker et al., 2002), not physical or structural properties (e.g., size or shape of climbing holds).

Gibson (1979) proposed that humans perceive action possibilities or affordances offered by the environment. An affordance is a property of the environment taken with reference to the perceptual-motor skills or action capabilities of a performer (Fajen et al., 2009) and perceiving is a process of detecting information for action possibilities in the environment. For instance, when passing through narrow spaces (e.g., gaps between defenders), attacking rugby players must perceive possibilities to cross the gap without colliding with, or being stopped by, defenders. Successful navigation through a gap depends on a rugby player's ability to adjust their movements so that perception of cross-ability remains possible (e.g., Correia et al., 2012).

Certain information sources in a performance environment invite actions (Withagen et al., 2012) and, as experience and skill shape their effectivities, athletes become better attuned to these inviting affordances. As mentioned previously, a gap between two defenders invites a rugby ball carrier to cross this gap if they perceive a sufficient width, and are moving at an initial running speed regulated to avoid interception by the defenders. Stronger coupling of perception and action can emerge from carefully designing relevant information for affordances into a practice task to help athletes regulate performance behaviours.

2.3. Constraints channel the emergence of behaviour

In the performer-environment system, performance emerges within constraints. Performance is not determined by internal (e.g., the mind) or external (e.g., a conditioning stimulus) organizers. To satisfy existing constraints, there are typically a limited number of stable solutions that can achieve specific desired outcomes for the performer-environment system (Araújo et al., 2006). Newell's (1986) model of three categories of constraints (organism, environment and task) is significant for understanding how behaviour emerges under constraints, operating at different timescales (performance, learning, development). Constraints, in Newell's (1986) model, have been defined as boundaries or features, which limit the form of behavioural solutions. That is, interacting constraints may channel (or not) the performer-environment system to achieve specific task goals. Behavioural patterns that emerge are more complex than the components that make up the system and cannot be predicted from the characteristics of the individual components in isolation. In cycling for instance, the perception of aperture 'cross-ability' relates to the combined properties of the rider (shoulder width) and the bike (handlebar width), and this person-plus-bike system's maximum action capabilities (e.g., the minimum passable aperture width; Vauclin et al., 2023, 2024).

Behaviour patterns in performance emerge under constraints, as less functional states of organization are dissipated. Changes in performance constraints can lead a system towards bifurcation points where choices emerge as more specific information becomes available, constraining the performer-environment system to switch to more functional paths of behaviour. To exemplify, Guignard et al. (2020) investigated effects of speed and fluid flow manipulation on inter-limb coordination when swimming in a traditional swimming pool, in comparison to swimming in a flume (i.e., swimming against the current). Their findings

emphasized that swimming in the flume, especially at high speed, narrowed the landscape of affordances as it decreased opportunities to glide (Guignard, Rouard, et al., 2020).

2.4. Performers in action as complex adaptive systems

The performer-environment system can be conceived as a complex adaptive system because behaviour organization exhibits properties of *non-proportionality* and *non-linear* dynamics (Davids et al., 2014). The *non-proportionality* that exists between behaviour and performance is exemplified by inevitable individual changes, when during practice a small change in behaviour can lead to a transition in performance and, conversely, a switching between two behavioural patterns can lead to a marginal change in the performance outcome (Chow et al., 2009). The *non-linear* relationship between behaviour and performance can be observed in sudden transitions between two behavioural states. For example, when transitioning from walking to running on a treadmill, although the task constraint (the belt speed imposed by the treadmill rising incrementally) increases linearly, locomotion coordination changes emerge in a non-linear manner.

Non-linearity also relates to system ‘multi-stability’ (Kelso, 2012) induced by the inherent degeneracy of perceptual-motor processes, suggesting that behavioural organization can vary structurally (i.e., movement coordination pattern or synergy), without compromising function in achieving the task-goal. Degeneracy of the perceptual-motor systems is the ability of many structurally body components (i.e., many coordination patterns) to perform similar function or yield similar outcomes (Edelman & Gally, 2001). For instance, during childhood, children can switch between various locomotor patterns (e.g., crawling, ramping, walking and climbing) to negotiate various obstacles and reach a target or an object. The multi-stable states of organisation available to humans implies that there is no one stable behavioural state to satisfy interacting constraints. This idea questions the putative ‘expert model’ of performance toward which all learners must transition in performance development (Davids et al., 2015; Seifert et al., 2013). Rather, there is potential for multiple stable performance solutions to emerge, depending on constraints and affordances offered by the environment, relative to a performer’s capabilities (Gibson, 1979). In sum, performance process and outcome do not share the same dynamics, but are co-determined and exhibited during the periods of stability, destabilization and reorganization that learners experience when transitioning to elite performance.

3. Learning, expertise and transfer

3.1. Learning

The ecological dynamics framework considers motor learning at the ecological scale. Processes such as education of intention, education of attention (attunement) and calibration (Fajen et al., 2009; Jacobs & Michaels, 2007) lead to a functional (re)organization of the number of components and sub-systems of the human body during skill learning. In ecological dynamics, a three stage learning model has been proposed: *search and exploration; discovery and stabilization; exploitation* (Araújo et al., 2009; Button et al., 2020; Davids et al., 2012). Research within in ecological dynamics investigated 1) the functional role of exploration in learning, and 2), how exploration interplays with exploitation (stabilization) within the dynamics of learning, suggesting that a greater gap between an individual’s repertoire and a to-

be-learned coordination pattern, may relate to a longer duration of an intermittent regime (also called metastability) in which exploration alternates with exploitation.

The *search and exploration* stage consists of *exploring the 'perceptual-motor workspace' and searching for solution(s) to achieve a task goal* (Newell, 1996; Pacheco et al., 2019). The perceptual-motor workspace encompasses all possible coordination patterns available for learners to explore during goal-directed activities (Newell, 1996; Pacheco et al., 2019). To enhance learning, this workspace can be constrained at task, organismic, or environmental levels (Newell, 1986) to invite learners' exploration within a landscape of affordances. Since many couplings of perception and action are possible in any situation, learners need to *educate their intentions* to specify what needs to be achieved in specific performance context (Jacobs & Michaels, 2007). Goals direct the attention of a learner to functionally explore (act) and perceive relevant informational variables for further performatory actions.

The first stage of learning involves the assembly of a movement coordination pattern that satisfies the learner's intention to achieve a task goal. At this early stage of learning, neither the information used to guide movement, nor the coordination pattern itself, need necessarily be the most effective way to move. Through search and exploration, the learner can soft-assemble a solution to achieve an intended task goal. For instance, Hacques et al. (2021) showed that the gaze path of learners in indoor wall climbing became more goal-directed, associated with lower exploratory hand movements and visual fixations with practice. Although search and exploration mainly reflect early stages of learning, they are also observed in skilled performers. Indeed, while beginners explore to learn, advanced performers learn to explore (Hacques et al., 2020), and skilled performers explore efficiently, the processes by which they extend their maximal action capabilities. For instance, beginners might rely on structural properties of the environment, such as the size of hold in climbing, assuming that big holds are easier to grasp, whereas large flat or round holds might be complex to grasp with one hand. Therefore, exploring different ways of grasping holds of different shapes (and not only of different dimensions), beginners could search for 'grasp-able' holds (according to their action capabilities). With practice, advanced performers discover the functional properties of holds as they learn to explore the hold 'grasp-ability' based on different sizes, shapes, orientation, and set at different distances from each other. Finally, skilled performers explore efficiently 'grasp-ability' of holds as they do not perceive holds separately (one by one), but rather as a sequence of holds, meaning that they perceive how to chain actions to transit between holds. Doing so, they perceive an additional functional property that is the 'use-ability' of a hold.

Second, with practice, learners *discover task solutions* and *stabilize* them during goal-directed performance by reorganizing movement system components. This process consists of *education of attention*. Without changing their intentions, learners become *perceptually attuned* to more useful informational variables. According to Jacobs and Michaels (2007), attention is effectively educated by learners detecting informational variables that specify environmental properties that they intend to perceive. In other words, learners converge from relying on sources of information that may be only partly useful in one situation (i.e., non-specifying) to sources of information that are more useful (i.e., specifying), under a variety of circumstances. Therefore, this stage includes the *stabilization of discovered performance solutions* but also the *exploration of the limits of these solutions* and consequently the *search for new information-movement couplings* (Davids et al., 2012). Hence at the second stage, the learner's objective is to gain better organisation of a movement solution. With better organisation comes temporary stabilization of preferred information-movement couplings and thus more consistency in achieving the desired task outcome. However, it is relevant to highlight that

absolute movement stabilization is not the goal. Instead, an effective balance between stability and flexibility is desirable. With the discovery of a (stable) solution, the learner can choose between *stability* (i.e., persistent behaviours) and *flexibility* (i.e., variable behaviours) when appropriate (Seifert et al., 2013; Warren, 2006).

Third, in the *exploitation* stage, learners become attuned to a wider range of informational variables that more precisely specify how to move effectively (Jacobs & Michaels, 2007). This process is called *calibration* and corresponds to scaling the perceptual-motor system to information. Withagen and Michaels (2002) hypothesized that calibration of behaviour is functionally organized, meaning that calibration is dedicated, not to the anatomical structures used in performing the behaviour, but to the function that a performance behaviour serves. At this final stage, the learner is becoming very efficient in exploiting movement system degeneracy for an immediate adaptation to situational demands and effective goal achievement. For example, elite tennis players, when playing on clay courts, use the clay surface to slide and break their locomotion and adjust their posture to hit the ball back with direction, power and timing.

These three stages of learning do not follow a linear improvement of performance and motor behaviour (i.e., qualitative changes of movement coordination pattern). Instead, it has been observed that *exploration* of new motor behaviour (early in learning) could alternate with *exploitation* and refinement of motor behaviour, reflecting an intermittent regime of performance (also called ‘meta-stable’ regime) (Hristovski et al., 2006; Kelso, 2012; Seifert et al., 2015). Meta-stability facilitates transitions between different coordination tendencies, enabling adaptation to surrounding constraints and the discovery of more functional performance solutions (Kelso, 2012). In a meta-stable region, learners can transit from stable performance behaviours to explore new movement opportunities, supporting exploration during motor learning (Komar et al., 2023; Seifert et al., 2015). Exploration through a meta-stable regime may emerge abruptly or gradually, with potential transitions between initial behaviours and developing possibilities until a new stable coordination pattern is established (Komar et al., 2023). For instance, Seifert et al., (2015) have shown how to design meta-stable performance regimes to facilitate destabilization of pre-existing skills and safe exploration (to avoid falling) in climbing. Findings confirmed that the double-edge route (affording both horizontal and vertical grasping patterns) corresponds to a meta-stable performance region favouring ‘safe’ exploration to learn because the learners reverted to a stabilized movement pattern (Seifert et al., 2015). Therefore, exploration appears less risky, and the learner is more attracted to exploratory activities. In return, the results of the transfer test confirmed that designing a meta-stable region of performance favoured functional and adaptive behaviours, because climbers learn to explore and, subsequently, use effective exploratory strategies that can facilitate transfer of learning to performance in novel climbing environments (Seifert et al., 2015). These findings confirmed expectations of the effectiveness of a balanced strategy of exploration and exploitation (or stabilization) to facilitate transfer in the perceptual-motor workspace (Pacheco & Newell, 2015).

Exploration is indeed visible when different coordination patterns are tracked trial to trial throughout a learning period. There is a need to quantify transitions between those coordination patterns during learning and most importantly to quantify how certain patterns become dominant for some time and how they can be adapted or disappear later. Recent research has modelled the evolution of transitions between coordination patterns, based on the probabilities of appearance of each pattern at each point of time during learning. This approach used Drift Markov Modelling (DMM) to investigate exploratory processes, and modelled the meta-stable regime of performance in motor learning (Seifert et al., 2024). Using

DMM, Komar et al. (2023) identified three dynamics of learning arm-leg coordination in breaststroke swimming: 1) the appearance of new coordination patterns, 2) the disappearance of the initial/beginner coordination patterns, and 3) the exploratory dynamics with successive appearance/disappearance of coordination patterns, corresponding to a metastable regime with few coordination patterns that are neither stable, nor really unstable. In another study about the dynamics of visual-motor skill acquisition in a climbing task, DMM has been used to model how the visual system meets two demands simultaneously: the online control of a current movement (e.g., grasping a hold), and the anticipatory search for environmental constraints (e.g., the route path) that may shape future movements (Kalligeris et al., 2024). DMM modelling showed how learners alternated between online control of movement (when learners seek a hold, they attempt to grasp the surface in a most effective way: perceiving to act) and proactive control of movement (when learners search the route path to chain actions in a fluent way: acting to perceive) (Hacques et al., 2022).

3.2. Sport Expertise

Research within ecological dynamics has investigated the functional role of movement coordination variability used for task goal achievement, suggesting that more skilled athletes exhibit: 1) better adaptability (subtle blend of stability and flexibility); 2) better exploitation of degeneracy properties and multi-functionality in the movement system; 3) better decision making among modes of action (skilled athletes master more complex modes of action); 4) seek a concatenation of affordances in a dynamic assembly of overall action sequences; 5) better transfer of skill and of learning.

Previous research has provided evidence for the adaptive and functional role of movement and coordination variability in satisfying interacting constraints (e.g., Davids et al., 2006). Evidence suggests that experts exhibit more adaptive behaviours, signifying that the perceptual motor system is stable when needed, and flexible when relevant. Indeed, both *stability* and *flexibility* are essential to skilled performance under different constraints, because it reflects adaptability (Warren, 2006). *Adaptability* refers to adapted behaviour to a set of constraints, revealing stability against environmental perturbations. Adaptive behaviours reflect flexibility to facilitate functional performance solutions to emerging constraints that dynamically interact. For instance, if the task goal for an icefall climber is to anchor their ice axes in the ice surface, they can demonstrate modes of functional stability, by ‘swinging’ ice axes against the icefall to create specific anchorages. But if the existing holes and structure of an icefall already provides support, an ice climber can demonstrate functional flexibility by searching to ‘hook’ the ice axes into the existing surface structure which affords support on the ice surface (Seifert, Wattebled, et al., 2014). Such adapted behaviours are characterized by stable and reproducible movement patterns. These patterns are stable functional forms of movement that are consistent over time, resistant to perturbations, reliable and reproducible, and a relatively similar pattern may emerge under different task and environmental constraints. It is important to note that movement behaviours are not stereotyped and rigid, but flexible (i.e., adaptive). Although movement coordination patterns can reveal regularities and similarities within their structural components, skilled ice climbers are not fixed into rigidly stable solutions but can adapt movement coordination patterns in a functional way, exploiting system degeneracy. Although both less-skilled and skilled ice climbers could hook their blades in existing holes of the icefall, only elite ice climbers are calibrated to useful informational variables (i.e., deep holes; holes orientated downward; holes surrounded by solid ice), perceived to support actions (Seifert, et al., 2014). Therefore, when a hole is deep, skilled ice

climbers hook it, whereas when a hole looks small and surrounded by fragile ice, they swing their ice axes beforehand to carve out a stable hold. In summary, to achieve a similar function (i.e., anchoring the blade of the ice axis), skilled ice climbers exploit perceptual-motor system degeneracy (Seifert et al., 2014).

Research reveals that more skilled athletes are better able to exploit system degeneracy as they are better attuned and calibrated than less skilled athletes to relevant informational variables for action. Also, more skilled athletes have broader effectivities or a skills repertoire and higher maximal skill levels (action capabilities) (Seifert et al., 2021; Vauclin et al., 2024), allowing them to flexibly switch quickly between different perceptual-motor solutions. Indeed, in climbing tasks of various complexity (i.e., reach to touch, reach to grasp, reach and remove, reach to move up), more skilled climbers demonstrate greater maximal reaching distance in more complex tasks than less skilled climbers (Seifert et al., 2021). Similarly, in a crossing aperture task by bike, more skilled cyclists can cross narrower apertures than less skilled cyclists (Vauclin et al., 2024). However, when accuracy of calibration of action to information was scaled to maximal action capabilities, less skilled climbers (Seifert et al., 2021) and cyclists (Vauclin et al., 2024) were not less accurate than more skilled athletes as they did not act further away from their action boundaries and they did not overestimate their action capabilities. These findings are elucidating, because in climbing and cycling, risk of falling could lead to injury and accident; therefore, regardless of athlete skill level, they seemed to engage in the task by locating a safety margin.

Degeneracy of neurobiological systems invites us to reconsider the role of behavioural variability in performance and expertise. Degeneracy supports adaptive flexibility because it underlies system *multi-functionality* (Kelso, 2012) or *pluri-potentiality* (Mason, 2010), a property that ensures an organism's functional ongoing engagement with the performance environment. *Multi-functionality or pluri-potentiality* corresponds to structures (e.g., movement coordination patterns) that can become mobilized under one set of constraints, but which may potentially become even more mobilized under another set of constraints (Mason, 2010). For example, Seifert et al. (2014) manipulated task constraints for individuals swimming with the front crawl for 200m by constraining the glide duration; notably, they investigated behavioural adaptations during performance in a freely-chosen condition of the glide with arms, compared to conditions when maximal and minimal glide durations were specified for performers. Interestingly in a maximal glide duration condition, swimmers were able to increase their leg beat-kicking up to unexpected 10 beat kicks (whereas 2, 4 and 6 beat kicks are the most common observed patterns) to functionally compensate for the long glide phase with their arms (Seifert, Komar, et al., 2014).

Research on experienced decision-making has revealed that skilled football players' performance on video-based tests does not appear to predict on-field decision-making (van Maarseveen et al., 2018). This could be because decision-making expressed by action on-field is grounded in a performer's skills. For example, Paterson et al., (2013) required skilled footballers to judge their intended action prior to an on-field free-kick execution and for a video-simulation of this task in a laboratory. Results revealed that participants were more cautious during the on-field task, indicating that they would strive towards more challenging goal locations in the video task, compared to the on-field condition. Moreover, even though participants selected apparently easier decisions on-field, the success of players to execute kicks to their intended location only occurred on about 25% of trials. From an ecological dynamics perspective, decision making during performance emerges in a landscape of attractors (stable system states), which reflect different potential task solutions (Araújo et al., 2006, 2009). Athletes search the task landscape so that a viable option selected is the strongest

attractor at a given moment, with other options having less strength of attraction. For example, Hristovski, Davids, Araújo, et al., (2006) demonstrated that decision making of boxers, leading to the utilization of variable punching actions, was adapted as the distance from the opponent (punchbag) changed. Further from the punchbag (~1.2 m), boxers were attracted towards the execution of a jab punch. Closer to the punchbag, left and right hooks tended to emerge. Moreover, a critical distance was observed (~0.6 m), that was referred to as a ‘metastable’ region, where boxers were able to integrate, and smoothly transition between, a combination of different punches. Hristovski, Davids, Araújo, et al., (2006) highlighted that, in any given instance, the environment is not an attractor landscape of *neutral* action possibilities. Affordances are relational and, therefore, accessible to individuals with the abilities to act on them. Possibly, affordances are selected based on information for the next affordance (Araújo et al., 2019). In tennis, Carvalho et al., (2014) studied how sequential behaviours, expressed as successive strokes in a rally, were based on conditionally-coupled affordances. A goal-directed displacement index was developed as an eco-physical measure to simultaneously consider the distance of competing players in relation to two on-court reference points: the central line of the court and the net during competitive performance. A player with an advantage is perceiving and creating affordances for the other (Fajen et al., 2009), where the other is invited (pressured) to act upon such affordances, since they are open and responsive to play in the rally. The stability of the interactions between players is highly constrained by the co-adaptations (co-positioning) of the players (near or away from the central line of the court, or from the net) and the pattern of interactions developed during play (cross-court or down-the-line rallies). In this performance environment, a player with an advantage tries to create a successively more unstable context for the other player to de-stabilize the existing spatial-temporal coordination between them (Carvalho et al., 2013).

3.3. Transfer and representative learning design

Generalized transfer of skill refers to the influence of prior experiences under a particular set of interacting constraints on performance or learning in a new performance environment. Transfer could be positive or negative (i.e., an individual achieves respectively a higher or lower performance level in the new context). Transfer is often conceived on a continuum from ‘near’ to ‘far’ task transfer, based on the degree of similarity between one task and another, or degree of similarity between a new skill and one already learned (Button et al., 2020; Oppici & Panchuk, 2022). In ecological dynamics, transfer can be better captured by a ‘specific’ to ‘general’ continuum, and not just by a ‘near’ to ‘far’ continuum (Button et al., 2020; Oppici & Panchuk, 2022; Seifert et al., 2016). While near-far transfer continuum considers exclusively skill transfer between two task-goals or two skills, the specific-general continuum considers the coupling between the abilities and the intended task goal within the current environment. Specific transfer is predicated on attunement to specifying information (i.e., information that specifies goal-relevant affordances). General transfer emerges when actions are regulated with non-specifying informational variables (Button et al., 2020; Oppici & Panchuk, 2022; Seifert et al., 2016). In other words, what transfers is an athlete’s ability to *attune* their perception and action to task dynamics. In fact, the transfer of learning implies transfer of both *attunement* and *calibration* to the new context. The *transfer of attunement* has been presented as the ability to detect information with different action systems (de Vries et al., 2015) or as the ability to detect and exploit reliable information to guide action in different contexts of performance (Huet et al., 2011). When learners’ attention during practice is directed toward reliable information, this attunement facilitates the transfer of a perceptual

motor performance to new contexts, even when available information is less reliable.

Regarding the *calibration* process in learning, an individual might *recalibrate* their actions, meaning that they may rescale the perceptual motor system following a disturbance that makes coupling of perception and action less functional (Brand & de Oliveira, 2017). The perceptual-motor system needs to be recalibrated when an individual's action capabilities or body dimension changes over short or long timescales or when perception is altered. However, the individual might also *transfer calibration*, which occurs when the re-organisation of perception-action coupling in one action transfers to another action (Brand & de Oliveira, 2017). *Recalibration* and *transfer of calibration* requires exploratory activity that is effective, only if individuals are attuned to relevant information. The source of information was still available after disturbance if the perceptual-motor skill had been thoroughly learned. Seifert et al. (2016) tested whether *recalibration* occurred functionally between indoor climbing walls where fingers and feet are used to support body weight in icefall environments in which ice axes are adjusted to support and control body weight and use of extremities for ascent. One can expect that *generality* of transfer between previous experiences on an indoor climbing wall and performance on an icefall to be obvious, as in both climbing environments, climbers have to control body weight with respect to the environmental constraint of gravity, and use limb extremities (Seifert et al., 2016). However, *specific* transfer involves a highly coupled performer-environment system, such as the complex system made up of climber, ice tools, and icefall, which does not emerge in indoor climbing. In ice climbing, these tools are used by ice climbers to explore the physical properties specific to the icefall environment (density and thickness) in order to estimate ice fragility (Seifert et al., 2016; Seifert, Wattebled, et al., 2014).

In traditional approaches to learning design, arguably too much emphasis has been placed on practice tasks structured for the repetitive reproduction of specific *actions* (Button et al., 2020). For example, learners are typically taught to swim in comfortable, clear and calm aquatic environments (Kjendlie et al., 2013), mainly for safety and logistical reasons. However, such physical education approaches fail to simulate the varied environmental constraints, such as currents, tides, cold temperatures, weather or waves (i.e., major determinants of aquatic environments), characteristic of open water environments (Guignard, Button, et al., 2020). The specific-general transfer continuum was neatly illustrated by Oppici and Panchuk (2022) within a pertinent example. They suggested that specific transfer from a pool to open water may be observed as an experienced pool-swimmer typically adopts a streamlined position in open water to minimise drag and propel themselves forcefully in a desired direction. As the swimmer practices in open water, they may also learn to utilise non-specifying information invoking a more general form of transfer (or 'attunement to surrounding affordances'). Hence specific and general forms of skill transfer interact, which helps us to understand why some water safety skills (like floating or swimming) in open water can be challenging for pool-trained learners. Ecological dynamics, underpinning principles of nonlinear pedagogy, promotes the design of representative tasks in which learners can acquire foundational aquatic skills that they need to transfer to varied outdoor environments, typically presenting a richer range of affordances than indoor swimming pools (Button et al., 2023).

Moreover, *attunement* and *calibration* of the perceptual-motor system to reliable information appears to be a prerequisite for any form of transfer from one environment to another. If this prerequisite is respected, the quantity of exploratory activity necessary to adapt actions to the new environment depends on the intensity and nature of the disturbance. To test this hypothesis, Hacques et al. (2021) designed a learning protocol in a climbing task with a complex route path soliciting learners to explore functional ways to grasp climbing holds and to chain grasping actions. This learning protocol was investigated in three transfer routes

manipulating either the distance between handholds, the orientation of the handholds or handholds shape (Figure 1). Findings revealed that learners can effectively adapt climbing actions when new properties (*Distance route*) invite superficial adaptation (refinement of climbing actions). But there was less adaptation of climbing actions when new properties (*Orientation route*) induced deep behavioural adjustments (e.g., different grasping actions, different postures) (Hacques et al., 2021).

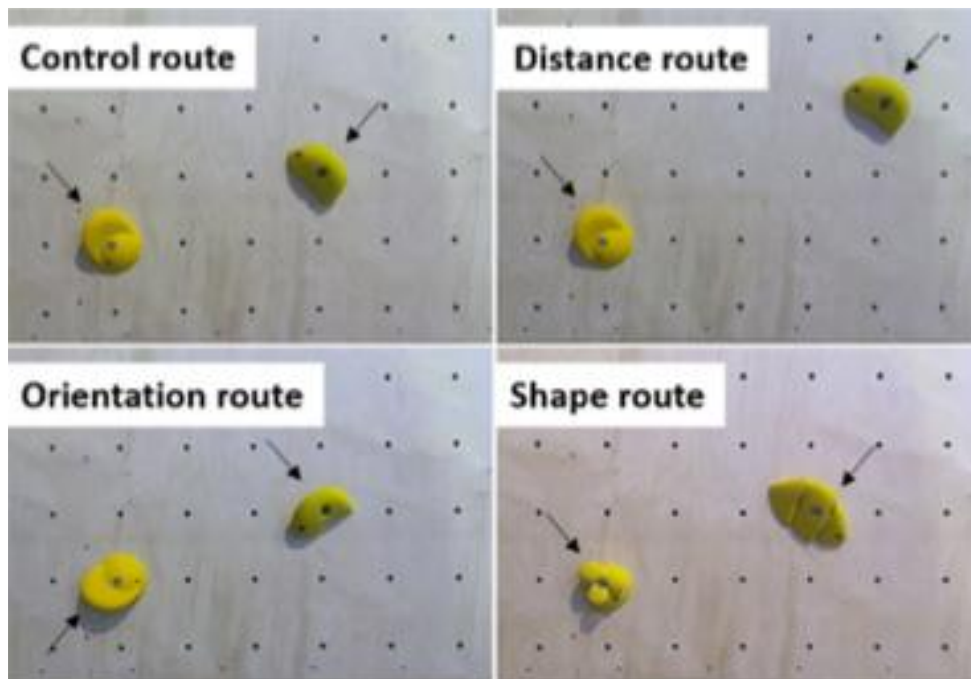


Figure 1. Manipulation of the handholds to create the transfer routes. The arrows indicate the preferential grasping enabled by the handhold.

In conclusion, to facilitate generalization or transfer from one environment (e.g., training session) to another environment (e.g., competition), practitioners should develop expertise in manipulating task constraints to support exploration of a new task to be performed and the exploitation of pre-existing behavioural patterns in their repertoire.

4. 'Talent'

An ecological dynamics approach conceptualizes 'talent' as a continuous refinement of a functional (goal-directed) relationship between an individual and a performance environment (Araújo & Davids, 2011a, Araújo et al., 2023). 'Talent', and consequently, sport skill can be refined through practice designs that emphasize *discovery* and *exploitation* of functional action solutions in a varied field of affordances to improve an individual's performance effectiveness. *Less structured* and *informal play*, games and practice activities might help to develop athletic potential in beginners, including children. It is important to recognise the need for children to play and engage in more general sports experiences and activities which form a crucial part of learning and development in the young of all species, including humans.

Ecological dynamics also stresses the importance of *early diversification* of practice experiences in children and youth, exposing learners to a rich variety of structured and unstructured games and play activities to develop them as individuals first, enhancing their

potential to engage athletically with different performance contexts, prior to the selection of a main sport at a later stage of childhood (Davids et al., 2017). Once an athlete, labeled as ‘talented’ starts to participate in a sport domain, there begins an intense socialization process where training, evaluation, institutionalization and framing takes place for continued development of skill. This is the formalized process of working on ubiquitous skills refining and refining them into sport skills. And this process differs from one sport to another. Practicing multiple sports during career development further explains that skill learning is not simply about potentiality, but also actuality (Araújo et al., 2023), i.e., how learning is expressed in contextualized expert performance.

Early identification, selection and specialisation models provide a brief snapshot of tendencies at a particular phase of development in a *nonlinear dynamical perception-action system*, changing through infancy and childhood into adolescence and beyond into adulthood and older age. Results of ‘talent’ identification assessments and tests administered at one point in time should be viewed as a temporary estimate of correlates for performance which might shed light on learning, but which will change because of the inherent nonlinearity in all human movement systems (Davids et al., 2017). Predictions on the likelihood of elite performance emerging in developing athletes are speculative due to the nonlinearity of human behaviours which are continuously shaped by interacting task, environmental and individual constraints. Ecological dynamics has emphasised the *continuous development* of potential in athletes throughout childhood and into adulthood, providing them with a range of less structured and more structured learning opportunities to develop perception and action tendencies and capacities to engage with dynamic performance environments.

5. Conclusion and practical implications

To summarize, ecological dynamics is an integrated framework with significance for understanding sport performance and human movement. Tenets of ecological dynamics can be investigated along three timescales: (1) Behaviour and performance; (2) Learning, expertise and transfer; (3) ‘Talent’ in sport. The practical implications of ecological dynamics invite movement practitioners to reconceive motor learning as a nonlinear process. Practitioners need to continuously work on enhancing an individual’s functionality of interactions with a performance environment through the process of *skill adaptation*. Skill adaptation may drive learners to engage more successfully with specific task dynamics. Five core principles of Nonlinear Pedagogy are: representativeness, constraints manipulation, informational constraints, task simplification, and functional variability (Chow et al., 2021). Educating practitioners’ own intentionality for ensuring that practice represents a performance environment, helps a learner to attune to relevant affordances for learning. Understanding and manipulating key constraints requires athletes to explore their perceptual and physical boundaries to satisfy task goals. Improving a performer’s awareness of key informational constraints supports them in directly modify their behaviours, enriching their capacity to engage with each practice context which they encounter. Through task simplification, practitioners can help to highlight key perception-action couplings appropriate to an athlete and promote an active form of problem-solving which is not encouraged when athletes are heavily instructed. Finally, and critically, when practitioners respect and promote functional movement variability, it helps an athlete to thoroughly explore the perceptual-motor workspace and not to be trapped in reproducing stable solutions that may not be suitable throughout their lifespans.

References

- Araújo, D., & Davids, K. (2011a). Talent development: From possessing gifts, to functional environmental interactions. *Talent Development and Excellence*, 3, 23–26.
- Araújo, D., & Davids, K. (2011b). What Exactly is Acquired During Skill Acquisition? *Journal of Consciousness Studies*, 18, 3(4), 7-23-7–23.
- Araújo, D., & Davids, K. (2018). The (Sport) Performer-Environment System as the Base Unit in Explanations of Expert Performance. *Journal of Expertise*, 1(3), 144–154.
- Araújo, D., Davids, K., Chow, J., & Passos, P. (2009). The development of decision making skill in sport: An ecological dynamics perspective. In *Perspectives on Cognition and Action in Sport* (Araújo, D, Raab, M, Ripoll, H, pp. 157–170). Nova Science Publishers.
- Araújo, D., Davids, K., & Hristovski, R. (2006). The ecological dynamics of decision making in sport. *Psychology of Sport and Exercise*, 7(6), 653–676.
<https://doi.org/10.1016/j.psychsport.2006.07.002>
- Araújo, D., Davids, K., & Renshaw, I. (2020). Cognition, Emotion and Action in Sport. In *Handbook of Sport Psychology* (pp. 535–555).
<https://doi.org/10.1002/9781119568124.ch25>
- Araújo, D., Dicks, M., & Davids, K. (2019). Selecting among affordances: A basis for channeling expertise in sport. In *Handbook of embodied cognition and sport psychology*. (pp. 557–580). The MIT Press.
- Araújo, D., Hristovski, R., Seifert, L., Carvalho, J., & Davids, K. (2017). Ecological cognition: Expert decision-making behaviour in sport. *International Review of Sport and Exercise Psychology*, 12(1), 1–25. <https://doi.org/10.1080/1750984X.2017.1349826>
- Araújo, D., Roquette, J., & Davids, K. (2023). Ubiquitous skill opens opportunities for talent and expertise development. *Frontiers in Sports and Active Living*, 5, 1181752.
<https://doi.org/10.3389/fspor.2023.1181752>
- Boschker, M. S. J., Bakker, F. C., & Michaels, C. F. (2002). Memory for the functional characteristics of climbing walls: Perceiving affordances. *Journal of Motor Behavior*, 34(1), 25–36. <https://doi.org/10.1080/00222890209601928>
- Brand, M. T., & de Oliveira, R. F. (2017). Recalibration in functional perceptual-motor tasks: A systematic review. *Human Movement Science*, 56(Part B), 54–70.
<https://doi.org/10.1016/j.humov.2017.10.020>
- Button, C., Seifert, L., Chow, J., Araújo, D., & Davids, K. (2020). *Dynamics of skill acquisition* (2nd edition). Human Kinetics Publisher.
<https://uk.humankinetics.com/products/Dynamics-of-Skill-Acquisition-2nd-Edition?variant=13580990316619>
- Button, C., van Duijn, T., Cocker, K., Trotter-Dunn, G., & Seifert, L. (2023). Does a combined swimming pool and open water education programme for children develop adaptable water safety competencies? *Journal of Sport and Exercise Science*, 7(2), 18–28.
<https://doi.org/10.36905/jses.2023.02.03>
- Carvalho, J., Araújo, D., Travassos, B., Esteves, P., Pessanha, L., Pereira, F., & Davids, K. (2013). Dynamics of players' relative positioning during baseline rallies in tennis. *Journal of Sports Sciences*, 31(14), 1596–1605.
<https://doi.org/10.1080/02640414.2013.792944>
- Carvalho, J., Araújo, D., Travassos, B., Fernandes, O., Pereira, F., & Davids, K. (2014). Interpersonal Dynamics in Baseline Rallies in Tennis. *International Journal of Sports Science & Coaching*, 9(5), 1043–1056. <https://doi.org/10.1260/1747-9541.9.5.1043>
- Chow, J. Y., Davids, K., Button, C., Rein, R., Hristovski, R., & Koh, M. (2009). Dynamics of multi-articular coordination in neurobiological systems. *Nonlinear Dynamics*,

Psychology, and Life Sciences, 13(1), 27–55. <http://www.ncbi.nlm.nih.gov/pubmed/19061544>

Chow, J. Y., Davids, K., Button, C., & Renshaw, I. (2021). *Nonlinear Pedagogy in Skill Acquisition An Introduction* (Routledge, Taylor&Francis).

Correia, V., Araújo, D., Cummins, A., & Craig, C. M. (2012). Perceiving and acting upon spaces in a VR rugby task: Expertise effects in affordance detection and task achievement. *Journal of Sport and Exercise Psychology*, 34(3), 305–321.

<https://doi.org/10.1123/jsep.34.3.305>

Davids, K., & Araújo, D. (2010). The concept of ‘Organismic Asymmetry’ in sport science. *Journal of Sports Sciences*, 13(6), 633–640.

<https://doi.org/10.1016/j.jsams.2010.05.002>

Davids, K., Araújo, D., Hristovski, R., Passos, P., & Chow, J. Y. (2012). Ecological dynamics and motor learning design in sport. In N. J. Hodges & A. M. Williams (Eds.), *Skill acquisition in Sport: Research, theory and practice* (2nd Editio, pp. 112–131). Routledge.

Davids, K., Araújo, D., Seifert, L., & Orth, D. (2015). Expert performance in sport: An ecological dynamics perspective. In J. Baker & D. Farrow (Eds.), *Handbook of Sport Expertise* (pp. 273–303). Taylor & Francis.

Davids, K., Bennett, S. J., & Newell, K. M. (2006). *Movement System Variability* (K. Davids, S. J. Bennett, & K. M. Newell, Eds.). Human Kinetics.

Davids, K., Güllich, A., Araújo, D., & Shuttleworth, R. (2017). Understanding environmental and task constraints on athlete development: Analysis of micro-structure of practice and macro-structure of development histories. In *Routledge handbook of talent identification and development in sport* (J. Baker, S. Cobley, J. Schorer&N. Wattie, pp. 192–206). Routledge, Taylor & Francis Group.

Davids, K., Hristovski, R., Araújo, D., Balague Serre, N., Button, C., & Passos, P. (2014). *Complex systems in sport*. Routledge, Taylor & Francis Group.

de Vries, S., Withagen, R., & Zaal, F. T. J. M. (2015). Transfer of attunement in length perception by dynamic touch. *Attention, Perception, and Psychophysics*, 77(4), 1396–1410.

<https://doi.org/10.3758/s13414-015-0872-y>

Edelman, G. M., & Gally, J. a. (2001). Degeneracy and complexity in biological systems. *Proceedings of the National Academy of Sciences of the United States of America*, 98(24), 13763–13768. <https://doi.org/10.1073/pnas.231499798>

Fajen, B. R., Riley, M. A. R. A., & Turvey, M. T. (2009). Information, affordances, and the control of action in sport. *International Journal of Sports Psychology*, 40(1), 79–107.

Gibson, J. (1979). *The ecological approach to visual perception*. Houghton Mifflin.

Guignard, B., Button, C., Davids, K., & Seifert, L. (2020). Education and transfer of water competencies: An ecological dynamics approach. *European Physical Education Review*, 26(4) 938–953. DOI: 10.1177/1356336X20902172

Guignard, B., Rouard, A., Chollet, D., Bonifazi, M., Dalla Vedova, D., Hart, J., & Seifert, L. (2020). Coordination Dynamics of Upper Limbs in Swimming: Effects of Speed and Fluid Flow Manipulation. *Research Quarterly for Exercise and Sport*, 91(3), 433–444. <https://doi.org/10.1080/02701367.2019.1680787>

Guignard, B., Rouard, A., Chollet, D., Hart, J., Davids, K., & Seifert, L. (2017). Individual–Environment Interactions in Swimming: The Smallest Unit for Analysing the Emergence of Coordination Dynamics in Performance? *Sports Medicine*, 47(8). <https://doi.org/10.1007/s40279-017-0684-4>

Hacques, G., Dicks, M., Komar, J., & Seifert, L. (2022). Visual control during climbing: Variability in practice fosters a proactive gaze pattern. *PloS One*, 17(6), e0269794. <https://doi.org/10.1371/journal.pone.0269794>

- Hacques, G., Komar, J., Dicks, M., & Seifert, L. (2020). Exploring to learn and learning to explore. *Psychological Research*. <https://doi.org/10.1007/s00426-020-01352-x>
- Hacques, G., Komar, J., & Seifert, L. (2021). Learning and transfer of perceptual-motor skill: Relationship with gaze and behavioral exploration. *Attention, Perception, & Psychophysics*, 83(5), 2303–2319. <https://doi.org/10.3758/s13414-021-02288-z>
- Hristovski, R., Davids, K., Araújo, D., & Button, C. (2006). Hox boxers decide to punch a target: Emergent behaviour in nonlinear dynamical movement systems. *Journal of Science and Medicine in Sport*, 5, 60–73.
- Huet, M., Jacobs, D. M., Camachon, C., Missenard, O., Gray, R., & Montagne, G. (2011). The education of attention as explanation of variability of practice effects: Learning the final approach phase in a flight simulator. *Journal of Experimental Psychology. Human Perception and Performance*, 37(6), 1841–1854. <https://doi.org/10.1037/a0024386>
- Jacobs, D. M., & Michaels, C. F. (2007). Direct Learning. *Ecological Psychology*, 19(4), 321–349. <https://doi.org/10.1080/10407410701432337>
- Kalligeris, E. N., Barbu, V. S., Hacques, G., Seifert, L., & Vergne, N. (2024). Unveiling the Persistent Dynamics of Visual-Motor Skill via Drifting Markov Modeling. *Nonlinear Dynamics, Psychology, and Life Sciences*, 28(4), 431–447.
- Kelso, J. A. S. (2012). Multistability and metastability: Understanding dynamic coordination in the brain. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 367(1591), 906–918. <https://doi.org/10.1098/rstb.2011.0351>
- Kjendlie, P.-L., Pedersen, T., Thoresen, T., Setlo, T., Moran, K., & Stallman, R. K. (2013). Can You Swim in Waves? Children's Swimming, Floating, and Entry Skills in Calm and Simulated Unsteady Water Conditions. *International Journal of Aquatic Research and Education*, 7(4). <https://doi.org/10.25035/ijare.07.04.04>
- Komar, J., Seifert, L., Vergne, N., & Newell, K. M. (2023). Narrowing the coordination solution space during motor learning standardizes individual patterns of search strategy but diversifies learning rates. *Scientific Reports*, 13(1), 2009. <https://doi.org/10.1038/s41598-023-29238-z>
- Mason, P. H. (2010). Degeneracy at Multiple Levels of Complexity. *Biological Theory*, 5(3), 277–288.
- Newell, K. M. (1986). Constraints on the development of coordination. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor development in children. Aspects of coordination and control* (pp. 341–360). Martinus Nijhoff.
- Newell, K. M. (1996). Change in movement and skill: Learning, retention and transfer. In M. L. Latash & M. T. Turvey (Eds.), *Dexterity and its development* (pp. 393–430). Erlbaum.
- Oppici, L., & Panchuk, D. (2022). Specific and general transfer of perceptual-motor skills and learning between sports: A systematic review. *Psychology of Sport and Exercise*, 59, 102118. <https://doi.org/10.1016/j.psychsport.2021.102118>
- Pacheco, M. M., Lafe, C. W., & Newell, K. M. (2019). Search strategies in the perceptual-motor workspace and the acquisition of coordination, control, and skill. *Frontiers in Psychology*, 10, 1–24. <https://doi.org/10.3389/fpsyg.2019.01874>
- Pacheco, M. M., & Newell, K. M. (2015). Transfer as a function of exploration and stabilization in original practice. *Human Movement Science*, 44, 258–269. <https://doi.org/10.1016/j.humov.2015.09.009>
- Paterson, G., van der Kamp, J., Bressan, E., & Savelsbergh, G. J. P. (2013). The effects of perception-action coupling on perceptual decision-making in a self-paced far aiming task. *International Journal of Sport Psychology*, 44, 179–196.

<https://doi.org/10.7352/IJSP2013.43.000>

Seifert, L., Araújo, D., & Davids, K. (2023). Avoiding organismic asymmetries in ecological cognition: Analysis of agent-environment couplings with eco-physical variables. *Adaptive Behavior*, 31(2), 163–168. <https://doi.org/10.1177/10597123221119690>

Seifert, L., Araújo, D., Komar, J., & Davids, K. (2017). Understanding constraints on sport performance from the complexity sciences paradigm: An ecological dynamics framework. *Human Movement Science*, 56(April), 178–180. <https://doi.org/10.1016/j.humov.2017.05.001>

Seifert, L., Boulanger, J., Orth, D., & Davids, K. (2015). Environmental Design Shapes Perceptual-motor Exploration, Learning, and Transfer in Climbing. *Frontiers in Psychology*, 6, 1819–1819. <https://doi.org/10.3389/fpsyg.2015.01819>

Seifert, L., Button, C., & Davids, K. (2013). Key properties of expert movement systems in sport: An ecological dynamics perspective. *Sports Medicine*, 43(3), 167–178. <https://doi.org/10.1007/s40279-012-0011-z>

Seifert, L., Dicks, M., Wittmann, F., & Wolf, P. (2021). The influence of skill and task complexity on perception of nested affordances. *Attention, Perception, and Psychophysics*, 83(8), 3240–3249. <https://doi.org/10.3758/s13414-021-02355-5>

Seifert, L., Kalligeris, E. N., Komar, J., Hacques, G., Barbu, V., & Vergne, N. (2024). The application of drifting Markov modelling to dynamics skill acquisition. In *Stochastic Modeling and Statistical Methods: Advances and Applications* (A. Karagrigoriou, S. Malefaki, I. S. Triantafyllou). Elsevier Science Publishers.

Seifert, L., Komar, J., Crettenand, F., & Millet, G. (2014). Coordination pattern adaptability: Energy cost of degenerate behaviors. *PloS One*, 9(9), e107839. <https://doi.org/10.1371/journal.pone.0107839>

Seifert, L., Wattebled, L., Herault, R., Poizat, G., Adé, D., Gal-Petitfaux, N., & Davids, K. (2014). Neurobiological Degeneracy and Affordance Perception Support Functional Intra-Individual Variability of Inter-Limb Coordination during Ice Climbing. *PloS One*, 9(2), e89865. <https://doi.org/10.1371/journal.pone.0089865>

Seifert, L., Wattebled, L., Orth, D., L’Hermette, M., Boulanger, J., & Davids, K. (2016). Skill transfer specificity shapes perception and action under varying environmental constraints. *Human Movement Science*, 48, 132–141. <https://doi.org/10.1016/j.humov.2016.05.004>

van Maarseveen, M. J. J., Oudejans, R. R. D., Mann, D. L., & Savelsbergh, G. J. P. (2018). Perceptual-cognitive skill and the in situ performance of soccer players. *Quarterly Journal of Experimental Psychology*, 71(2), 455–470. <https://doi.org/10.1080/17470218.2016.1255236>

Vauclin, P., Wheat, J., Wagman, J. B., & Seifert, L. (2023). A systematic review of perception of affordances for the person-plus-object system. *Psychonomic Bulletin Review*, 30(6), 2011–2029. <https://doi.org/10.3758/s13423-023-02319-w>

Vauclin, P., Wheat, J., Wagman, J. B., & Seifert, L. (2024). The effect of experience on the perception of affordances for aperture crossing in cycling. *Psychology of Sport and Exercise*, 74, 102698. <https://doi.org/10.1016/j.psychsport.2024.102698>

Warren, W. H. (2006). The dynamics of perception and action. *Psychological Review*, 113(2), 358–389. <https://doi.org/10.1037/0033-295X.113.2.358>

Withagen, R., de Poel, H. J., Araújo, D., & Pepping, G.-J. (2012). Affordances can invite behavior: Reconsidering the relationship between affordances and agency. *New Ideas in Psychology*, 30(2), 250–258. <https://doi.org/10.1016/j.newideapsych.2011.12.003>

Withagen, R., & Michaels, C. (2002). The calibration of walking transfers to crawling:

Are action systems calibrated? *Ecological Psychology*, 14, 223-234-223–234.