Individual-environment interactions in swimming: The smallest unit for analysing the emergence of coordination dynamics in performance?

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Abstract

Displacement in competitive swimming is highly dependent on fluid characteristics, since athletes use these properties to propel themselves. It is essential for sport scientists and practitioners to clearly identify the *interactions* that emerge between each individual swimmer and properties of an aquatic environment. Traditionally, the two protagonists in these interactions have been studied separately. Determining the impact of each swimmer's movements on fluid flow, and vice versa, is a major challenge. Classic biomechanical research approaches have focused on swimmers' actions, decomposing stroke characteristics for analysis, without exploring perturbations to fluid flows. Conversely, fluid mechanics research has sought to record fluid behaviours, isolated from the constraints of competitive swimming environments (e.g. analyses in two-dimensions, fluid flows passively studied on mannequins or robot effectors). With improvements in technology, however, recent investigations have focused on the emergent circular couplings between swimmers' movements and fluid dynamics. Here, we provide insights into concepts and tools that can explain these on-going dynamical interactions in competitive swimming within the theoretical framework of ecological dynamics.

Key points

- Swimming movements are characterised by continuous interactions between individuals and the aquatic environment: water is essential to progression, yet it also acts as a brake on swimmers' displacement.
- Ecological dynamics is a theoretical framework that provides concepts and tools to investigate the continuous coupling of performers and the performance environment in swimming, providing an indivisible entity for analysis.
- Key ideas in ecological dynamics (constraints and affordances) are highlighted to help coaches to design representative practice contexts for athletes that simulate competitive performance environments in swimming.

1. Introduction

In swimming, complex multi-articular actions must be coordinated in an aquatic environment that highly constrains locomotion (water is 800 times denser than air [1]). Swimmers propel themselves forward by organising actions in an environment offering both support and resistance; hence, propulsion is created by applying forces to the water and negotiating its fluid properties like density and viscosity [2]. To investigate propulsion and, more broadly, human behaviours in aquatic locomotion, scientists have traditionally focused *separately* on biomechanical analyses of actions in swimmers (using kinematic, kinetic and EMG measures), or on fluid motion properties (with experimental or numerical flow visualisations). However, propulsion cannot be understood in terms of either swimmer movements or fluid motion in isolation because it always emerges from the *interactions* between an individual swimmer's behaviours and the fluid dynamics. Yet these person-environment interactions are rarely analysed, highlighting an ambiguity in our current understanding of human movements more generally. In swimming they prompt questions like: 'What is moved during swimming?' and 'Who moves what?'. Possible responses might be: 'The water' or 'The swimmer' is moved or even 'The swimmer moves the water' or 'The water moves the swimmer' [3]. Trying to understand a swimmer's locomotion, without considering the impacts on fluid motion, can be as pernicious for performance investigations as would be the study of 'optimal fluid motion' without taking into account the swimmer's movements [4].

Anotherimportant goal in competitive swimming research is to elucidate strategies that swimmers use to exploit fluid motion as it emerges throughout their progression in the water: 'We need to learn more about the way the water reacts when we swim' [5]. The functional, interactive relations between a performer and a performance environment have yet to be studied in aquatic environments, perhaps due to the lack of an appropriate theoretical framework for interpreting this relationship and its robustness/flexibility in ecological performance environments. In this paper, we discuss ecological dynamics as a theoretical framework for understanding the nature of the continuous interactions between a swimmer and an aquatic environment [6,7].

According to ecological dynamics, performer–environment relationships are the smallest, relevant unit of analysis for understanding coordination and control in human behaviour [8-10]. This multidimensional framework has been shaped by research in several fields, and the findings have been integrated to explain human behaviours in sport performance, with major contributions from the theory of constraints on dynamical systems [11-13], ecological psychology [14], and the complex systems approach in neurobiology [15-17]. In his theory of *direct perception*, Gibson [14] argued that animals (i.e. humans) perceive and act on substances (e.g. water), surfaces (e.g. swimming pool walls), places (e.g. a swimming pool), objects (e.g. fins) and events (e.g. an open-water competition) in the environment, without needing to integrate representations of the world to perceive it [8]. This theory suggests that perception guides an athlete's actions and, in turn, his/her actions shape on-going perceptions (i.e. leading to a coupling of perception and action to support performance behaviours [7]). While performing, athletes perceive information for *affordances* (opportunities for action), which are used to achieve task goals, leading to a tight, cyclical relationship between the information picked up in a performance environment and the organisation of action [14]. Indeed, the perception of information for affordances (functional properties of the environment, specific to a performer's characteristics [18,19]) emerges as athletes become attuned to a performance environment, which indicates how athletic skill and expertise are enhanced in sport [20]. Affordances are predicated on the reciprocity of perception and action [19] (i.e. affordances must be perceived, perception must guide action, and actions are implicit in affordances {Adolph:2015ti}).

Behavioural transitions, and more broadly, the emergence, perturbation, stability/loss of stability in complex adaptive systems have been extensively studied in ecological dynamics [6,7,9]. This framework uses tools and concepts of dynamical systems theory to understand phenomena at an ecological scale of analysis (i.e. individual–environment interactions), supporting the idea that the way an individual interacts with his/her environment leads him/her to actualize or reject certain affordances in order to achieve a specific task goal [8]. At this level, laws of control have been identified to describe and capture system behaviours [8]. The key challenge of such an approach is to capture the most relevant *order parameter* that best describes the collective system dynamics of a performer acting in a performance environment [21]. The manipulation of *control parameters* –that is, nonspecific parameter(s) moving the system through a variety of state changes [22]– is a primary step in characterising the order parameters of a complex adaptive system [21] displaying self-organising tendencies [23] under a set of interacting constraints [13]. In complex nonlinear neurobiological systems, self-organisation is the principle by which "*temporal, spatial or spatial-temporal patterns evolve without being imposed on the system from the outside*" (p. 56) [11]. Thus, such an open system, composed of a multitude of elements (i.e. bones, muscles, joints, limb segments, etc.), will tend towards self-organisation to reduce its dimensionality and act functionally in performance environments for which it has evolved [24]. The emergence of functional behaviours is continuously shaped by three categories of constraints that can influence control parameters, which in turn can act on the system order parameters: organismic (i.e. relative to the individual characteristics of a performer), environmental (i.e. external physical and social constraints surrounding a performer) and task (i.e. relative to the specific goals of an activity) [13]. These constraints continually reduce the number of configurations that a complex adaptive system can adopt in a performance environment [25,26]. Consequently, appropriate manipulations of these constraints may prepare a performer to functionally respond to events in a competitive performance environment by exhibiting properties of *adaptability* [6]. Adaptability refers to the subtle blend between behavioural *stability* and *flexibility*, in the sense that stability is the robustness of behaviour under conditions of perturbation, and flexibility is the superficial refinement of behaviours to adjust to constraints. In dynamical systems, a slight modification in surroundings might lead to a substantial change in behaviours, called a bifurcation [11], exhibiting a transient *loss of system stability* that foreshadows the possible emergence of a new motor pattern. Because performers are sensitive to information surrounding them (for affordances under constraints), they can continuously adapt to coordinate actions [28].

In aquatic locomotion, each action that an athlete performs induces continuous specific fluid motions, and at the same time fluid motions constrain each athlete's on-going behaviours (i.e. due to the strong coupling between individuals and their environment). Since the information in the surrounding environment includes the swimmer's movements, an important challenge is to understand how modifications in a perceptual-motor landscape can perturb (or support) a swimmer's behaviour. These ideas suggest the complexity and usefulness of studying human behaviours during swimming locomotion from an ecological dynamics perspective. Sport biomechanics and fluid mechanics have provided fundamental knowledge that can be integrated within the ecological dynamics theoretical framework, warranting a critical literature analysis, focusing on: (i) the sensorimotor organisation of swimmers in aquatic environments, and (ii), the perturbations in fluid flows due to the presence or movements of swimmers. We consider key concepts of ecological dynamics in explaining coordination dynamics during human aquatic locomotion and demonstrate how these ideas provide an appropriate theoretical rationale to investigate the individual–environment system. Finally, practical implications for coaches and swimmers are described, suggesting how they might functionally manipulate constraints to facilitate the emergence of appropriate behaviours during interventions, based on the principle of representative learning design [29]. This principle governs the design of practice tasks that faithfully simulate the constraints of a competitive performance environment [29,30].

2. Swimmer's sensorimotor organisation in aquatic environments

It is generally agreed that the arm provides 70 to 85% of total propulsion in front crawl swimming [31,32], which has led to extensive research on upper limb kinematics and kinetics. When moving in the water, hands –and more generally the swimmer's body– encounter resistances caused by the differential in pressure between the front and back portion of the hands (or body) [33]. These resistances, known as *drag*, always emerge in the direction opposite to the line of movement [33,34]. A second force is applied to hands as they move through water: *lift*. This force is exerted perpendicular to the direction of drag [33,34] and, like drag, lift is caused by the pressure differential between the two sides of an object. When a hand progresses through water, water molecules will generally flow at a lower velocity under the hand than above it, creating the pressure differential that helps to raise the hand [2,34,35]. It is important to determine both drag and lift since the resultant force from these two components is propulsion [33].

One approach to determining lift is to consider the hand as a hydrofoil, with the dorsal side presenting a longer surface than the ventral side. This phenomenon has been explained by Bernoulli's theorem, which considers that pressure is inversely proportional to velocity [2]. Therefore, it might explain how lift emerges in human aquatic locomotion, since the tri-dimensional hand shape allows a pressure differential from high to low (a force from the ventral side of the hand/foil to the dorsal side). However, Bernoulli's theorem has been exclusively applied to studies of steady flows –that is, flows presenting an intact or attached boundary layer [33]. The boundary layer is the quantity of water molecules that is moving in contact with an object during its displacement. When the boundary layer separates (characteristic of *unsteady* flows), the conditions necessary for Bernoulli's theorem to suggest how lift is produced are no longer present. Clearly, a swimmer's passage will disturb fluid flows, perturbing molecules and causing unsteady water flows [33,36]. This insight emphasises the limitations of applying Bernoulli's theorem to understand aquatic locomotion, suggesting the need for further theoretical explanations of human propulsion in water.

Miyashita proposed that the propulsive forces that drive the swimmer forward are created by the swimmer's arms as they push water backwards [31]: according to Newton's third law of motion, every action is compensated by an equal and opposite reaction. To maximise forward motion, a swimmer should therefore produce high forces directed backwards [37] (i.e. the stronger the action produced in a backward direction, the higher the reaction obtained in a forward direction). Therefore, the best strategy for human aquatic locomotion would be to maintain the arm in an extended position throughout the underwater portion of the stroke (the paddle-wheel theory of propulsion according to Maglischo [33]). However, Counsilman [39] and Silvia [40] do not support a strict application of the action–reaction principle to enhance aquatic propulsion [38], rather, they noted that swimmers' hands followed an S-shaped pattern underwater. Schleihauf [41] provided videos of the arms three-dimensional pattern during a single stroke cycle: the hand moved successively downward, upward, under and beside the body. To measure propulsion differences generated during such a diagonal underwater pattern and motion directed exclusively backwards, Bixler [42] tested a hand/arm model. He demonstrated that the propulsive force swimmers produce with such S-shaped patterns was only slightly lower (8N) than the propulsive force they could produce during straight movements. These computer simulations revealed that, although similar levels of propulsion emerge from the two patterns, the distance covered by an arm underwater is greater for the diagonal action [42]. This was justified by the need to push inert masses of water and extend the duration of propulsive phases during the stroke [39].

Based on Bernoulli's theorem and Newton's third law of motion, researchers have attempted to divide the arm stroke into different phases [43] using multiple reference points such as arm/trunk angles, spatial parameters, and the angular velocity of the arm. The main issue was to distinguish the propulsive and non-propulsive phases of the arm stroke to establish the most effective propulsion when a swimmer interacts with water, notably by functionally coordinating the propulsion of the two arms [44,45]. To circumvent the indirect measurement of propulsion by using kinematics, several devices have been developed. For instance, Hollander et al. [46] proposed the measuring active drag (MAD) system, with swimmers pushing off from pads positioned below the water surface. Force transducers registered the swimmers' forces on the pads, but a major limitation of this analysis is that fluid behaviours were not considered since the swimmers gained support from these artificial fixed pads. Berger et al. [47] then evaluated the forces using an arm and hand model in a towing tank. Force transducers were appropriately used to evaluate arm drag and lift forces, but this passive assessment of propulsion still did not provide any information on the flow configurations that emerge during action. Later, Takagi and Wilson [48] investigated fluid pressures on a hand model and a real hand during a freestyle stroke performed in a flume. Recently, the pressure of water acting on the swimmers' hands (i.e. the perception of fluid flow) {Cesarini:2016vg, Ungerechts:2016un} has been registered by sensors and this signal was immediately transformed into sound played in a swimmer's ears, providing real-time auditory feedback. The sonar feedback system(pioneer work of Chollet et al. {Chollet:1992us}) fits the actions of the athlete, both during front crawl or breaststroke swimming {Cesarini:2016vg}. Consequently, it was possible to perceive from the sound that some of the movements performed by the swimmers were less coordinated or less symmetrical providing constructive insights for coaches to adapt future training sessions and swimmers to adapt their actions. Although these devices provide advanced methods to assess the generation of propulsion in water, they did not clearly investigate fluid flows and focused mainly on hand and arm kinetics.

From these kinematic and kinetic analyses of propulsion, unsurprisingly, little consensus has emerged on how swimmers should best place their arms and hands to effectively propel themselves forward. Bernoulli’s theorem, although initially promising for research in swimming propulsion, is too limited to explain motion in dynamic aquatic environments. In addition, the applicability of Newton’s third law of motion alone has not been fully demonstrated in the study of actions in an ecological performance context, suggesting a significant gap between theoretical analyses of propulsion and the provision of information on fluid flows that swimmers can use to organise their actions in water. The key point that bears repetition is that propulsive actions of an individual athlete in water induce fluid perturbations that need to be understood to optimise forward displacement in swimming.

3. Fluid perturbations from swimmer’s movement

Due to its physical properties, a fluid will deform continuously [49] when a shear force is applied (e.g. a foot kick or arm movement in swimming), even with a very low magnitude [50,51]. Each action a swimmer performs will, therefore, perturb fluid flows, which will in turn induce changes in surrounding energy flows, providing new perceptual information about the performance environment. Similarly, a sudden change in fluid dynamics may perturb a swimmer’s movements or offer new opportunities to interact (known as affordances in ecological dynamics) with the surrounding environment (exploiting available forces from vortices, lift, drag, and more generally intrinsic fluid properties, etc.). Since the relationship between an athlete and an aquatic environment is currently difficult to assess, numerous studies have manipulated the nonspecific *control parameters* of this system (e.g. flow speed [52], swimming depth [53,54]) to facilitate the study of aquatic locomotive behaviours.

For instance, an increase in flow velocity may cause transitions in fluid behaviours from laminar to turbulent states. When fluid particles move at low velocities, and in a constant straight-line trajectory, they can essentially be considered as moving in distinct layers or laminae. No cross-layer macroscopic mixing occurs [51], and the flow is considered laminar [49]. In contrast, *turbulent* flow has irregular and chaotic motions, indicating macroscopic mixing displacements perpendicular to flow direction [51]. Transitional flow behaviours occur between these two states and the presence of a swimmer will, therefore, perturb the fluid flows in this unstable and dynamic aquatic environment, inducing components of resistance, collectively termed *drag*. This multi-component parameter is composed of friction drag (forces acting tangential to the surface of the swimmer), form drag (dependent upon the shape or form of the swimmer) and wave drag (attributable to wave formation around the swimmer) [52]. It evolves as fluid velocity increases [52], and passive wave drag accounts for more than 50% of the total resistance encountered by elite swimmers at the water surface [53]. Vennell et al. [53] also emphasised the impact of swim depth on wave drag generation: the deeper the swimmer, the lower the wave drag, with no contribution at depths beneath 1 m (for the flow speeds under consideration in this study). These data imply that manipulating a control parameter might induce perturbations in fluid flows (i.e. creating frontal resistances at higher velocities and at the surface), provoking adaptations in swimmer behaviours.

Numerous methods have been designed to understand how purposive human movement might perturb fluids (for reviews, see [55] and [56]), ranging from experiments (i.e. tufts methods) to robotics and mathematical modelling. Flow visualisation was initially undertaken using the tufts method [34,57]. This consists of positioning small, thin pieces of coloured plastic all over the swimmer's body [57], indicating how flows encompass the swimmer's body in response to his/her actions on the fluid. This method was an initial step in investigating the functioning of the complex performer–environment system in water. For instance, during front crawl glide, woollen tufts applied to the upper limbs described a backward alignment [34]. It is however difficult to understand the precise nature of fluid motions: do the observed alignments refer to a constant flow speed or to flow accelerations in the opposite direction to a swimmer's displacement? Consequently, this method is limited to fluid visualisations at the *interface* of a swimmer's body and the fluid, but does not provide possibilities for investigating other fluid perturbations. Secondly, the analyses were performed frame by frame, and it is feasible that substantial tufts movements might have occurred between two consecutive frames. Despite the value of the tufts technique (i.e. affording observation of free swimming motions without perturbations from intrusive recording equipment), no insights on overall fluid behaviour have been provided.

An attempt to visualise such fluid behaviours over a length of time during performance was made by injecting bubbles into a stretch of water to analyse their motion when the swimmer passed through them [4]. A similar method is particle image velocimetry (PIV), a technique that uses a laser to track illuminated particles introduced into fluids (see [58]). This experimental approach has been used in competitive swimming to identify fluid motions associated with an upper limb stroke [59-61], a sculling sequence [62] and a dolphin kick [63]. A pioneer PIV work [59] focused on fluid perturbations occasioned by a front crawler's hand. This two-dimensional analysis revealed that adaptations in hand orientation were linked to the emergence of a *starting vortex* on the dorsal aspect of the hand (the water particles adopted a circular motion [4]). A second vortex was observed around the hand, rotating in the opposite direction to the first vortex, creating changes in fluid momentum. This interaction led to jet flows between the two vortices and a modification in fluid hydrodynamics (lift force on the hand that contributes to thrust production [59]). Such results were complemented with 2-D [60] and 3-D [61] PIV studies to analyse the stroke of a robotic arm in water. In both approaches, the motion resulted in the production of vortices [4], similar to those previously observed [59] when the hand adapted its orientation. An important advantage of PIV is that it does not disturb the swimmer's actions [55] in experiments. However, this method needs further investigation since current studies are limited by issues of transfer to competitive swimming conditions (i.e. 2-D analyses or on 'inanimate objects').

The next issue concerns the efficacy of mathematical modelling to investigate fluid flows, such as computational fluid dynamics (CFD) [64]. This technique uses computers to solve a series of equations that calculate, for any point in space around an object, the relevant properties (i.e. velocity, pressure, turbulence, etc.) of the fluid flowing around that object [65]. These analyses are performed inside a numerical flow domain (i.e. an artificial flume discretised into a finite number of elements), upon which the equations are iteratively solved, and have been used for a wide range of applications in swimming research [65]. The pioneering work of Bixler and Schloder [64] investigated effects of water flow against a disk with dimensions similar to those of a human hand. By modifying disk orientation and flow characteristics (constant or variable acceleration), they found that hand acceleration (from 2.84 to 5.84 m/s) strongly increased propulsive drag by up to 40%. Following this study, interest turned to evaluating water resistances during glide periods [54,66-69]. Investigators scanned the swimmer's whole body and tested resistances as a function of position (arms extended at the front or along the body) and depth. It appeared that passive drag decreased when depth increased: water drag is maximum at 0.25 m depth, and minimal around 0.75 m depth [68]. Thus, it became clear that swimmers' actions induce different fluid behaviours and that therefore fluid behaviours and swimmer actions need to be considered as an *interactive dynamical system* [7,9,10]. To investigate the impacts of swimmer movements on fluid flows, more recent CFD/PIV studies have tested models in different configurations (i.e. manipulation of head position [70], or finger spread [71-75]) or in full dynamic mode (during the dolphin kick [76-78] or the front crawl [79]). For instance, maintaining the streamlined head position might decrease drag values by 20% at high swimming speeds during glide [70]. Closer to actual swimming conditions, Cohen et al. [79], animated a numerical model based on the kinematics of a swimmer performing a complete front crawl stroke cycle (the swimmer was moving against the fluid flow, contrary to previous studies). In this simulation, high-speed fluid motions were observed during the arm pull and push sequences and likewise during the leg kick. The arms and hands generated ring-shape vortices travelling towards the kicking legs. In addition, a wave in front of the head could be visualised, as is typically observed in competitive environments. Recent articles [79,80] are even closer to an ecological dynamics perspective since they: (i) considered the swimmer moving at the surface of the water, and (ii), offered a visualisation of vortices in three dimensions during unsteady fluid conditions (i.e. competitive swimming [33,36]). Contrary to experimental methods, mathematical modelling has offered a rapid evolution in fluid flow visualisation: from the beginning (i.e. motions of a swimmer's body components tested in static conditions and underwater) to the latest simulations (i.e. at the surface, in unsteady conditions and including motion in the model). A considerable amount has been learned about the constraints of fluid motions on actions from this body of work [65].

Nevertheless, the majority of these studies investigated situations with fluid flows at the centre of analysis instead of investigating specific and continuous individual–environment interactions. Here we highlight the need for research from an ecological dynamics perspective to explain the interactions between swimmer movements and changes in aquatic environments.

4. Circular coupling between a swimmer's behaviour and fluid dynamics

"*Nowhere in sport is performance so dependent on the* interaction *of the athlete with the surrounding medium than in competitive swimming*" (p. 547) [56]. To properly understand this interaction, ecological dynamics offers a theoretical framework quite different from that of traditional theories of sport performance (which separately focus on the performer and the environment) since it considers the individual–environment system as the relevant scale of analysis [9,10,81]. Ecological dynamics integrates key ideas from ecological psychology [14], according to which behaviour is regulated by information that arises from an individual–environment complex to continuously guide and shape the athlete's actions.. Through experience and practice, the individual and the performance environment become more tightly integrated as a self-organising and dynamical system coupled by information [8,23]. According to the theory of *direct perception* [14], perception is an active process. Indeed, perceivers seek information and optimize it rather than passively receiving it {Adolph:2015ti}. Both individual–environment and perception–action reciprocities are reflected by the notion of *affordances* {Adolph:2015ti}. Affordances are invitations or opportunities for action relative to an individual's own action capabilities and a specific performance environment [20]. From this perspective, swimmers have opportunities to make action choices in a whole *landscape of affordances* (accepting or rejecting them) as a function of intentions and goals that may be continuously changing [14]. In this sense, "the observer *may* or *may not* perceive or attend to the affordance, according to his/her needs, but the affordance, being invariant, is always there to be perceived" {Gibson:1979uo} (p.130). Accepting or rejecting affordances is a rapid and unreflective process {Rietveld:2014tg}, in relation to the situation individuals are facing, and the future actions they will generate.. S electingappropriate affordance(s) is an ubiquitous and continuous process {Withagen:2012ta}, culminating in goal-directed behaviours. *Direct perception* is mainly related to haptic and visual sensory systems {Gibson:1979uo}. Haptic perception in swimming has enormous significance , for instance the perception of gliding when fluid is rapidly flowing between the fingers. Rather, the visual sensory system will be solicited to capture all information that may emerge in the surrounding aquatic environment (e.g. localise the T-line on the floor symbolising the 5-m when approaching the wall). With experience, an individual becomes more attuned to specifying information for action (Fajen et al. 2009). This means that expert swimmers tend to rely a range of perceptual variables that specify a relevant property of a performance environment. In this respect, the term 'relevant' signifies functionality as this property enables an individual performer to achieve a specific task goal with efficacy. In other words expert swimmers exploit environmental constraints with efficacy through perceptual attunement and calibration to functional informational variables [19] (such as density and viscosity in relation to depth of water, state and speed of the fluid flow) specifying effective actions. This is the *education of intention* {Jacobs:2007cs}. Education of intention is characterised by becoming more efficient in detecting informational variables that are elementary for the performance challenge individuals face. However, this particular intention–variable relationship may change over time, and another variable may become more appropriated to detect In swimming, this idea implies that fluid motions will constrain swimmers' actions, which in turn will perturb fluid dynamics, creating a dynamical and self-organised individual–environment system. These interactions are impossible to assess directly during competition, and consequently recent studies have tried to use new technologies (i.e. PIV or CFD) or training devices (e.g. flumes, fins and paddles) to gain a general and indirect (i.e. *artificial*) overview of this coupling [55].

Ecological dynamics offers a new perspective for assessing these functional interactions, requiring investigators to manipulate swimmers' actions and/or flow dynamics to measure the impact on the performer–environment system. Such an interactive system exhibits properties of reciprocity between its constituents {Adolph:2015ti}: acting on one or other constituent will influence the whole system. The underlying idea is that interventions should be based on manipulations of a set of interacting constraints [13,83] to facilitate the emergence of adaptive behaviours. Interacting constraints both facilitate and bound the organisation of actions in neurobiological systems [13]. Their manipulation may foster swimmers' adaptability to better prepare them to face challenges in novel performance contexts. Adaptability is a hitherto understated aspect of competitive swimming performance since individuals need to continuously adapt their motor coordination to the different sequences of a competitive event. For example, at the start, during free swimming with opponents moving around them, after the emergence of fatigue, in the turns, and at the final touch on the pad to validate their mark. Stable behaviours correspond to the swimmer resisting environmental perturbations, whereas flexibility is related to the exhibition of functional behaviours emerging in specific environments. Adaptability is generally associated with expertise {Seifert:2013ig}, in that experts exhibit stable movements but are not limited to these motor solutions. Rather, when a perturbation appears, they are able to flexibly modify their behaviour to respond to the challenge. Swimmers' adaptability corresponds to *adapted* interactions with a set of constraints (task, organism, environment), but also *adapt-able* behaviours (i.e. evolvability and creativity {Seifert:2013ig}). Evolvability and creativity behaviours have clearly been identified {Seifert:2014bd}. Investigators s have required swimmers to maximise the glide during front crawl performance at constant velocities (1.16 m/s), measuring the leg kick per stroke that will result from these specific instructions. They observed that some experts considerably increase the number of leg kicks per stroke cycle, adopting an unusual 8 or even 10 leg kick pattern. The constraint associated with the atypical glide led swimmers to increase the contributions of the leg kick to maintain the required speed, demonstrating important properties of adaptability. Assessing the adaptability of swimmers may be beneficial for: (i) coaches to design training situations and guide swimmers toward *adapted* and *adapt-able* behaviours to face unpredictable and dynamic situations they encounter in competitions (e.g. a change in the resistances or support the water offers to the swimmers), and (ii), scientists to scan the repertoire of stable system states *and* examine the range of flexibility of each stable state, in order to maintain similar performance output, whatever the constraints of an aquatic environment. Adaptability may be a valuable indicator to investigate higher-order variables such as coordination.

In swimming, the manipulation of constraints (the constraint-led approach [84]) aims to destabilise or perturb the coupled integration of a swimmer and an aquatic environment (e.g. properties like flow, resistances, currents, vortices, eddies, ripples). This strategy has been tested in swimming studies by increasing aquatic resistance using a parachute (i.e. constant resistance attached to a swimmer during movement) and manipulating speed to investigate stroke adaptations and coordination parameters {Telles:2011uh, Schnitzler:2011ud}. In these experimental conditions, aquatic resistance is higher than traditionally encountered in free motion, since the parachute creates a bigger frontal area opposed to displacement. In study by Telles et al. [86], the increased resistance caused a change in inter-arm coordination (exemplified by a change in the Index of Coordination [44]) from catch-up to opposition mode, or even to a superposition mode {Schnitzler:2011ud}. This superposition mode is usually only exhibited by expert swimmers suggesting that the use of the parachute may help sub-elite swimmers to better coordinate actions againsthigh resistances. These behavioural adaptations indicated that sprinters displayed better continuity in their propulsive actions –that is, less interruption between the propulsion of the two arms and lower intra-cyclic velocity variations. Additionally, the parachute led to a shorter catch (i.e. non-propulsive phase) and a longer push (propulsive), reinforced by increases of force impulses and peak push forces. Tethered swimming [88-90] is another technique to manipulate the swimmers' environment: individuals are attached to the pool wall by a non-extensible cable and must maintain their swimming position [88]. This induces temporal modifications in the aquatic stroke in comparison to classical swimming conditions: pull and push durations increase, whereas the non-propulsive phase (recovery) decreases, resulting in a global increase in the entire stroke time [88,90]. In both parachute and tethered situations, the resistances' increase was such that any moment without propulsion strongly affected velocity [86], leading to behavioural modifications of the swimming stroke. These adaptations could be to: (i) increase the time spent in propulsive phases, (ii) decrease their frontal projected area, (iii) increase the continuity of their propulsive actions, or (iv), increase the force they developed to progress against the artificial resistances. This constraint-led approach illustrates the circular coupling between perception and action (in these conditions swimmers faced greater resistances than in classic free swimming, so they adapted their behaviours), illustrating how performance emerges from the on-going interactions between an individual and his/her environment.

Mathematically, resistances are linked to swimming velocity, as suggested by the formula: $R = \frac{1}{2}\rho S v^2$, with R the resistances, ρ the density, S the surface opposed to displacement, and v the swimming velocity. It could be argued that swimming velocity can act as a control parameter to reveal changes in the swimmer–aquatic environment coupling: ‘I-shaped’ swimming path (i.e. straight motion of the arm underwater) is associated with sprint events, facilitating a maximisation of propulsion under these task constraints [91]. Conversely, during endurance events, the ‘S-shaped’ pattern can be adopted to produce the most efficient stroke. An increase in velocity may be associated with reduced medio-lateral amplitude of the swimming path to produce the best propulsion in minimum time. Testing the impact of swimming speed (from low to maximal) on coordination patterns revealed that the catch-up mode of coordination disappeared near 1.8 m/s (pace for 200-m), with a superposition or opposition mode emerging [92,93]. Swimmers’ strategies are dependent on velocity: at low paces, they favour movement patterns that reduce hydrodynamic resistances; conversely, at sprint pace, they want to diminish the time between the successive propulsive arms actions (i.e. maximise propulsion). Other components that might be indirectly linked to a possible increase of swimming resistances are of relevance to the constraints-led approach. For instance, if not well performed, breathing may induce asymmetry, resulting in lower body streamlining {Lerda:2001vj}. Recording air passing through the mouth with microphones {Cardelli:2000by;Lerda:2001vj} will help swimmers to better synchronise their exhalation with the underwater push and their inhalation with the first half of the recovery. Practising with such biofeedback will certainly lead swimmers to rely more on specifying informational variables for action in constraining competitive environments {Jacobs:2007cs}.

Another strategy is to increase swimmers’ propulsive areas for modifying the typical coupling between individuals and their aquatic environment. This is typically achieved with swimming paddles [86,94-96] or fins [97,98], both of which are conducive to higher thrust production than traditional swimming conditions. Depending on the body surface exposed to water, new spatiotemporal strategies emerge in swimmers, helping them to move larger masses of inert water: with large paddles, they increase the time needed to complete one stroke cycle by increasing the time spent in the entry, catch and recovery phases of the front crawl [96]. Such ‘anthropometrical adjustments’ can act as *organismic constraints*, similar to expertise, age, gender, or psychological states (for a review, see {Seifert:2008tu}). The consideration of such constraints is necessary for coaches and scientists to properly capture how swimmers can exploit their own capabilities and attributes. For example, {Seifert:2010wk} reviewed the gender effect for swimming performance. Beyond obvious differences in performance that may arise from lower stature exhibited by females (i.e. 13 cm shorter, 15 to 18 kg lighter than males for North Americans), hydrodynamics principles impacted differently on females and males. Indeed, it seems that males, with a more central distribution of fat, have a worse static floating position than females, revealing possible training situations based on floatability.

Instead of manipulating swimmer movements by adding resistances or increasing propulsive areas, researchers might focus on fluid properties since these modifications of the performance environment may lead to a reorganisation of system degrees of freedom underpinning a swimmer's actions. For instance, testing swimmers in a flume (i.e. where the fluid flows forward) will change their perception of flows on propulsive areas, with a possible decrease in glide duration at the point of hand enters the water [99-101]. This example illustrates how swimmers must attune and calibrate to new information that emerges from changes in an aquatic performance environment in order to utilise affordances that specify action [19]. There are many different types of constraints that might be manipulated to assess impacts on motor behaviours that swimmers adopt during performance, as highlighted by Seifert et al. [45,93].

A major challenge for the constraint-led approach remains in determining and designing relevant practice tasks to ensure swimmers will extend or reinforce their behavioural repertoire to be more adaptive in unpredictable and dynamical competitive environments. Therefore, coaches and sport scientists need to design representative practice tasks that simulate changes in competitive environments to ensure adaptability and skill transfer. In the ecological dynamics framework, the notion of *representative design* shapes experimental and practice environments so that observations and acquired skills can be linked to emergent functional behaviours in a specific performance context [30]. Pinder et al. [29] developed the concept of *representative learning design* to help sport scientists and coaches to create learning situations that integrate interacting constraints on movement behaviours. They pointed to a need to "*adequately sample informational variables from the specific performance environments, and ensure the functional coupling between perception and action processes*" (p.151) [29]. The relevance of the concept was demonstrated in sports {Araujo:2007tz, Davids:2012wh}, for instance during dry-land dives form a springboard(see {Barris:2013ix}), or for the ball striking action in cricket. Results demonstrated that hitting a cricket ball projected from a machine does not afford the same information that cricketers face in competition, when a 'real' opponent bowls the ball (in this situation, information from a bowler;s actions before ball release may help the batteranticipate the ball's trajectory) {Pinder:2009kh}.

5. Representative learning design for human aquatic locomotion

Representative learning design describes the composition of practice task constraints that represent performance environment settings [29]. This conditions the acquisition or reinforcement of multi-articular coordination patterns that becomes strongly dependent on affordances design in practice tasks {Seifert:2016hz}. Aquatic locomotion is performed in an environment offering both support to propel forward, and resistances, from aquatic viscosity and density properties {Toussaint:2002vd}. Researchers have the possibility to design training environments with three main performance objectives: (i) maximise propulsion, (ii) limit resistances, and (iii), develop propulsive efficiency. Indeed, generation of propulsion in a fluid is always accompanied with loss of mechanical energy (around 20 %), that is transferred to water moving backward instead of moving the swimmer forward {Toussaint:2005tc}.

Accelerating small masses of water at high velocity leads to lower efficiency than accelerating larger masses of water per unit of time at a low velocity. From this perspective, the constraints-led approach may be used to maximise swimmers' efficiency, notably by *amplifying* their perceptions (e.g., drag can be artificially amplified by using fins, paddles or a swimming flume). The main goal in using these experimental *perturbations* is to encourage swimmers of all skill levels to transfer acquired skills from practice contexts to continuously changing performance environments: they must be able to adapt their behaviours to all the unexpected situations that can emerge in competition. For instance, open water swimmers continuously face dynamic and unpredictable environments, since they perform their competitions in natural contexts. It could be useful for them to train in a flume that *artificially increases drag*. However, since the interactions between a swimmer and an aquatic environment are unique, training will have a more powerful impact when an *individualised* learning approach is taken.

Future research needs to model the three dimensional fluid flow around a swimmer in a fully unstable condition (comparable to competitive swimming). Investigations could directly couple the compliant behaviours of a swimmer's skin and body with local flow conditions, revealing the resulting direct influence on vortex production during propulsion. This approach seems hardly imaginable at this present time, despite numerical advancements in Computational Fluid Dynamics, that make the technique an interesting tool for the study of fluid motion in swimming.

6. Conclusion

Since swimmers' movements induce fluid flow modifications in the aquatic environment, which, in turn, perturb swimming performance, the interactions between each swimmer and a performance context need to be adequately captured during practice. In this review, current understanding of human aquatic locomotion was presented, followed by a discussion of the limitations of some investigative approaches. Research ideas to consider performer–environment interactions as the smallest scale of analysis were proposed through the theoretical framework of ecological dynamics. Finally we addressed some useful ideas to enhance the representativeness of practice contexts that could be used to identify the emergence of typical behaviours as a function of fluid motion specificities. Among them, the manipulation of resistive forces in swimming (i.e. swimming in a flume, tethered or with a parachute) may be used by coaches during training sessions to guide swimmers' adaptations to a dynamic range of situations that are likely to be encountered in competitive performance environments.

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