UNIVERSITAT DE BARCELONA

Unified Framework for the Study of Sport-Related Behavior

Pablo Vázquez Justes

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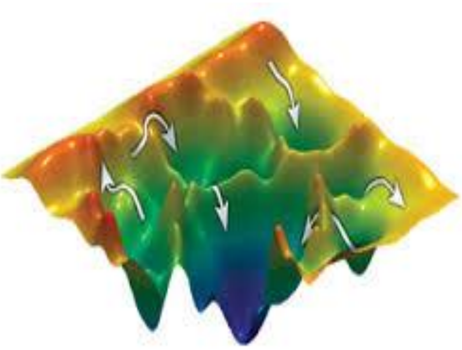
Tesi doctoral

Unified framework for the study of sport-related behavior



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INSTITUT NACIONAL D’EDUCACIÓ FÍSICA DE CATALUNYA
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Programa de Doctorat: “Activitat Física, Educació Física i Esport”

Unified Framework for the Study of Sport-Related Behavior

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*A la Cristina i a l’*Aina.
Als meus pares.

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Πάντα ῥεῖ
Panta Rei (tot flueix)

(Heràclito)

Unified framework for the study of sport-related behavior

The present thesis comprises seven chapters. The first chapter contains a general introduction of the thesis, and chapters 2, 3, 4 and 5 compile four studies with their own references. Chapter 6 includes the general discussion of the main results, and the conclusions. Chapter 7 contains the list of references of chapters 1 and 6.

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ABSTRACT

A high disciplinary specialization and development of context-specific languages in sport science has promoted its current fragmentation and a lack of communication and transfer of knowledge among scientists. However, common general principles can be found among apparently unrelated disciplines and phenomena under study when the focus is put on the processes and dynamics of change. In fact, dynamic approaches are changing the research scenario in areas as distant as biology and social sciences, among others. The Nonlinear Dynamical Systems Theory (NDST), which has already undertaken a paradigm shift in several scientific fields, has been recently applied to the study of human coordination and sport-related behavior. This theory offers key concepts and a common language which can provide a unified framework for sport science (and for science in general), and thus, contributes to promote transdisciplinarity.

The objective of this thesis is to show how seemingly unconnected sport-related behavior extracted at individual and social levels can be studied by using the same dynamic principles and concepts. Several experiments where different collective variables are tested under the influence of different types of constraints are presented. Concerning the organismic level, the evolution of the performance level in function of the workload was modelled, and the dynamics of kinematic and psychological variables during static and dynamic exercises performed until failure was analysed. Concerning the social level, the attitudes of sport fans in connection with the number of wrong referee decisions were also studied. The results show how all these collective variables share common dynamic features such as stability, instability and nonlinear change of state, regardless of the level and time scale of analysis. In conclusion, the NDST can provide a unified framework to study different types of sport-related phenomena and thus contribute to the integration of

scientific knowledge and facilitation of the transfer of theoretical explanatory principles among disciplines.

RESUM

L’elevada especialització disciplinar i el desenvolupament de llenguatges dependents de contextos específics en el marc de les ciències de l’esport ha promogut l’actual fragmentació i manca de comunicació i transferència de coneixement entre científics. No obstant això, quan l’atenció es posa en els processos i les dinàmiques de canvi, es poden trobar principis generals comuns entre disciplines i fenòmens aparentment no relacionats. De fet, els enfocaments dinàmics estan canviant l’escenari de recerca en àrees tan distants com la biologia i les ciències socials, entre d’altres. La teoria de sistemes dinàmics no lineals (TSDN), que ja ha emprès un canvi de paradigma en molts camps científics, ha estat recentment aplicada a l’estudi de la coordinació humana i el comportament relacionat amb l’esport. Aquesta teoria ofereix conceptes clau i un llenguatge comú per proporcionar un marc unificat per a la ciència de l’esport i per a la ciència en general, contribuint a promoure la transdisciplinarietat.

L’objectiu de la present tesi és mostrar com fenòmens aparentment inconnexos relacionats amb l’esport i extrets a nivells individual i social poden ser estudiats utilitzant els mateixos conceptes i principis dinàmics. Es presenten diversos experiments on diferents variables col·lectives són testades sota la influència de diferents tipus de constrenyiments. A nivell de l’organisme, es va modelar l’evolució del nivell de rendiment en funció a la càrrega, i es van analitzar les dinàmiques de variables cinemàtiques i psicològiques durant exercicis dinàmics i estàtics realitzats fins a l’exhauriment. A nivell social, les actituds de fans en funció del nombre de decisions arbitrals errònies van ser també estudiades. Es

mostra com totes aquestes variables col·lectives comparteixen dinàmiques comuns que es caracteritzen per l'estabilitat, inestabilitat i el canvi d'estat no lineal, independentment del seu nivell i escala temporal d'anàlisi. En conclusió, la TSDN pot proporcionar un marc unificat per estudiar diferents tipus de fenòmens relacionats amb l'esport, i contribuir així a integrar el coneixement científic i facilitar la transferència de principis teòrics explicatius entre disciplines.

LIST OF ABBREVIATIONS

fBm	Fractional Brownian motion
fGn	Fractional Gaussian noise
NDST	Nonlinear Dynamical Systems Theory
PES	Perceived Exertion Shifts
RPE	Rate of Perceived Exertion
TUT	Task Unrelated Thoughts
TRT	Task Related Thoughts

GENERAL INTRODUCTION

The search for minimum principles that explain the maximum number of phenomena is a tacit motive in science. However, the high disciplinary specialization and the development of context-specific languages have entailed a lack of communication and transfer of knowledge among scientists (Hristovski, 2013).

In the past, there has been growing success in modelling and explaining different levels of matter organization by common universal concepts. The initial ideas of Newton to integrate different phenomena such as celestial mechanics, earthly tides and falling bodies into the law of universal gravity could be the beginning of this trend. Maxwell followed him unifying the apparently distinct phenomena of electricity and magnetism into a unified electromagnetic theory. Einstein unified the notions of space, time, matter, energy and gravity into an even more general theory and started a program of unifying the fundamental forces of nature in a framework today known under the name of "The Grand Unifying Theory" (GUT). Other types of unifying approaches in physics and chemistry have followed by using similar formalisms and explanations based on mathematical approaches (Landau, 1969; Haken, 1964; Wilson, 1975; Glansdorff & Prigogine, 1971). Although integration has been proved as a successful strategy for the scientific development, the tremendous growth of science has mostly produced further specialization and fragmentation. In addition, contemporary education, based on a fragmented structure of topics, contributes little to the development of the integrative competencies and knowledge considered essential for science and society.

According to recent research results, the fragmentation tendency has been particularly evident in sport science during the last decades (Hristovski, et al., 2016). The focus of each discipline on different levels of organized matter produces that the phenomena under study seem almost totally unconnected. A special case is the distance among biology and social sciences, apparently incommensurable. Nonetheless, from a complex systems point of view it is known that there are commonalities among the behavior of biological and social systems. The common principles can be found when the focus is put on the dynamics, i.e., in the process that describes and explains how coordinated behavior emerges, persists, adapts and changes in a variety of systems operating at multiple levels of description (Kelso, 1995). In fact, there are commonalities between the diversity of dynamic processes dwelling on different levels and time scales in biological and social entities because they are embedded in similar dynamic laws (Eissing et al., 2011). As our world is made of dynamic processes and not of timeless structures, it naturally follows that it is better explained by Nonlinear Dynamical Systems Theory (NDST) approaches, and that the NDST general principles and concepts may become an integrating language for science, and sport science in particular (Hristovski, 2013). The NDST approach is useful to build a unifying framework in sport science because it has changed the research in a number of areas and has introduced general concepts which are valid for all levels of analysis (from molecular to social).

At the end of the '70s, the first works applying NDST principles to animal and human movement organization (Kelso, Southard & Goodman, 1979, Kugler, Kelso & Turvey, 1980) appeared. These early works provided a fruitful perspective for the study of the human movement and a systematic research was established through the called 'coordination dynamics approach' (Kelso, 1995). This approach, which has been already applied to diverse sport contexts and sport related phenomena (see Balagué, Torrents, Hristovski, Davids & Araújo, 2013 and Balagué, Torrents, Hristovski, & Kelso, 2016 for a review), use NDST principles, and specifically Haken's synergetics theory, to study functional significant patterns of coordinated behavior such as moving, perceiving, feeling, thinking, deciding, learning, etc. (Kelso, 1995, 2009). The studies showing the integration of biological systems in the vertical axis (at different levels and time scales) are of particular interest. For instance, Balagué, Hristovski, Vainoras, Vázquez and Aragonés (2014) show how the dynamics of psychological and kinematic collective variables is reproduced in the path to exhaustion, and Ric et al. (2016) have identified the dynamics of tactical behaviour in soccer on different time scales. As the previously mentioned research, this thesis uses a set of concepts based on NDST principles that will be defined in the next section.

1.1. NDST concepts

Living systems are composed of many heterogeneous components that interact among themselves and, as a whole, interact with their environment. The macroscopic variables that are essential for describing the coordinated behavior of such systems are called *collective variables* because they emerge from the cooperative behavior of components. We also refer to them as ‘order parameters’ or ‘coordinative variables’ because they capture the coordinative behavior of the system components.

For a given set of *constraints* (i.e. influential factors), the dynamic behavior of the system, represented by the trajectory of the *collective variable*, might converge in their evolution to a stable state and dwell in such state infinitely. The stable state is called *attractor*, because it attracts the behavior of the *collective variable* towards it (see Figure 1). Its antipode is the unstable state called *repeller* (Figure 2). If for a set of *constraints* the *collective variable* is placed close to the *repeller*, the system will be pushed far away from it

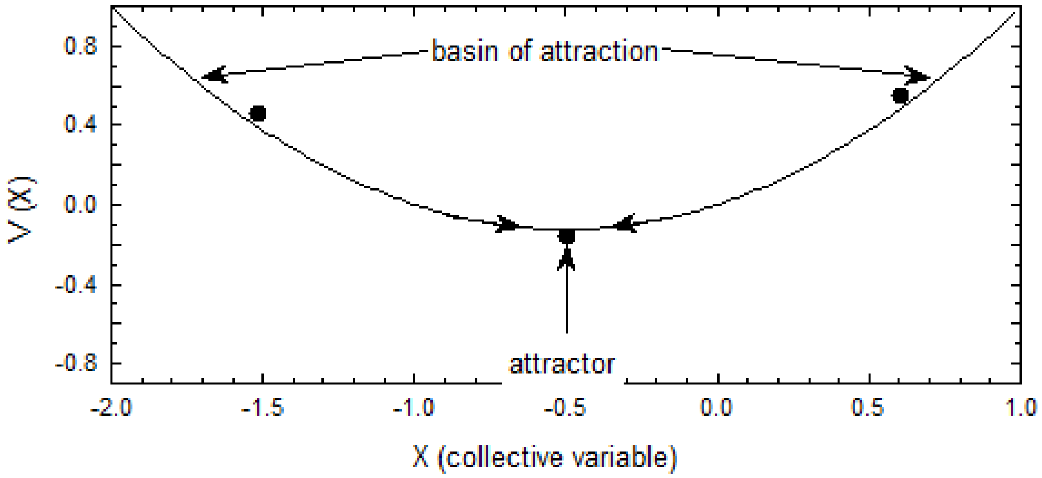

Figure 1. The *attractor* (the minimum of the potential function V) represents the stable state of the collective variable X. The area around the *attractor* (the function V given as a bold curve) is the *basin of attraction*. Each point in the *basin of attraction* represents the state of the system (black ball), which will be spontaneously pulled towards the minimum, i.e., the *attractor* (see the arrows).

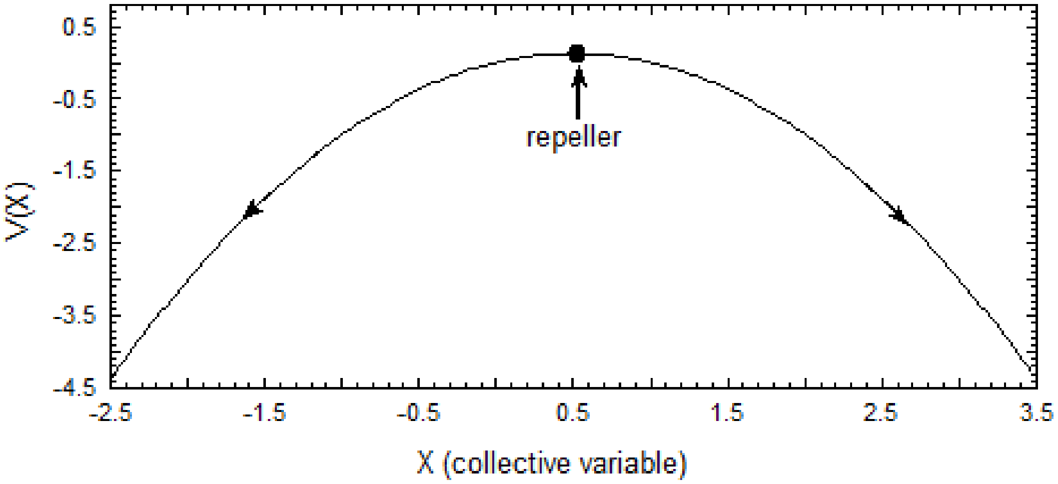

Figure 2. A *repeller* (the maximum of the function) represents an unstable state of the collective variable (X). If the system is put at any point on the potential function (black bold curve) it will slide towards plus or minus infinity. This state being unstable cannot exist.

There are two broad classes of dynamical systems: linear and non-linear. Linear systems are monostable, i.e., the evolution of the behavior of the *collective variable* on time converges into one stable solution (Figure 1). In this kind of systems, the dynamics (i.e. the rate of change in time) of the collective variable will be proportional to the change in the *constraints*, i.e., a small change in the *constraints* influencing the *collective variable* will produce a small change in the *collective variable* behavior, and a large change in the influencing set of *constraints* will produce a large change in the *collective variable* behavior (Hristovski, Balagué & Schöllhorn, 2014). Nonlinear systems, however, are quite different because they may contain stable and unstable states (Figure 3), i.e., they enable multi-stability for a given set of constraints.

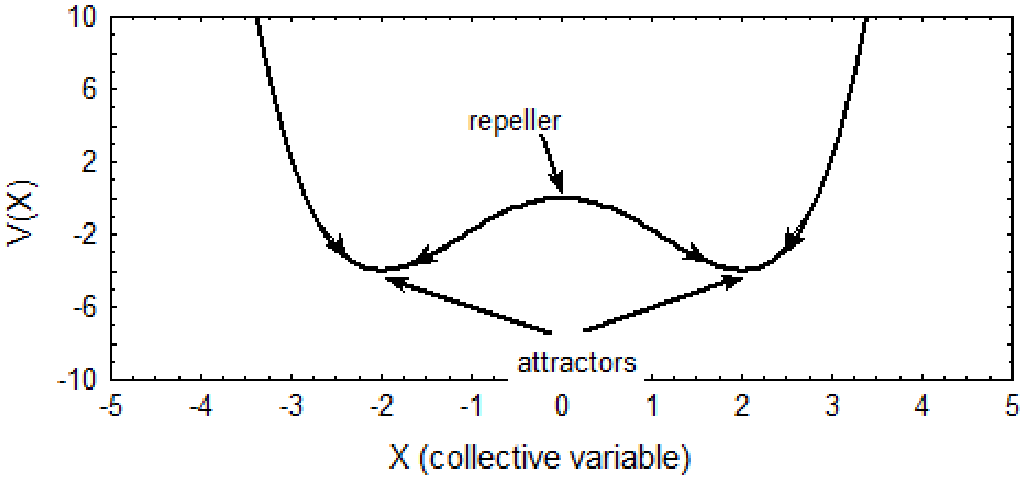

Figure 3. Bistability in a non-linear system and coexistence of unstable and stable states (*repellers* and *attractors*) of the collective variable X. Note that the situation is different than in Figure 1 and 2. If we position the system at the *reppeller* point it will not be attracted towards plus and minus infinity but towards a finite state (one of the symmetric states around 0). The non-linearity enables multi-stability.

Such *multi-stability* can be reached by changing the value of some *constraints* that influence the behavior of the *collective variable*. Therefore, nonlinear systems enable other behavioral finite states of the collective variable instead of containing only one solution. In other words, the *stable states* often coexist with *unstable states* (see Figure 3). Having more than one available state, the non-linear system allows for a switching dynamics among these states (Figure 4). This capacity of non-linear systems is called *metastability* (Bovier & den Hollander, 2015). There are many mechanisms that produce *metastability*. The one represented on Figure 4 is *metastability* under presence of disturbances (*fluctuations*). In this case the disturbances are the ones that push the system from one stable state to the other. For other, more involved, types of metastable dynamics see (Bressler & Kelso, 2001; Rabinovich, Huerta, Varona & Afraimovich, 2008).

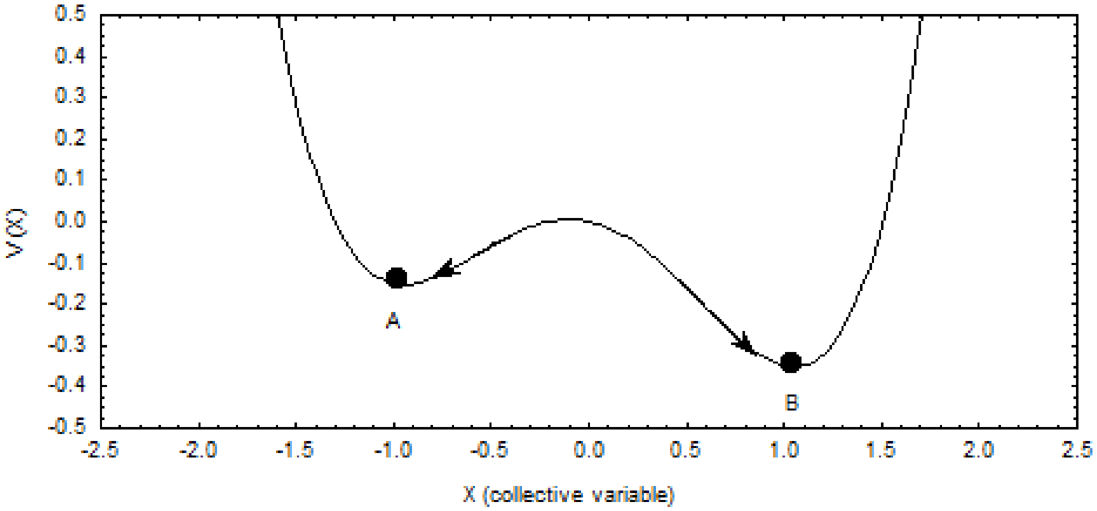

Figure 4. *Metastability* in a potential landscape V. Under a presence of disturbances the system can switch from stable state A to stable state B of the collective variable X and vice versa. One can imagine a landscape with more than two stable states and more collective variables. The potential landscape shows *multistability*, but under the presence of disturbances the dynamics is metastable.

In general, the stability and instability of the system depend on the influence of a set of *constraints*. These influential *constraints* (or their combination) are known as *control parameters* because they control the system properties (stability and instability). While *stability* is defined as the capacity of the system to recover its attractor state after a perturbation, *instability* means the inability of the system to recover its *attractor* state. As the *control parameters* come closer to some critical value, there is an increase in the *fluctuations* (variability) of the *collective variable*, and it takes increasingly more time for such variables to recover its *attractor* state after a perturbation. This phenomenon is called *critical slowing down* (Figure 5).

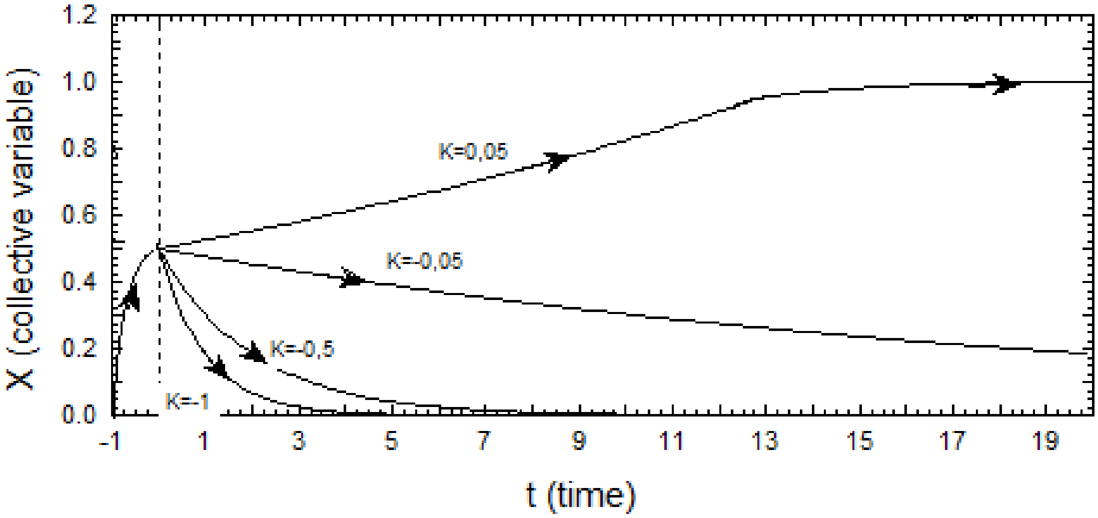

Figure 5. *Critical slowing down* and loss of stability (*phase transition*). As the control parameter K approaches the critical value K = 0 from negative values K<0 we see that the collective variable X relaxes toward the stable state X = 0 after a perturbation (given by the upward arrow in the interval -1 < t (time) < 0) increasingly slowly. For K = -1 it quickly recovers the stable collective state X = 0, but for K = -0.05 the recovery towards the stable state is much slower. Finally, for K = 0.05 (a slightly larger value than the critical K = 0) the system never recovers the X = 0 collective state. It transits to the newly stabilized collective state X = 1.

Both the increase of *fluctuations* and the *critical slowing down* reflect the loss of the cooperative behavior among the system components in unstable states. At a critical point, the previous order of the *collective variable* decays and a new order starts to be formed (Figure 5). This event is called a *phase transition* and lasts for a very short time compared to the time during which the system was in a stable state.

During the *phase transition* the cooperative behavior of the system components changes and enhances the new way of cooperation. This process starts with the formation of a small nucleus of components that contains the new cooperative behavior while other components are still in a weakly coupled state. The neighbouring components to the nucleus, under direct influence of the new behavior, start to behave consonantly. This enhances the collective behavior and even more components are recruited just by enhancing the newly attained collective cooperative behavior. This is akin to an avalanche process. Thus, the collective behavior enslaves the individual behavior of the components. This is the well-known *slaving principle* introduced by Haken (1987) in which the enslaved components stabilise the behavior of the *collective variable* by nonlinear interactions until a finite stable state is reached. In other words, the enslaved components, due to their cooperative behavior, stabilise the collective behavior and the collective behavior governs the components. This hierarchical interaction between levels is known as *circular causality*.

It is important to note that in all non-living and living systems there are always deviations around the stable *attractor* state of the system. These deviations (or *fluctuations*) are a result of other processes that exist on the smaller and quicker (micro) spatio-temporal scales than the *collective variable* under study. Living systems are capable to adaptively maintain the *attractor* by correcting these deviations either unconsciously (e.g. reflexes) and/or consciously (e.g. intentions). This stabilizing control via temporally organized synergies is reflected in the time variability structure of the coordinative variables under study. *Variability* of the collective variables may be of 3 different types: sub-diffusive (antipersistent fractional Brownian motion), diffusive (pure Brownian motion) and superdiffusive (persistent fractional Brownian motion). One of the frequently used models to explain these types of variability (fluctuations) is the change of the structure of the potential landscape within which the system moves (e.g. Maisuradze, Liwo, & Scheraga, **2009)**. For rugged hierarchical landscapes the *variability* is sub-diffusive because the system often is being trapped in small local valleys, i.e. attractor basins and hops between them (see Figure 6 left panel). When the potential landscape is smooth than, the local trapping is absent, and system moves more easily within and between the global basins of attraction so that the dynamics can become diffusive or superdiffusive (see Figure 6 right panel).

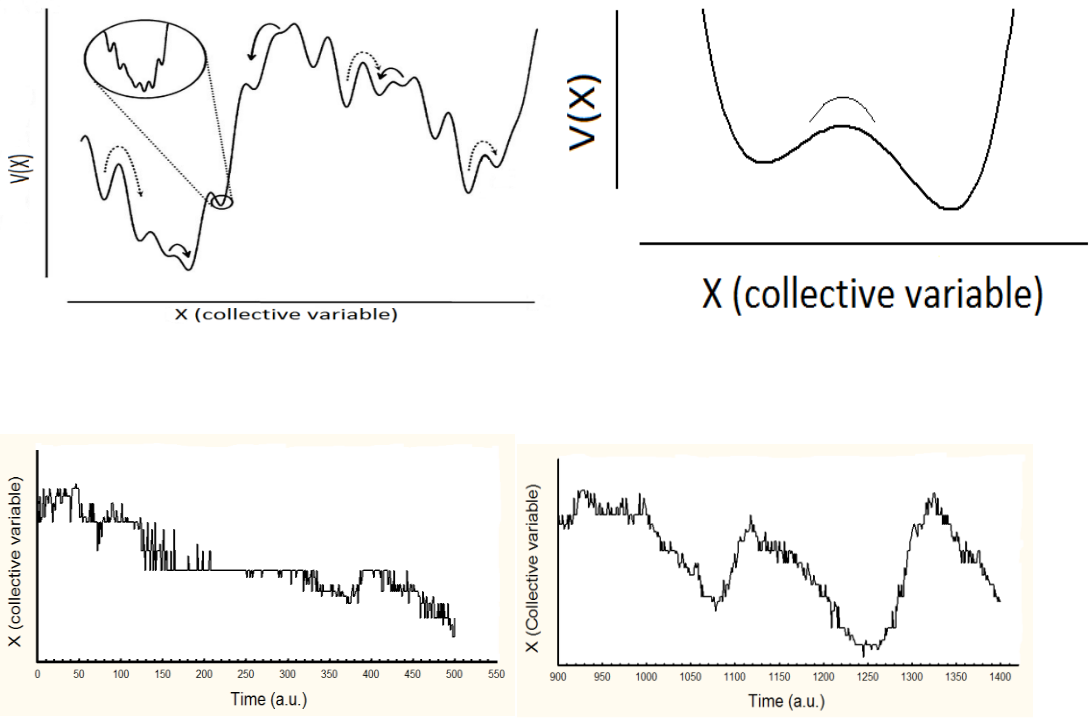

Figure 6. Two different potential landscapes V (X) and the associated fluctuation dynamics. Left panel: A rugged hierarchical potential landscape with many nested valleys that trap the motion of the system. Right panel: A smooth bistable potential landscape that does not trap strongly the system. As a result, the system more freely moves within the landscape

The objective of this thesis is to show how seemingly unconnected phenomena related to sport-behavior can be studied by using the same NDST general principles and concepts. The hypothesis that sport-related behavior can be studied in a unified way is based on the assumption that the mind, the body and the environment are guided by the same general dynamic principles, and that these principles operate at different time scales.

1.2. NDST concepts and experimental studies

In relation with the objective of this thesis, six different experiments collected in 4 different papers were conducted. In each of them the behavior of different collective variables (extracted at social, organismic, kinematic and psychological levels of analysis, respectively) and operating at time scales from miliseconds to minutes were studied under the influence of different control parameters (workload, time on task or number of referee decisions).

Study I. Constraints controlled metastable dynamics of exercise-induced psychobiological adaptation

Hristovski, R., Venskaityte, E., Vainoras, A., Balagué, N., & Vázquez, P. (2010). Constraints controlled metastable dynamics of exercise-induced psychobiological adaptation. *Medicina, 46*, 447-53.

This position paper includes four different studies.

Ia) In the first study, the collective variable was defined as the performance level (organismic level of analysis) and the control parameter was the workload. The results show how for certain workload values the performance level changes its behavior through instability, going from one stable state defined as overreaching (i.e. positive effect of training) to an overtraining state (i.e. negative effect of training).

Ib) In the second study, the collective variable was defined as the elbow angle (kinematic level of analysis) and the control parameter was the time on task. The results show how as the time on task (and thus, the accumulated effort) grows, the elbow angle changes its behavior through instability (enhancement of fluctuations), going from one stable state defined as a fluctuating dynamics around the task goal (i.e. 90º elbow flexion) to the resting state defined as 0º elbow flexion (coinciding with the task disengagement).

Ic) In the third study, the collective variable was defined as the attention focus (psychological level of analysis), formed by task unrelated thoughts (TUT) and task related thoughts (TRT), and the control parameter was the time on task. The results show how as the time on task increases, the attention focus passes through instabilities (TUT/TRT switches), from one stable state defined as keeping the self-imposed TUT to a stable TRT state when approaching exhaustion.

Id) In the fourth study, the collective variable was defined as the volitional state (psychological level of analysis) formed by UP volition/DOWN urges and the control parameter was the time on task. The results show how as the time on task enlarges, the initial UP volitional state changes through instability (UP/DOWN switches) to a final DOWN stable state close to exhaustion.

Study II. Dynamics of Perceived Exertion in Constant Power Cycling: Time and Workload-dependent Thresholds

Balagué, N., Hristovski, R., Gracía, S., Aguirre, C., Vázquez, P., & Razon, S., & Tenenbaum, G. (2015). Dynamics of Perceived Exertion in Constant Power

Cycling: Time and Workload-dependent Thresholds. R*esearch Quarterly for Sport and Exercise, 86*, 371-378. doi: 10.1080/02701367.2015.1078870

In this experiment, the collective variable was the Perceived Exertion Shifts (PES) (psychological level of analysis) and the control parameter the time on task. The results show how for certain workload values (hard and very hard intensities) the PES dynamics changes its behavior going from a fluctuating dynamics state (increment/decrement of PES) to a non-fluctuating dynamics state (just PES increments). In contrast, for moderate and extremely hard intensities the non-fluctuating dynamics was the only stable state.

Study III. The path to exhaustion. Time-variability properties of coordinative variables during continuous exercise

Vázquez, P., Hristovski, R., & Balagué, N. (2016). The path to exhaustion. Time-variability properties of coordinative variables during continuous exercise. *Frontiers in Physiology, 7*. doi: 10.3389/fphys.2016.00037

In this experiment, the collective variable was also the elbow angle (the same collective variable as in study 1) and the control parameter was the time on task. The results show how as the time on task increases, the elbow angle variability profile changes, going from an anti-persistent fluctuation dynamics to a persistent fluctuation dynamics.

Study IV. Formation of coherent attitudes in sports fans

Hristovski, R., Balagué, N., & Vázquez, P. Formation of coherent attitudes in sports fans. (submitted).

In this experiment, the collective variable was defined as the attitude of fans formed by the opinion, emotional and action layers (social level of analysis) and the control parameter was the number of incorrect referee decisions against the fans favourite football team. The results show how as the number of the incorrect decisions increases, the attitudinal patterns of fans change through instability, going from a neutral attitudinal state to the formation of a coherent attitude pattern (at the opinion, emotional and action levels, respectively).

The elbow angle appears as a collective variable in two different papers because the same experiment was conducted with two different purposes. While study Ib tests the effects of time on task on the elbow angle stability, study III analyses the structure of the variability of the elbow angle fluctuations during the effort.

STUDY I

Hristovski, R., Venskaityte, E., Vainoras, A., Balagué, N., & Vázquez, P. (2010).
Constraints controlled metastable dynamics of exercise-induced psychobiological adaptation. *Medicina*, *46*, 447-53.

Constraints-controlled metastable dynamics of exercise-induced psychobiological adaptation

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Key words: *adaptation; exercise; fatigue; performance; metastability; bifurcation; constraints; soft-assembly; self-organization.*

Summary. *A fundamental question in the theory of psychobiological adaptation and specifically of sports training is the problem of how adaptation to sports performance demands occurs as a consequence of systematic exercise. In this position paper, we review some results of our previous and current research conducted on several different levels of exercise-induced effects. Based on these results, we contend that the control of psychobiological systems during exercise is constraints based. Constraints direct the flow of behavioral changes on a rugged metastable landscape. Such adaptive behavior is soft-assembled, consisting of context-sensitive cooperative configurations of system components that dwell on different time scales.*

Background

One reason why biological systems are titled as "complex" is because they are hard to be understood within the framework of one underlying theory that would, at least in general, explain the basic principles of their functioning. On the other hand, this is the main aim of scientific theories: the explanation of maximal set of phenomena using minimum number of independent principles. The integrative functioning and the multivariability of biological systems is a trivial but disturbing fact for any scientist striving to capture the big picture of biological systems. At the first glance, from these considerations it would seem that complex biological systems could not satisfy the aims of general scientific theories. There may be fragmented, highly specialized explanations for different domains of biological systems, but not unified principles able to deal with biological complexity. This is the current state of affairs in the majority of sciences dealing with the biological order.

Any macroscopic behavior of a complex adaptive system, e.g. a sport performance, is a result of an immense number of highly coordinated spatio-temporal processes. In other words, macroscopic behavior is a collective effect of sets of highly interdependent components within the system, i.e. a result of their synergy in space and time. Not so recently it has been shown (2) that such collective (or cooperative) effects can be successfully studied by searching for, so-called task-specific, and hence, soft-assembled, collective variables, which capture the coherent, coordinated behavior of system component processes. It has been argued that these collective variables, otherwise called "order parameters" since they represent the macroscopic state of biological order, are the most adequate for studying complex systems behavior. Presumably, the reason for this is because these variables capture system behavior in its approximately linear, but also nonlinear regime of operation. These variables are best determined close to the points of qualitative, discontinuous change where a large set of other variables become subservient to them and the behavior of the system becomes low dimensional. As they contain compressed information of all subservient variables, they also become the most informative quantities, i.e. "informators" to the external observers (e.g. researchers) about the macroscopic behavior of complex systems (3).

One viable way of investigating the type of integration of any complex system seems to be by testing the behavior of collective variables under the change of constraints. Complex adaptive systems may exhibit different kinds of collective behavior such as stationary, nonstationary, i.e. metastable, periodical, or chaotic behavior. The mode of behavior depends basically on the configuration of constraints, i.e. control parameters, variables that do not specifically prescribe or impose the behavior of

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[1] Actually some complexity measures are based on the estimating the difficulty of an observer to infer a model of the system of interest or on the convergence of model's predictions with system's behavior (1).

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the system but constrain it indirectly. In short, the control of dynamical systems is constraints based. For a certain configuration of constraints, nonlinear systems suffer a qualitative change of its behavior, a partial or complete rearrangement of its component interactions and hence a discontinuous change of the order parameter. These events are so-called bifurcation phenomena. One reason why this phenomenon arises is because there is more than one possible stable state and this property, i.e. multistability, stems from the nonlinear interactions between system components.

Metastability is an inherent property of multistable complex adaptive systems (4). It is usually invoked as a mechanism responsible for their behavioral flexibility and is manifested in the transient and nonstationary evolution of such systems (5). Metastable behavior typically arises when there are many weakly stable or weakly unstable system states so that it switches spontaneously among various cooperative configurations of its degrees of freedom. These and other connected concepts of nonlinear dynamics seem to be universal in a sense that they can be detected in systems widely separated with respect to their level of organization or material substrate. Nonlinear effects such as bifurcations, metastability, hysteresis have been already observed at various levels of organization of psychobiological systems subject to exercise and some of them will be briefly reviewed here.

In contrast to the conceptual universality, there is a vast diversity in the nature of the collective variables (order parameters) and associated control parameters characterizing the variety of behaviors that emerge. Presumably, this diversity is, in part, a consequence of the accumulated contingencies and evolutionary stabilized context dependencies of biological systems. It is this unity of universal phenomena and context dependency that is a hallmark of complex adaptive system behavior. Our aim in this position paper is to show how exercise-induced phenomena at different time scales and levels of biological system organization strongly indicate nonlinear integrative mechanisms at work as manifested by the dynamics of a variety of context dependent, task-specific, i.e. soft-assembled, collective variables.

Performance level. Nonlinearities in dose-effect interactions in sports training process

By the 1980s of the last century, two general types of organismic adaptive responses to exercise were experimentally firmly established (6). These adaptive effects dwell on time scales of days, weeks, and months. Both depend mostly on the temporal concentration of the workload. For lower workload density, a positive effect accumulates on approximately daily basis. The second one, so-called long delayed training effect, the positive training effect develops after prolonged suppression of the performance variable, on time scales of few weeks to few months.

First, what becomes immediately visible from Fig. 1 (A and B) is that there is no one-to-one mapping between the workload provided by training stimuli, i.e. dose, and the training effect. By slowly increasing the workload and then decreasing it, a "memory effect" is being produced, i.e. a lasting increase in the performance. It is important to note,

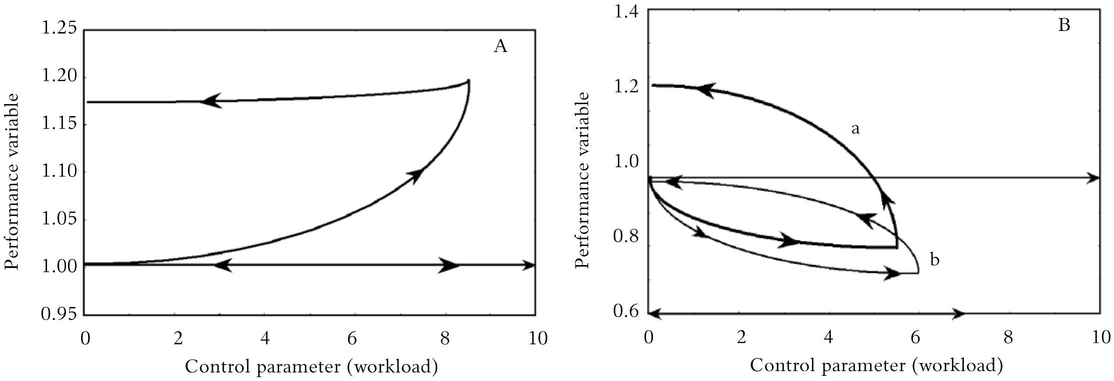

Fig. 1. Two general types of adaptation to training workload represented in the control space

A. Increasing the workload increases the performance. During decreasing the workload, performance does not follow the same path but typically follows a less steep trend. B. Trajectory (a) depicts the so-called long delayed training effect where during the increasing phase of the workload, a suppression of the performance variable is attained (an overreaching phase), and during the decreasing phase of the workload, a positive training effect follows. For a small change of the workload increasing history one gets trajectory (b). The overreaching phase does not convert into positive training effect, but to an overtraining phase depicted by asymptotic convergence of the performance toward the initial state while decreasing the workload. This event marks the overreaching to overtraining bifurcation (adapted from 10).

however, that these residual, i.e. "memory effects," are transient, that is, strictly speaking, they are not stable states (attractors) of system's dynamics toward which the performance would tend in the long term. This means that the changes of the coupling tendencies of component processes within the complex psycho-physiological system are of ephemeral character, i.e. they are soft-assembled, and are prone to reconfigure asymptotically if the kind of workload, i.e. context, that stimulated their emergence ceases to exist. These temporary stable configurations corresponding to temporal characteristics of training stimuli may dwell on different time scales (7, 8). Such behavior points to the inherently metastable, i.e. temporary stable, dynamics of the exercise-induced couplings in complex neurobiological systems. It indicates that coordinative metastability of functional components of system may be a generic mechanism that underpins the flexibility and capacities for adaptation and re-adaptation of athletes toward ever changing environmental demands.

Second, a small change in the workload history may produce an overtraining effect (6) (see Fig. 1 B and the explanation therein). Because bifurcations, i.e. qualitative discontinuous changes, and hysteresis effects are demonstrably present in these performance variables, it seems reasonable to assume that the maxima of physical abilities like power, strength, speed, and so forth may be treated as collective variables (informators) of athletes conceptualized as complex adaptive systems. This seems reasonable since maximal values of these variables are being attained by the, at the moment, best possible coordination of component processes encompassing the whole interval from metabolic to interorganic levels. As informators, they inform external observers about the level of the athlete-task coupling fitness (9).

The overreaching-overtraining bifurcation seems to be a very important indicator of the highly nonlinear integration of the human psychobiological components. The recovery period needed for overcoming the overtraining consequences may be naturally explained as a nonlinear hysteresis effect. Since overtraining may be classified as a fatigue phenomenon, it follows that there may be a scaling relationship between different types of fatigue phenomena spanned on different time scales (7, 8, 11). More generally, such considerations mean that sports training has to be modeled as a multiscaled process (12) dwelling on a metastable rugged energy landscape (7).

Electrophysiological level. Metastability of heart dynamics

Recent research appears to indicate a potential advantage of a fractal framework application for analyzing cardiovascular signal data. These data are largely analyzed using traditional time and frequency domain measures. However, such measures may not be detectable by traditional analysis methods. The complementary role of advanced signal analysis methods and emerging multiscale techniques is, therefore, an important frontier area of investigation (13, 14). Moreover, the attenuation of an oscillatory pattern or its impaired responsiveness to a given stimulus can also reflect an altered target function and thus can furnish interesting prognostic markers. The dynamic assessment of these changes may provide important diagnostic and prognostic information, not only in relation to cardiovascular, but also noncardiovascular changes. As linear methodologies fail to provide significant information in conditions of extremely reduced variability (e.g. strenuous exercise, heart failure) and in presence of rapid and transient changes, the development of new nonlinear approaches seems to provide a better framework for the cardiovascular system investigation (15) as a part of a complex adaptive system.

In particular, techniques based on mono- and multifractal analyses, raised from nonlinear dynamics, have been successfully applied to the investigations of living systems (14). However, it is relevant to understand which methods should be selected and applied. Observational studies have suggested that some indices describing nonlinear dynamics, such as fractal scaling exponents, heart rate turbulence, and deceleration capacity, may provide useful prognostic information in various clinical settings and their reproducibility may be better than that of traditional indices. For example, approximate entropy, a nonlinear index of heart rate dynamics, which describes the complexity of RR interval behavior, has provided information on the vulnerability to atrial fibrillation (16).

In a recent study, standard 12-lead ECG signals were recorded during provocative exercise tests. Athletes accomplished a typical Rouffier test protocol. During the test on bicycle ergometer, they underwent protocol, which consisted of warm-up (100 W) and load (200 W). The volunteer participants were 14 healthy long-distance runners aged 20±2.4 years. Computerized ECG analysis program "Kaunas-load" was used for data recording and analysis. The parameter discriminants calculated from the following ECG time series were duration of RR interval taken from the II standard lead, duration of QRS complex, duration of JT interval, and amplitude of ST segment taken from the V standard lead. Two synchronous time series (x_n:=0, 1, 2,..) and (y_n:=0, 1, 2,..), which represent the ECG parameter measurements, were structured and analyzed using the numerical characteristics of the second-order matrix and the main components of it (17, 18):

$$A_n := \begin{bmatrix} x_n & x_{n-1} - y_{n-1} \\ x_{n+1} - y_{n+1} & y_n \end{bmatrix} \qquad (1)$$

The most informative characteristics raised from matrix definitions and it was discriminants of matrix:

$$\mathrm{Dsk}\ A_n=((x_n-y_n)^2+4((x_{n-1}-y_{n-1})*(x_{n+1}-y_{n+1}))) \qquad (2)$$

Complexity measure, reflecting the degree of coupling between heart electrophysiological variables, was expressed as the value of discriminant (Dsk). If the value of discriminants decreases and is close to zero, the interaction between two synchronous numerical time series (ECG signals) increases, but the complexity of the adaptive system decreases.

ECG signals recorded during exercise tests were used to identify and analyze the coupling dynamics of heart electrophysiological parameters in order to reveal dynamical peculiarities of the human body processes and fatigue, depending on different scales of observation. Reduced discriminant of RR interval and QRS complex concatenation during exercise test indicate the increase of coherence between these indices. The onset of workout is conditioned by dynamical changes of regulatory processes, which are likely a combination of central and peripheral factors.

The variability of registered signals accompanied by alterations according to provocative physical load enabled the formation of a new stable state through fluctuations. The analysis of different levels of the system revealed different fluctuation dynamics. An examination of supplying (cardiovascular) system was carried out by the evaluation of the ST segment and JT interval coupling, which allowed detection of endogenous, functional changes within the heart (see Fig. 2 A and B). The instant increase of fluctuations level was noticed at the onset of the exercise test in the interaction of ST segment and JT interval, and the values of discriminants were relatively higher than in systemic level concatenations.

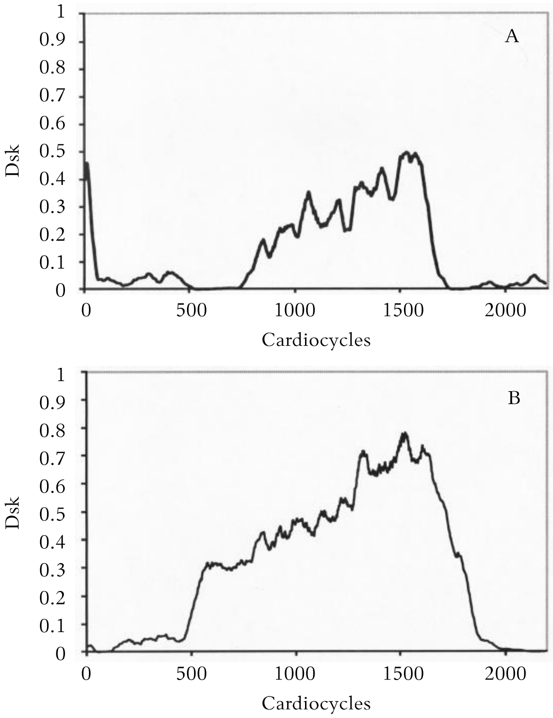

Fig. 2. Concatenation dynamics between RR interval and QRS complex (A) and between ST segment and JT interval (B) in the participant V.M. during bicycle ergometry

Depending on the scale of observation notably differentiated the level of fluctuations and consequently the values of interactions expressed by discriminants of the matrices. The faster and substantial transitions of the dynamics to the new state were indicated in subsystemic level (coherence of ST segment and JT interval, see Fig. 2B). Fluctuations of coupling dynamics result in the emergence of substantially new stable state and suggest decreased resistance to fatigue. Finally, the analysis of the typical individual behavior of the dynamic physiological system shows that provocative exercise test induces an increase of fluctuations as the fatigability enhances. The coherence between parameters often is being modulated in an individual-dependent manner revealing their local functionality with respect to the global context. The dynamic coupling between heart electrophysiological parameters shows characteristic patterns of a context dependent metastable, soft-assembled functioning, typical for flexible adaptive biological systems.

Kinematic level. Why and how exercise terminates? Metastability and exercise termination

Exercise termination is a macroscopic event. It is manifested as an abrupt shift of the activity, toward lower energy expenditure levels or rest. The activity shift exists on a much shorter time scale than the activity itself, which may dwell on scales of seconds, minutes to hours. In a recent study (11), we sought to pinpoint the possible mechanism of exhaustion-induced exercise termination. On 5 days during 2 weeks, six participants who were familiar with the task performed a quasi-isometric arm-curl exercise holding an Olympic bar with an initial elbow flexion of 90 deg to the point of spontaneous termination of the exercise due to exhaustion. Participants were encouraged to persist to exhaustion even if the initial position was lost, so the task constraints did not include a constant exertion requirement.

As shown in Fig. 3 (for details see 11), it seems very likely that as fatigue develops, the instability encompasses higher control loops presumably responsible for attention, motivation, and so forth.

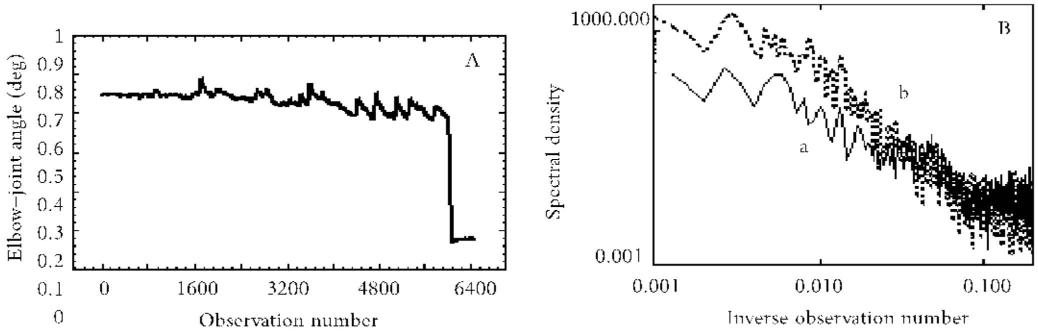

Fig 3. A. Time series of the elbow-angle data of participant 1. B. A typical difference of power spectral density values of the online fluctuations of the elbow angle in the first (a) and the last (b) third of the quasi-static exercise. The elbow angle variability difference becomes larger already on subsecond interval and grows toward larger time scales signifying developing instability of the system under fatigue.

The power spectrum data showed a globally correlated enhancement of variability of the order parameter of the quasi-isometric action kinematics, the elbow-joint angle. Hence, from the dynamical point of view, the exercise-induced fatigue represents an ever-increasing destabilization of the previous configurations of the neuromuscular network and their continual reconfiguration, under immediate organismic, task, and environmental constraints. In a word, fatigue, seen dynamically, may be viewed as a typical constraint-induced self-organization of metastable, soft-assembled configurations of action system components.

On the other hand, since the system before termination dwells close to the instability point, many contingent and also emergent accidental events (a small increment of discomfort or pain, onset of nausea, dizziness, and so forth) may sufficiently perturb the already destabilized action system's organization. This may trigger the exercise termination, i.e. the switch toward the low activity, rest state, being a global minimum of the rugged metastable energy landscape. In this sense, the exercise termination is an emergent phenomenon: a consequence of fatigue-induced instability/dissolution of the couplings within the distributed control loops responsible for the maintenance of the intended activity. This means that the system flows through its dynamical states controlled by immediate constraints, and there is no need for a specialized exercise-termination module or a superordinate "calculations performing algorithm" within the brain that would be responsible for controlling and switching off the activity by exerting commands to the periphery. What suffices is a distributed neuromuscular network of components that self-organize under constraints into a local, ephemeral, or eventually a global energy minimum state. This nonlinear, *constraint-based control* of the exercise flow and termination is also experimentally demonstrable in the hysteresis behavior of the collective variable with respect to some physiological constraints (19).

Psychological level. Emergence and dynamics of task-related thoughts and urges to terminate during exhausting exercise

For a long time it has been known that close to exercise termination, the attention focus becomes more adhered to task-related thoughts (TRT). This fact may be a consequence either of a deliberate strategy used by athletes or simply because TRT are more easily attainable close to the exercise termination. If the last is correct than one might ask, why is this so? We conducted two preliminary experiments with aim to shed a light on these issues from dynamical viewpoint. In the first experiment, participants were asked to impose and maintain intentionally any kind of task-unrelated thought (TUT) and during the treadmill exercise (80–90% of HRmax) to report about possible spontaneous switches to TRT. In the second experiment, another group of participants was asked to report about the spontaneously emerging urges to terminate the quasi-isometric exercise (80% of 1 RM) by uttering "down" and "up" if/when the motive to persist recovered. Both exercises were performed until exhaustion. From the time series obtained in the first experiment (Fig. 4A), we calculated the dwell times, that is times the system spends in one of the states, i.e. TUT or TRT, and probabilities of finding the system in one of those states for 10 nonoverlapping time windows. From the time series obtained in the second experiment (Fig. 4B), we calculated the probabilities of finding the system in "up" or "down" states, also for 10 nonoverlapping windows.

Preliminary results of both experiments show that as exercise unfolds, probabilities of switching to the TRT states and emergence of urges to terminate the exercise (down states) grow (see Fig. 4 A and B).

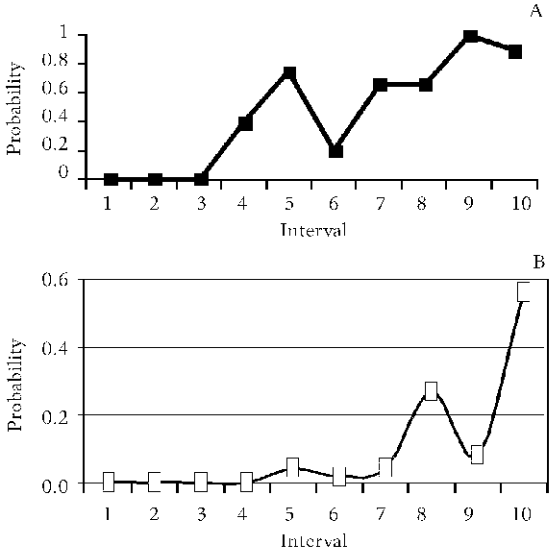

Fig. 4. A. Change of probability of finding the system in the "task-related thought (TRT)" state. B. Probability of finding the system in the "urge to terminate" state. The horizontal axis represents the observed time window.

In other words, the intentionally imposed states that were intended to be kept over the whole exercise period switched spontaneously, i.e. involuntarily, to their antidotes. Consciously accessible urges[2] to cancel emerged with growing probability in the brain-body system under the increasing bodily changes. These data indicate the possibility that systems participating in the control of exercising activity are themselves subject to dynamic instabilities. That is, brain systems do not only integrate peripheral information but are also strongly constrained by it, and this is evidenced by the change and lost of stability of intentionally imposed motives and the type of the attention focus as the fatigue develops. In both cases, initially imposed states passed from stable into metastable phase and ultimately became absolutely unstable spontaneously giving a way to the unique dynamically globally stable state (20). This fits neatly with the data discussed previously about the developing instabilities during the voluntarily maintained exercising activity. The bifurcations in the dynamics of these variables make them viable candidates for representing the task-specific collective behavior in these separate psychobiological levels.

In general, it is highly likely that developing dynamic instabilities within the whole neuro-muscular axis, encompassing the psychological, physiological and motor/action domains are a hallmark of psycho-physiological fatigue and a general principle of exercise termination. The termination is triggered always when the previous cooperative dynamic state becomes absolutely unstable or is perturbed by some contingency, so that it finds the global energetic minimum, a unique state that remains stable.

Conclusions

The dynamics of biological integration is highly likely to be nonlinear, soft-assembled, and metastable. Generally, the exercise-induced effects and control may be explained through the "*self-organization under constraints*" paradigm. This generic mechanism would enable the immense behavioral flexibility of biological systems in their permanent striving to adapt to task and environmental demands. It seems likely that a viable way of studying psychobiological adaptation under exercise is the study of collective variables, which are products of the cooperative, coordinated interactions among component processes. As shown in this paper, potential collective variables may be observed at different levels of the human psychobiological continuum. Especially significant should be the study of the reconfigurations of such coordinated dynamics on different time scales and at the same time, the study of key control parameters, i.e. configurations of constraints, that act upon the stability properties of such coordinated states. Exercise-induced psychobiological adaptation likely evolves as a consequence of such soft-assembled, ephemeral, cooperative states dwelling on different time scales.

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[2] Note that these urges are simply consciously interpreted collective states of the affective-motivational components of the psycho-physiological system of the athlete.

Sukelta fizinio krūvio ir kontroliuojama apribojimais nestabili psichobiologinės adaptacijos kaita

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Raktažodžiai: adaptacija, pratimas, nuovargis, atlikimas, metastabilumas, bifurkacija, apribojimai, tolygi atranka, saviorganizacija.

Santrauka. Esminis psichobiologinės adaptacijos teorijos, ypač sporto mokslo klausimas – kaip pasireiškia adaptacija priklausomai nuo sportinio krūvio poreikių. Šiuo aspektu mes nagrinėjame kai kurių ankstesnių mūsų ir dabartinių mokslinių tyrinėjimų rezultatus, gautus analizuojant įvairių lygių fizinio krūvio sukeltas pasekmes. Remiantis šiais rezultatais, galima teigti, kad psichobiologinės sistemos kontrolė krūvio metu pagrįsta apribojimais, kurie yra tiesioginis elgsenos pokyčių srautas, pagrįstas metastabilumu. Toks adaptacinis elgesys yra tolygiai pasirenkamas, jis sudarytas iš jautrių kooperacinio pobūdžio sistemos elementų, kurie pasireiškia skirtingose laiko skalėse.

References

1. Badii R, Politi A. Complexity. Hierarchical structures and scaling in physics. Cambridge Nonlinear Science Series 6: Cambridge University Press; 1997.
2. Haken H. Synergetics. An introduction. Heidelberg: Springer; 1983.
3. Haken H. Information and Self-Organization. A macroscopic approach to complex systems. Heidelberg: Springer; 2000.
4. Friston KJ. Transients, metastability and neuronal dynamics. Neuroimage 1997;(5):164-71.
5. Fingelkurts AA, Fingelkurts AA. Making complexity simpler: multivariability and metastability in the brain. Int J Neurosci 2004;114(7):843-62.
6. Verkhoshansky YV. Programirovanie i organizacija trenirovochnogo processa. (Programming and organization of the training process.) Fizkultura i Sport. Moskow; 1985.
7. Hristovski R, Kocarev Lj, Dimitrovski D. Long-range correlations in training patterns. An evidence for the fractal nature of the training process. In: Hughes M. Franks I.M, editors. Computer science and sport iii and performance analysis of sport v. Centre for Performance Analysis. UWIC. Cardiff; 2001. p. 41-7.
8. Hristovski R. Korelacii so dolg opseg vo vremenskite trenazni obrazci i hierarhiski dinamichki modeli na trenazniot (Long-range correlations in the temporal training patterns process and hierarchical dynamical models of training process.) Fizicka Kultura 2004;32(1-2):20-3.
9. Van Orden GC, Kloos H, Wallot S. Living in the pink: intentionality, wellbeing and complexity. In: Hooker CA, editor. Philosophy of complex systems. Handbook of the philosophy of science. Amsterdam: Elsevier. In press 2010.
10. Hristovski R. Nelineino modelirane na vzaimodejstvijata mezdu trenirovochen stimul i trenirovochen efekt. (Nonlinear modeling of training stimuli – training effect interactions.) Sport Science 1998;2:180-4.
11. Hristovski R. Balagué N. Fatigue-induced spontaneous termination point – nonequilibrium phase transitions and critical behavior in quasi-isometric exertion. Hum Mov Sci 2010;29(4):483-93.
12. Hristovski R. Sportskiot trening kako sinergetski i multifraktalen fenomen. (Sports training as a synergetic and multifractal phenomenon.) Proceedings of the First Scientific Conference on Science and Sport. Skopje, Macedonia; 1996. p. 164-7.
13. Costa MD, Peng CK, Goldberger AL. Multiscale analysis of heart rate dynamics: entropy and time irreversibility measures. Cardiovasc Eng 2008;8:88-93.
14. Voss A, Schulz S, Schroeder R, Baumert M, Caminal P. Methods derived from nonlinear dynamics for analysing heart rate variability. Philos Transact A Math Phys Eng Sci 2009;28:367(1887):277-96.
15. Montano N, Porta A, Cogliati C, Costantino G, Tobaldini E, Casali KR, et al. Heart rate variability explored in the frequency domain: a tool to investigate the link between heart and behavior. Neurosci Biobehav Rev 2009;33(2):71-80.
16. Huikuri HV, Perkiömäki JS, Maestri R, Pinna GD. Clinical impact of evaluation of cardiovascular control by novel methods of heart rate dynamics. Phil Trans R Soc A 2009;367(1892):1223-38.
17. Berskiene K, Lukosevicius A, Jarusevicius G, Jurkonis V, Navickas Z, Vainoras A, et al. Analysis of dynamical interrelation of electrocardiogram parameters. Electronics and electrical engineering. Technologija (Kaunas) 2009;7(95):95-8.
18. Smidtaite R, Navickas Z, Vainoras A, Bikulciene L, Poskaitis V. Evaluation of coherence of t-wave in different leads. Electronics and Electrical Engineering. Technologija (Kaunas) 2009;5(93):113-6.
19. Balagué N, Hristovski R. Modeling physiological complexity: dynamic integration of the neuromuscular system during quasi-static exercise performed until failure. In: J. Wiemayer, A. Baca & M. Lames, editors. Sportinformatik gestern, heute, morgen: Festschrift zu Ehren von Prof. Dr. Jurgen Perl, Gelebte, Sportwissenschaft; 2010. Band 4. p. 163-71.
20. Balagué N, Hristovski R, Vázquez P. Emergence and dynamics of task-related thoughts during fatiguing exercise. In: Korkusuz FH, Tsolakidis EE, editors. Proceedings of the 15th Annual Congress of the European College of Sport Science; 2010 Jun 23-6; Antalya, Turkey, p. 666.

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STUDY II

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Dynamics of Perceived Exertion in Constant-Power Cycling: Time- and Workload-Dependent Thresholds

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Purpose: The purpose of this study was to test the dynamics of perceived exertion shifts (PES) as a function of time and workload during constant-power cycling. **Method:** Fifty-two participants assigned to 4 groups performed a cycling task at 4 different constant workloads corresponding to their individual rates of perceived exertion (RPEs = 13, 15, 17, and 19, respectively). PES ("increased"/"decreased" perceptions) without magnitude were reported when they occurred. PES "increased" percentages in different nonoverlapping temporal windows and for each workload were calculated to study the time- and workload-dependent relations, respectively. **Results:** A fluctuating PES dynamic characterized the cycling at RPE-13 and RPE-15. In contrast, a nonfluctuating PES dynamic characterized the cycling at RPE-17 and RPE-19. A time-dependent PES threshold, manifested as a switch from PES fluctuating to nonfluctuating dynamics, emerged in the RPE-15 condition near volitional exhaustion. A workload-dependent PES threshold occurred from RPE-15 to RPE-17. **Conclusions:** Time- and workload-dependent thresholds were revealed studying the PES dynamics in constant cycling. Monitoring PES can complement or provide an alternative to the use of physiological measures for an accurate control of training workloads.

Keywords: dynamical systems, fluctuating dynamics, perceived effort shifts, voluntary exhaustion

The subjective feeling of heaviness and strain stemming from physical effort, so-called perceived exertion (PE), has been widely adopted for evaluating the subjective perception of exercise intensity (Noble & Robertson, 1996). A linear relation between the reported rate of perceived exertion (RPE) and workload intensity, or "time on task," has been shown in several studies (Baldwin et al., 2003; Borg, 1998; Crewe, Tucker, & Noakes, 2008). Recent findings have suggested that the linear increase of RPE during physical effort could be a product of the low-resolution sampling rate (minutes) or the typically imposed rating strategies (St. Clair Gibson et al., 2006; Tucker et al., 2006). RPE was recorded in real time in only a few studies (i.e., as the participants experienced increased sensation of effort; Aragonés, Balagué, Hristovski, Pol, & Tenenbaum,

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2013; Nakamura et al., 2008). Moreover, Aragonés and colleagues (2013) found shifts in the RPE dynamics as a function of the RPE resolution sample during constant cycling. The percentage of RPE fluctuations (i.e., switching between higher- and lower-scale values) increased when RPE was reported every 15 s rather than every minute. Nonmonotonic shifts of RPE were recorded in even-paced running as periods of flat RPE interjected by sharp increases with no reduction of RPE (Thomas, Stone, Thompson, St. Clair Gibson, & Ansley, 2012). Although RPE reductions are rarely described in the literature, fluctuations in the feeling of heaviness during constant exercise are frequently mentioned. These fluctuations are typically attributed to metabolic adjustments at the exercise outset (Haller & Vissing, 2002). Nevertheless, further scientific inquiry is needed.

The practice of monitoring only *PE shifts* (PES; i.e., "increase"/"decrease" in perceptions) without expressing their magnitude and reporting them in real time has revealed that PES follow a dominant fluctuating dynamic during constant-power cycling performed under different conditions (duration, intensity, and termination) switching toward a nonfluctuating dynamic when approaching volitional exhaustion (Aragonés et al., 2013). Although fluctuations are a hallmark of biological signals evidenced when monitoring physiological (Bassingthwaighte, Liebovitch, & West, 1994) and psychological (Delignières, Fortes, & Ninot, 2004; Gilden, 2001; Van Orden, Holden, & Turvey, 2003) variables, they are sometimes viewed as artifacts (Tucker et al., 2006). The dynamical systems approach assigns to these variables a functional role resulting from the changing interaction and adaptation of the working system to its environment (Van Orden, Kloos, & Wallot, 2011). A fluctuating dynamic and thresholds in psychobiological variables (e.g., distinguishing stable and unstable phases) have been detected previously while testing constant and incremental power exercises performed up to volitional exhaustion (Balagué, Aragonés, Hristovski, García, & Tenenbaum, 2014; Hristovski, Venskaityte, Vainoras, Balagué, & Vázquez, 2010).

The study of PES dynamics led Aragonés and colleagues (2013) to establish two effort phases during continuous cycling until volitional exhaustion. The first phase was characterized by fluctuating PES (i.e., alternation of "increase"/"decrease") in reports; the second phase, approaching the exercise termination point, was characterized by a continuous "increase" in reports. While fluctuating PES dynamics reflect a stable state, the nonfluctuating dynamics are associated with instability and imminent cessation of exercise. Thus, the purpose of the current study was to evaluate the PES time-dependent and PES workload-dependent thresholds for a wide range of workload intensities (e.g., from moderate to very heavy on Borg's scale) as criteria to detect critical effort volumes and effort intensities of training and competition. The detection of such thresholds allows for the development of efficient training strategies geared to prolong the stable time phases (e.g., below the threshold) or delay the unstable phases (e.g., above the threshold; Balagué, Hristovski, Vainoras, Vázquez, & Aragonés, 2013).

Work rate based on RPE instead of physiological variables has been increasingly supported during the last decades as a valid training methodology (Dunbar et al., 1992; Kang, Chaloupka, Biren, Mastrangelo, & Hoffman, 2009). Researchers have proposed the use of ordinal instead of cardinal scales such as the Borg's RPE (Laming, 1997; Stewart & Brown, 2004) because there is no long-term internal absolute scale for measuring sensations and judgments in psychophysical tasks are context-dependent. The assessment of PES dynamics does not require numerical scale and can allow for reporting changes of any magnitude, thereby providing an alternative, or complementary, method to the commonly used RPE values for monitoring workloads.

In the present study, we investigated the time- and workload-dependent PES dynamics during a cycling task performed at four constant-power workloads corresponding to the individual RPEs of 13, 15, 17, and 19. We hypothesized that during cycling at RPE-13 and RPE-15, the fluctuating PES dynamics would dominate. Conversely, we hypothesized that during cycling at RPE-17 and RPE-19, the nonfluctuating PES dynamics would dominate. Furthermore, we expected that PES would show sharp transitions (i.e., "thresholds") from fluctuating to nonfluctuating dynamics as a function of both "time on task" and workload intensity.

METHOD

Participants

We conducted a power analysis (Faul, Erdfelder, Lang, & Buchner, 2007) using moderate effect size $f = .25$, $\alpha = .05$, $1 - \beta = .95$, with four RPE conditions, four repeated measures with .50 mean correlations, a noncentrality parameter λ of .26, $df = 9$, 144. The sample size needed was $n = 52$. Fifty-two Caucasian physical education students (27 male and 25 female) with no sport specialization but engaged in a wide range of aerobic activities at least three times a week volunteered to participate in this study. Following an incremental test to establish their peak power output (PPO), they were randomly assigned to four constant-workload groups ($n = 13$ each) corresponding to selected Borg's RPE 6-to-20 anchors: RPE-13 (i.e., *somewhat heavy*), RPE -15 (i.e., *heavy*), RPE-17 (i.e., *very heavy*), and RPE-19 (i.e., *extremely heavy*). The groups' characteristics are displayed in Table 1. Independent group assignment was applied to avoid training adaptation typically present in repeated measures of the same group (Céline et al., 2011; Green,

TABLE 1
Gender Distribution, Means and Standard Deviations for Age, and BMI (kg/m^2) in the Four Initial RPE Intensities

	Gender Distribution		*Age*		*BMI*	
RPE 6–20 Scale	*Men*	*Women*	*M*	*SD*	*M*	*SD*
13	7	6	22.09	4.02	21.38	1.32
15	7	6	21.59	3.84	21.05	1.12
17	7	6	20.81	3.08	20.88	0.91
19	6	7	22.87	3.26	21.57	1.09

Note. RPE = rate of perceived exertion; BMI = body mass index.

Pritchett, McLester, Crews, & Tucker, 2007). Prior to the onset of the study, participants completed a medical questionnaire to provide their health status information. Subsequently, they read and signed the informed consent form. The study was approved by the review board of the researchers' institution.

Study Design and Procedure

The study's design consisted of random assignment of the participants into four independent experimental conditions, each one performing a constant-power cycling task at different workload intensities while reporting their PES. One week prior to the experiment, participants performed an incremental PPO test (adapted from Hutsebaut, Brunet, Thibault, & Hutsebaut, 2002) to determine the workload corresponding to their individual RPE (i.e., 13, 15, 17, or 19 on the 6–20 Borg's scale). All participants were already familiarized with Borg's scale and the PES reporting procedures of this experiment and had been using them in constant and incremental power-cycling exercises at least three times during the previous 2 months. Prior to the onset of the experiment, participants were informed about the characteristics of the cycling task and were provided with written instructions for the "PES monitoring."

Peak Power Output Test

The RPE 6-to-20 scale and its original rating instructions (Borg, 1998) were handed out and verbally explained prior to the PPO test. The PPO test consisted of an initial load of 20 W (for women) and 25 W (for men) followed by increases of 20 W/min (for women) and 25 W/min (for men) until participants could not keep the required cadence (70 rpm) for 5 consecutive seconds in the sitting position. During the last 10 s of every imposed workload increment, participants were asked to self-monitor and report verbally their RPE on the RPE 6-to-20 Borg's scale with the corresponding anchors placed in front of them. The workload values corresponding to RPE of 13, 15, 17, and 19, respectively, were recorded for each participant. If the same RPE value was reported in two consecutive increments, the highest workload value was registered. When a clamped RPE value (13, 15, 17, or 19) was not reported by a participant, the value corresponding to the same Borg's RPE 6-to-20 anchor (12, 14, 16, or 18, respectively) was recorded.

Cycling Task

The cycling task was performed on a cycle ergometer (Sport Excalibur 925900) with saddle and handlebar specifications adjusted to fit the preference of each participant, and it remained identical for both sessions (PPO test and main experiment). The task included two consecutive parts: an incremental warm-up and constant-power cycling performed up to volitional exhaustion (except for the RPE-13 group). The cadence was kept at 70 rpm (Stebbins, Moore, & Casazza, 2014). The warm-up started with a 2-min rest, and then the power output was increased by 20 W/min (for women) and 25 W/min (for men) until reaching the workload fixed in the PPO test as RPE of 13, 15, 17, and 19, respectively. At this moment, the second part (i.e., constant-power exercise) began and continued up to volitional exhaustion when participants could no longer maintain the fixed pedaling cadence for 5 consecutive seconds while in the sitting position. The RPE 6-to-20 Borg's scale was placed in front of the participants during the warm-up period and was removed from their view following the completion of the warm-up. The workload corresponding to the initial RPE was kept until the point of volitional exhaustion. Only in the RPE-13 condition did participants stop after cycling continuously for 20 min because previous research has shown that individuals with similar levels of fitness were able to maintain the pace for more than 60 min at RPE-13 without reaching volitional exhaustion (Aragonés et al., 2013). Only participants with the same RPE values of the PPO test for the target workloads were included in the analysis.

PES Monitoring

During the constant-power exercise, participants monitored their PES according the following instructions: "After completing your warm-up, we ask you to self-monitor and report any shift in your perception of exertion (including light shifts) as soon as they occur, using finger signs: thumb up for any increased PE (meaning "increase") and thumb down for any decreased PE (meaning "decrease"). Any questions?" The PES ("increase" or "decrease") and the time of reporting were recorded.

Once the test began, participants performed the cycling task without being exposed to any verbal or other communication except when they could not keep the pace. All trials were video-recorded to cross-validate the accuracy of the collected data. Upon task completion, participants answered two questions to assess their adherence to: (a) the cycling task (i.e., "Have you pedaled as long as you can, achieving your exhaustion point?"), and (b) the PES-monitoring procedure (i.e., "Have you reported all the shifts in your perception of exertion, including light shifts, as soon as they have occurred?"). An 11-point Likert-type scale with anchors ranging from 0 (*not at all*) to 10 (*greatly*) was used by the participants to answer both questions.

Data Analysis

The PES ("increase"/"decrease") while performing the four constant-power workloads were plotted for each participant to obtain time- and workload-dependent relations in the data series. To study the time-dependent relations of PES, the series were divided into five (RPE-13–15), three (RPE-17), and two (RPE-19) equal nonoverlapping temporal windows (time until test termination of each participant/5, 3, or 2, respectively) to obtain percentages of PES "increase" in those windows:

$$\frac{\textit{Number of PES "increase" in each time window} \times 100}{\textit{Number of total PES in that time window}} \quad (1)$$

The number of windows within each of the four workloads was established with respect to the total number of reports obtained during the test (a minimum of five reports per window was required). When percentages of PES "increases" were 0% or 100%, PES were considered to display nonfluctuating dynamics; when those differed, PES were considered to display fluctuating dynamics.

The null hypothesis of a constant median over time was tested by means of a nonparametric repeated-measures Friedman analysis of variance (ANOVA). Wilcoxon matched-pairs test analysis was also performed to assess statistically significant differences between each couple of windows.

To study the workload-dependent relations of PES, the median and standard deviation of the PES "increase" percentages within each workload were calculated. The null hypothesis of a constant median for four different intensities was tested through a nonparametric Kruskal-Wallis ANOVA. Mann Whitney U matched-pairs test analysis was also performed to assess statistically significant differences between intensities and between genders. We used an alpha level of .01 for all statistical tests and computed effect sizes (Cohen's *d*, 95% CI) to demonstrate the magnitude of standardized mean differences.

RESULTS

All participants reported maximal commitment to the task and reporting requirements of the experiment. Table 2 shows the mean and standard deviation of the PPO test and the workload and time to volitional exhaustion obtained in the four different constant-cycling workloads. Figure 1 displays an example of the individual time series of the PE reports for each.

TABLE 2
Means and Standard Deviations for PPO Test (W), Power Output (W), and Cycling Time (s) in the Four Initial RPE Intensities

	PPO		*Power Output*		*Duration*	
RPE 6–20 Scale	*M*	*SD*	*M*	*SD*	*M*	*SD*
13	298.15	41.11	193.07	37.4	1,200	0.00
15	291.92	41.81	236.92	43.03	781.15	165.66
17	305.62	43.13	269. 23	38.9	346	87.5
19	296.79	40.28	295.00	38.4	153.7	30.5

Note. PPO = peak power output; RPE = rate of perceived exertion.

Time-Dependent PES

All participants cycling at RPE-13 showed a dominant PE fluctuating dynamic during the 20-min cycling (i.e., nonsignificant differences in PES "increase" percentages where found among the five temporal windows). Participants' cycling at RPE-15 showed a dominant fluctuating PES dynamic from Window 1 to Window 4. Nevertheless, close to the volitional exhaustion point, they shifted to a dominant nonfluctuating PES dynamic (continuous "increase" reports; see Figure 2). The median percentage began at 67% (first window), was reduced to 60% (third window), and increased progressively to 100% (fifth window). Repeated-measures Friedman ANOVA revealed a significant effect, $\chi^2(13, 4) = 28.91$, $p < .01$, of exertion time on PES "increase" percentages among the five windows. Wilcoxon matched-pairs test analysis showed statistically significant differences between the fifth and first, $Z(26) = 3.06$; $p < .01$, $ES = 1.98$ (0.80, 3.18), the fifth and the second, $Z(26) = 3.06$, $p < .01$, $ES = 3.26$ (1.69, 4.81), the fifth and the third, $Z(26) = 2.9$, $p < .01$, $ES = 2.10$ (0.92, 3.18), and the fifth and the fourth, $Z(26) = 2.67$, $p < .01$, $ES = 1.31$ (0.41, 2.21), temporal windows. Accordingly, a threshold defining two main effort phases was revealed: The first (from Window 1 to Window 4) was characterized by a predominant fluctuating dynamic, and the second (Window 5) was characterized by a predominantly nonfluctuating dynamic. All participants cycling at RPE-17 and RPE-19 showed a dominant nonfluctuating PES dynamic during the trial to exhaustion. Nonsignificant differences in PES "increase" percentages among the three exertion time windows in the RPE-17 condition and among the two exertion time windows in the RPE-19 condition were found.

Workload-Dependent PES

Figure 3 compares the medians and standard deviations of the PES "increase" percentages obtained in each cycling workload. The percentages grew progressively from 63% at RPE-13 to 100% at RPE-17 and RPE-19. A Kruskal-Wallis

ANOVA revealed significant differences among the workload intensity conditions, $H(190, 3) = 54.81, p < .01$. Mann Whitney U matched-pairs test analysis revealed a significant effect between the following pairs of workloads: RPE-13 and RPE-17, $U(24) = 579.5$, $Z = -4.62$, $p < .01$, $ES = 1.23$ (0.69, 1.73); RPE-13 and RPE-19, $U(24) = 293.0$, $Z = -5.85$, $p < .01$, $E = 1.4$ (0.71, 2.10); RPE-15 and RPE-17, $U(24) = 471.5$, $Z = -5.14$, $p < .01$, $ES = 1.64$ (1.05, 2.20); and RPE-15 and RPE-19, $U(24) = 189.5$, $Z = -5.55$, $p < .01$, $ES = 2.44$ (1.56, 3.30). The nonsignificant difference between RPE-13 and RPE-15 and the difference between RPE-15 and RPE-17 together with a reduction in variability indicated solid evidence of a workload-dependent PES threshold (see Figure 4). Gender failed to be a significant factor in the PES dynamics within each of the workload groups.

DISCUSSION

Time- and workload-dependent PES dynamics were studied under four different constant-power cycling conditions. The "time on task" effect revealed a dominant fluctuating PES dynamic while cycling at RPE-13 and RPE-15. However, a PES threshold defining two-phase patterns was evident at RPE-15: The first phase was dominated by a fluctuating PES dynamic, and the second phase was characterized upon reaching volitional exhaustion by a nonfluctuating PES dynamics (i.e., reporting a continuous PES "increase"). The nonfluctuating PES dynamic was completely dominant while cycling at RPE-17 and RPE-19. The workload-dependent results revealed that PES "increase" percentages grew with power output reaching maximal values at RPE-17 and RPE-19. A threshold between RPE-15 and RPE-17 was manifested by a sharp increase of PES "increase" percentages and a sharp reduction in the variability between both workloads.

From a methodological point of view, our results confirmed previous findings suggesting that reporting only PES ("increase"/"decrease") without expressing their magnitude and reporting them in real time revealed a fluctuating PES dynamic during constant-load cycling (Aragonés et al., 2013). This type of perceived effort monitoring has some advantages with respect to reporting

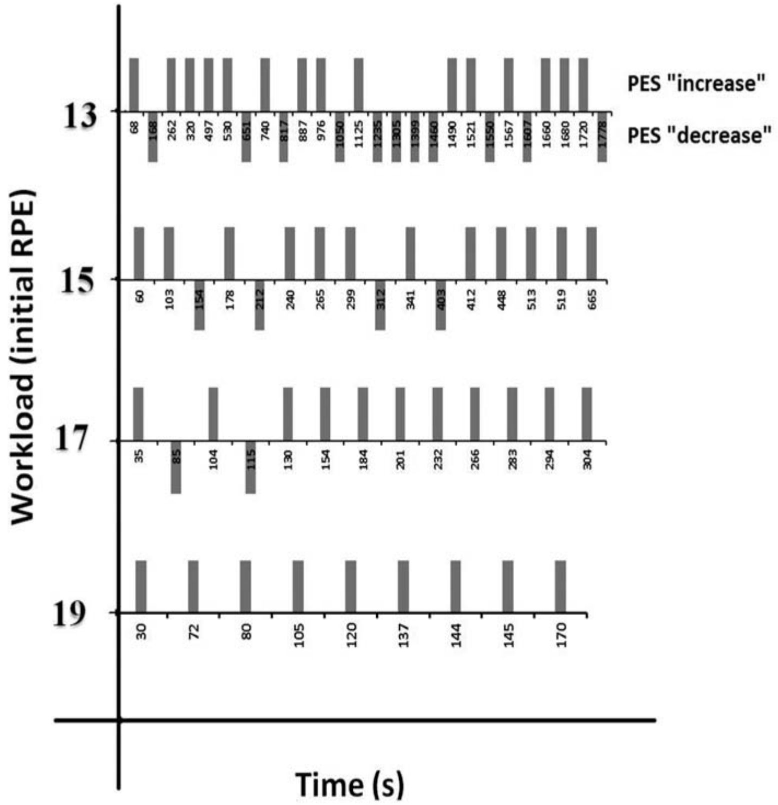

FIGURE 1 Example of one typical individual time series standardized by time in each workload expressed by initial rate of perceived exertion (RPE; 6–20) to compare the dynamics of reporting perceived exertion shifts (PES) "increase" and "decrease" (notice that the reports have no magnitude). While cycling at RPE-13, participants showed an alternation of "increase/"decrease" reports (fluctuating PES dynamics). The "increase" reports dominate at RPE-17, RPE-19, and close to exhaustion at RPE-15 (nonfluctuating PES dynamics).

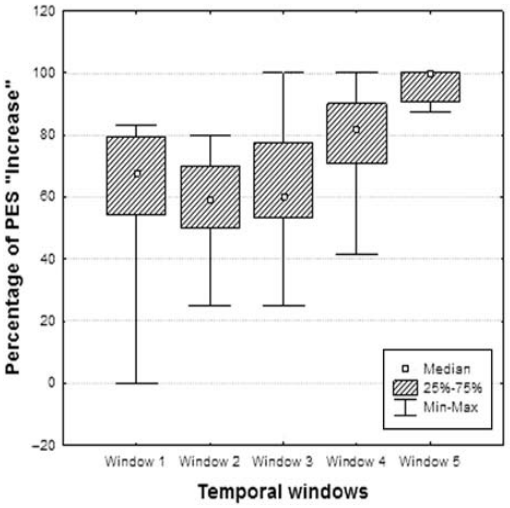

FIGURE 2 Time-dependent median percentages of reporting perceived exertion shifts (PES) "increase" when cycling at a workload corresponding to initial rate of perceived exertion (RPE)-15. A time-dependent threshold is observed between the first four time windows (fluctuating PES dynamics) and the Time Window 5 (nonfluctuating PES dynamics).

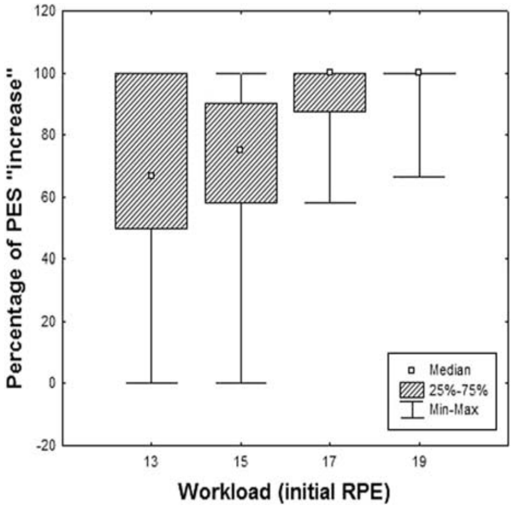

FIGURE 3 Workload-dependent median percentages of reporting perceived exertion shifts (PES) "increase." A workload-dependent threshold is observed between cycling at initial rate of perceived exertion (RPE)-15 (dominant fluctuating PES dynamics) and RPE-17 (dominant nonfluctuating dynamics).

RPE values for the control of training. Specifically, monitoring increases/decreases in PE (a) may help in overcoming the rating problems derived from the lack of a long-term internal absolute scale of sensation and the corresponding confounding sequence effects (Stewart & Brown, 2004); (b) may not require an absolute rating scale and a test administrator to induce an associative (i.e., tuning into bodily symptoms of fatigue) state; (c) can allow for reporting PES of any magnitude (including very light effort) in real time; and (d) can help reveal PES fluctuations (Aragonés et al., 2013). With that said, it is important to note that the PES monitoring method might impair the use of simultaneous cognitive strategies or their assessment such as the attention focus (see Razon, Basevitch, Land, Thompson, & Tenenbaum, 2009). To avoid a potentially priming effect associated with prompting answers and collect all PES when occurring, the reports of the current study were not incited, and thus, participants had to constantly monitor their PE. Under such consistent associative focus, two different regimes of PES dynamics were recorded, fluctuating and nonfluctuating. Thus, the associative focus could not be considered per se as a reporting bias in this experiment.

Consistent with our findings, previous work has also reported a two-phase PES dynamic (i.e., switching from a predominant PE fluctuating dynamic to a nonfluctuating dynamic when approaching volitional exhaustion) while cycling at similar intensities (Aragonés et al., 2013). This PES dynamic is particularly relevant with respect to interpretations of PES fluctuations as data collection artifacts. As such, it seems hard to explain how artifacts practically vanish nearing exercise termination or at very heavy workloads as shown in the current results. The present results also suggest that volitional exhaustion is not only related to the RPE values, but also to the nonfluctuating PES dynamics.

The fluctuating PES dynamics present while cycling at RPE-13 and most of the time at RPE-15 seemed to keep the system's stability and allowed for exercise adherence. In contrast, the dominant nonfluctuating PES dynamics apparent close to volitional exhaustion at RPE-15 and during RPE-17 and RPE-19 seemed to reflect the opposite and hinted toward the system's instability (Hristovski &

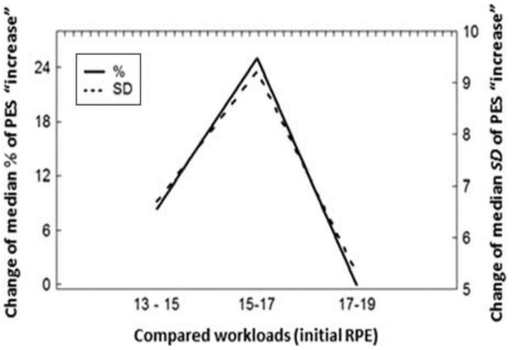

FIGURE 4 Median percentages of perceived exertion shifts (PES) "increase" reports (left axis) and their standard deviations (right axis) comparing pairs of workloads expressed by initial rate of perceived exertion (RPE). A workload-dependent threshold is revealed between cycling at initial RPE-15 and RPE-17. *SD* = standard deviation.

Balagué, 2010). When PES fluctuates, the participant is continuously creating new psychobiological synergies to enable the task's continuation. The stabilization of every new synergy increases the efficiency of the system and might decrease the PE; the destabilization in turn results in the opposite effect (Aragonés et al., 2013). This phenomenon can help explain the dominant fluctuating PES while cycling at RPE-13 and RPE-15, as well as the co-occurrence of sensations of easiness and heaviness during self- and even-paced exercises (Thomas et al., 2012).

Therefore, at the point of termination and shortly preceding it, participants are unable to form a new synergy that would stabilize the PE. Similar unstable fluctuating dynamics close to volitional exhaustion have been found when testing other psychobiological variables such as volition and thought processes during constant and incremental power exercise (Balagué et al., 2014; Balagué, Hristovski, Aragonés, & Tenenbaum, 2012; Tenenbaum, 2001; Tenenbaum & Connolly, 2008), thereby confirming the robustness of the current findings. In such context, volitional exhaustion is explained by the lost of stability mechanism (Balagué et al., 2013; Hristovski & Balagué, 2010).

Based on the present findings, some practical implications for testing and training can be issued. Instead of controlling the training and competition workloads merely on the basis of metabolic and physiological indexes, the self-monitored PES method proposed herein may not only contribute to the accuracy of self-perception in the performer, but can also prove to be a reliable tool for individualized monitoring practices. The PES dynamics along with the RPE values may assist in recognizing the stability or instability profile of the individual cycling workloads. Under the time-dependent and workload-dependent PES thresholds, individuals can adhere in the task, but above these thresholds, volitional exhaustion is soon approaching. Additionally, to increase task adherence, while performing at around RPE-15, it may be beneficial to increase the PES fluctuating phase (below the time-dependent threshold found here) where PES "decreases" are still possible. Specifically, when nearing the volitional exhaustion point, as PES dynamics became nonfluctuating, the cycling task ceased imminently (2–3 min following the last rating). This notion was also confirmed while cycling at RPE-17 and RPE-19 where participants reached volitional exhaustion earlier than 6 min and 3 min into the cycling, respectively.

Concerning the study's limitations, participants in this study were young and active individuals. Consequently, caution is warranted when generalizing current findings—especially those related to absolute workloads or cycling times—to participants who vary in fitness levels. However, the consistency of the PES dynamic and its thresholds, which was evident in each of the participants, and not only as a workload condition mean, suggests that the qualitative results of this study may as well hold true for participants with different fitness levels. Additionally, perceptual sensations of effort seem to be determined by the task characteristics and conditions (Hutchinson & Tenenbaum, 2006; Razon et al., 2009; Stanley, Pargman, & Tenenbaum, 2007). Future studies must evaluate the effectiveness of PES monitoring against conventional RPE reporting on alternative exercise modalities such as running and nonconstant exercise conditions such as incremental or interval training.

In conclusion, by studying time- and workload-dependent PES dynamics in constant cycling, a threshold was revealed upon approaching volitional exhaustion while cycling at RPE-15 and between the workloads corresponding to RPE-15 and RPE-17. Self-monitoring PES dynamics can complement, or provide an alternative to, the use of physiological measures for the control of training workloads. Although its effectiveness must be further established, due to its practical nature, this method should be considered closely within performance-related research and application realms.

WHAT DOES THIS ARTICLE ADD?

This study shows that monitoring PES ("increase"/"decrease") without expressing their magnitude and reporting them as they occur revealed a dominant fluctuating PES dynamic during constant-power cycling at RPE-13 and RPE-15. In contrast, a dominantly nonfluctuating (i.e., only "increase" in perceptions) PES dynamic was observed during cycling at RPE-17 and RPE-19. A time-dependent PES threshold was discerned while cycling at RPE-15. Specifically, the dominant fluctuating PES dynamic switches toward a nonfluctuating dynamic when approaching volitional exhaustion. PES was also shown to have a workload-dependent threshold; specifically, an abrupt change in the median percentage of PES "increase" along with its respective variance (*SD*) was evident when transitioning from RPE-15 to RPE-17. Monitoring the PE dynamics can complement, or be an alternative to, the use of RPE anchors and semantics for the control of training workloads. Taken together, findings from this study introduce a novel and potentially highly accurate tool to measure effort and exertion in physical performance settings.

REFERENCES

Aragonés, D., Balagué, N., Hristovski, R., Pol, R., & Tenenbaum, G. (2013). Fluctuating dynamics of perceived exertion in constant power exercise. *Psychology of Sport and Exercise*, *14*, 796–803.

Balagué, N., Aragonés, D., Hristovski, R., García, S., & &Tenenbaum, G. (2014). Attention focus emerges spontaneously during progressive and maximal exercise. *Revista de Psicología del Deporte*, *1*, 57–63.

Balagué, N., Hristovski, R., Aragonés, D., & Tenenbaum, G. (2012). Nonlinear model of attention focus during accumulated effort.

Psychology of Sport and Exercise, *13*, 591–597. doi:10.1016/j.psychsport.2012.02.013

Balagué, N., Hristovski, R., Vainoras, A., Vázquez, P., & Aragonés, D. (2013). Psychobiological integration during exercise. In K. Davids, R. Hristovski, D. Araújo, N. Balagué, C. Button, & P. Passos (Eds.), *Complex systems in sport* (pp. 82–102). London, UK: Routledge.

Baldwin, J., Snow, R. J., Gibala, M. J., Garnham, A., Howarth, K., & Febbraio, M. A. (2003). Glycogen availability does not affect the TCA cycle or TAN pools during prolonged, fatiguing exercise. *Journal of Applied Physiology*, *94*, 2181–2187. doi:10.1152/japplphysiol.00866.2002

Bassingthwaighte, J. B., Liebovitch, L. S., & West, B. J. (1994). *Fractal physiology*. New York, NY: Oxford University Press.

Borg, G. A. (1998). *Borg's Perceived Exertion and Pain Scales*. Champaign, IL: Human Kinetics.

Céline, C. G., Monnier-Benoit, P., Groslambert, A., Tordi, N., Perrey, S., & Rouillon, J. D. (2011). The perceived exertion to regulate a training program in young women. *Journal of Strength and Conditioning Research*, *25*, 220–224. doi:10.1519/JSC.0b013e3181aff3a6

Crewe, H., Tucker, R., & Noakes, T. D. (2008). The rate of increase in rating of perceived exertion predicts the duration of exercise to fatigue at a fixed power output in different environmental conditions. *European Journal of Applied Physiology*, *103*, 569–577. doi:10.1007/s00421-008-0741-7

Delignières, D., Fortes, M., & Ninot, G. (2004). The fractal dynamics of self-esteem and physical self. *Nonlinear Dynamics in Psychology and Life Science*, *8*, 479–510.

Dunbar, C. C., Robertson, R. J., Baun, R., Blandin, M. F., Metz, K. F., Burdett, R., & Goss, F. L. (1992). The validity of regulating exercise intensity by ratings of perceived exertion. *Medicine & Science in Sports & Exercise*, *24*, 94–99.

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*, 175–191.

Gilden, D. L. (2001). Cognitive emissions of 1/f noise. *Psychological Review*, *108*, 33–56. doi:10.1037/0033-295X.108.1.33

Green, J. M., Pritchett, R. C., McLester, J. R., Crews, T. R., & Tucker, D. C. (2007). Influence of aerobic fitness on ratings of perceived exertion during graded and extended duration cycling. *Journal of Sports Medicine and Physical Fitness*, *47*, 33–39.

Haller, R. G., & Vissing, J. (2002). Spontaneous 'second wind' and glucose-induced second 'second wind' in McArdle disease: Oxidative mechanisms. *Archives of Neurology*, *59*, 1395–1402.

Hristovski, R., & Balagué, N. (2010). Fatigue-induced spontaneous termination point: Nonequilibrium phase transitions and critical behavior in quasi-isometric exertion. *Human Movement Science*, *29*, 483–493. doi:10.1016/j.humov.2010.05.004

Hristovski, R., Venskaityte, E., Vainoras, A., Balagué, N., & Vázquez, P. (2010). Constraints-controlled metastable dynamics of exercise-induced psychobiological adaptation. *Medicina*, *46*, 447–453.

Hutchinson, J. C., & Tenenbaum, G. (2006). Perceived effort—Can it be considered gestalt? *Psychology of Sport and Exercise*, *7*, 463–476. doi:10.1016/j.psychsport.2006.01.007

Hutsebaut, P., Brunet, K., Thibault, G., & Hutsebaut, J. (2002). Protocol for the Maximum Aerobic Power (MAP) Test. *Canadian Cycling Association, 2002*(January), 1–9.

Kang, J., Chaloupka, E. C., Biren, G. B., Mastrangelo, M. A., & Hoffman, J. R. (2009). Regulating intensity using perceived exertion: Effect of exercise duration. *European Journal of Applied Physiology*, *105*, 445–451. doi:10.1007/s00421-008-0922-4

Laming, D. R. J. (1997). *The measurement of sensation*. London, UK: Oxford University Press.

Nakamura, F. Y., Okuno, N. M., Perandini, L. A. S., Caldeira, L. F., Simões, H. G., Cardoso, J. R., & Bishop, D. J. (2008). Critical power can be estimated from nonexhaustive tests based on rating of perceived exertion responses. *Journal of Strength and Conditioning Research*, *22*, 937–943. doi:10.1519/JSC.0b013e31816a41fa

Noble, B. J., & Robertson, R. J. (1996). *Perceived exertion*. Champaign, IL: Human Kinetics.

Razon, S., Basevitch, I., Land, W., Thompson, B., & Tenenbaum, G. (2009). Perception of exertion and attention allocation as a function of visual and auditory conditions. *Psychology of Sport and Exercise*, *10*, 636–643. doi:10.1016/j.psychsport.2009.03.007

Stanley, C. T., Pargman, D., & Tenenbaum, G. (2007). The effect of attentional coping strategies on perceived exertion in a cycling task. *Journal of Applied Sport Psychology*, *19*, 352–363. doi:10.1080/10413200701345403

St. Clair Gibson, A., Lambert, E. V., Rauch, L. H., Tucker, R., Baden, D. A., Foster, C., & Noakes, T. D. (2006). The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. *Sports Medicine*, *36*, 705–722.

Stebbins, C., Moore, J., & Casazza, J. (2014). Effects of cadence on anaerobic capacity following a prolonged, varied intensity cycling trial. *Journal of Sports Science & Medicine*, *13*, 114–119.

Stewart, N., & Brown, G. D. A. (2004). Sequence effects in categorizing tones varying in frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*, 416–430. doi:10.1037/0278-7393.30.2.416

Tenenbaum, G. (2001). A social-cognitive perspective of perceived exertion and exertion tolerance. In R. N. Singer, H. A. Hausenblas, & C. Janelle (Eds.), *Handbook of sport psychology* (pp. 810–820). New York, NY: Wiley.

Tenenbaum, G., & Connolly, C. T. (2008). Attention allocation under varied workload and effort perception in rowers. *Psychology of Sport and Exercise*, *9*, 704–717. doi:10.1016/j.psychsport.2007.09.002

Thomas, K., Stone, M. R., Thompson, K. G., St. Clair Gibson, A., & Ansley, L. (2012). The effect of self- even- and variable-pacing strategies on the physiological and perceptual response to cycling. *European Journal of Applied Physiology*, *112*, 3069–3078. doi:10.1007/s00421-011-2281-9

Tucker, R., Bester, A., Lambert, E. V., Noakes, T. D., Vaughan, C. L., & St. Clair Gibson, A. (2006). Non-random fluctuations in power output during self-paced exercise. *British Journal of Sports Medicine*, *40*, 912–917. doi:10.1136/bjsm.2006.026435

Van Orden, G. C., Holden, J. G., & Turvey, M. T. (2003). Self-organization of cognitive performance. *Journal of Experimental Psychology: General*, *132*, 331–350. doi:10.1037/0096-3445.132.3.331

Van Orden, G. C., Kloos, H., & Wallot, S. (2011). Living in the pink: Intentionality, wellness, and complexity. In C. A. Hooker (Ed.), *Philosophy of complex systems: Handbook of the philosophy of science* (pp. 639–682). Amsterdam, The Netherlands: Elsevier.

STUDY III

Vázquez, P., Hristovski, R., & Balagué, N. (2016). The path to exhaustion. Time-variability properties of coordinative variables during continuous exercise.
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The Path to Exhaustion: Time-Variability Properties of Coordinative Variables during Continuous Exercise

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The aim of this study was to detect qualitative changes in the structure of coordinative variable (elbow angle) fluctuations during a quasi-isometric exercise performed until exhaustion. Seven physical education students performed a quasi-isometric arm-curl exercise holding an Olympic bar (weight: 80% 1RM) with an initial elbow flexion of 90° three times over a period of 4 weeks. They were encouraged to persist, even if the elbow angle was lost, until the fatigue-induced spontaneous termination point (FISTP). Changes in both elbow angles were registered during the task through an electrogoniometer. Detrended Fluctuation Analysis (DFA) was conducted on the initial and final 1024 data points of the series and the associated Hurst exponents were obtained. Multi-way RM ANOVA analyses revealed a significant main effect of the Time on task on the Hurst exponent values but also revealed a significant Trial × Time on task interaction. In the initial (non-fatigue) condition participants tended to produce anti-persistent fBm fluctuations. In the final part before exhaustion a tendency toward persistent fBm was dominant. The trial to trial differences in time-variability structure points to an existence of a long-term variability in control strategies during exercise. The changes in the temporal structure of the elbow angle variability as effort accumulated reflected an increase in low-frequency fluctuations signifying a change in psychobiological mechanisms used to negotiate the task demands. The variability properties of the coordinative variable during exercise may provide information about the dynamic mechanisms that lead to exhaustion.

Keywords: anti-persistent fBm, persistent fBm, synergy, fatigue, exercise, detrended fluctuation analysis

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INTRODUCTION

Exhaustion is a ubiquitous phenomenon in physical activities, and it is particularly relevant in constantly performed tasks. Despite, however, the importance of understanding exhaustion for describing and predicting the limits of endurance, it has yet to be adequately modeled. Previous research, focused mainly on identifying and characterizing a specific site or process responsible for the exhaustion point, has generated a large body of results that, while important, are also controversial (Balagué et al., 2014a). Notably, reductionist approaches fail to consider the interaction dynamics that characterize complex psychobiological systems, ones capable of coordinating and reconfiguring their functions in order to fulfill continuously a task. Furthermore, exhaustion is a phenomenon manifested at the macroscopic level of action, and, therefore, it depends on a vast number of system component processes distributed across many levels and interacting over many time scales. Consequently, the study of coordinative or collective variables, which capture the dynamic products of interactions, would seem to offer an appropriate way of elucidating the mechanisms that lead to exhaustion during continuously performed motor tasks.

Due to the numerous terms and criteria used to describe exhaustion it is crucial to begin by clarifying some definitions of the term. The accumulation of effort is known to lead to the inability to maintain a predetermined task performance criterion, producing what is known as task failure (Gandevia, 2001). However, after task failure individuals who fulfill a predetermined task criterion are still able to continue the exertion at obviously lower intensity levels until total spontaneous task disengagement occurs. This spontaneous task disengagement, also known as the fatigue-induced spontaneous termination point (FISTP) (Hristovski and Balagué, 2010), is considered crucial for an adequate modeling of exhaustion.

Hristovski and Balagué (2010), using the elbow angle as a coordinative variable during a quasi-isometric exercise, showed how the FISTP was preceded by an enhancement of the elbow angle fluctuations on various time scales (from hundreds of milliseconds to tens of s). Because an intentional effort was needed to sustain the required elbow angle (90°) during the isometric contraction, the authors conclude that the enhancement of fluctuations reflects the impending instability of the neuromuscular axis, including the intentional processes of the performer.

In complex psychobiological systems the adaptability to task constraints is revealed by the emergence of synergies or coordinative structures forming action-perception cycles (Turvey, 1992). Synergies or equivalently coordinative structures (Kugler et al., 1980) have been defined as functional and context-sensitive units of biological action (Latash, 2008; Kelso, 2009). Components forming a particular synergy possess two characteristics: pleiotropy, i.e., capacity of same components to participate in different functional synergies (Glazier and Davids, 2009) and degeneracy, i.e., capacity of different components to be engaged in attaining the same goal (Edelman and Gally, 2001). The role of the components forming a motor synergy is their compensatory actions in preserving the task-goal performance of the psychobiological system.

In continuous motor tasks the control of a synergy is spread over some time interval. Hence, the compensatory effects of components of the system that form the synergy have to be also spread in time. Such adjustments to previous perturbations have to possess a temporal structure which does not allow the important performance variable, i.e., elbow angle, to make large fluctuations around the goal value but a structure which quickly reduces the fluctuations in any direction which deviates from the goal value. Quickly suppressed deviations, by applying counteracting actions would tend to produce smaller deviations around the goal value and thus a better, stabilizing, control. Hence, the temporal co-variation among the subsequent adjustments must be *negative* to enable the required constant task output by producing anti-persistent or sub-diffusive time variations. Otherwise, fluctuations of the component processes which would on average positively add to the already extant deviation would tend, especially on longer time scales, to produce larger deviations from the desired goal value, i.e., a destabilizing persistent or super-diffusive effect.

Such co-adaptive actions are applied by the neuro-musculo-skeletal system of performers by recruiting more/less motor units or/and engaging/disengaging energy transfer from other parts of body actions on the arm-bar system. These adjustments may be treated as components, i.e., elementary variables, of the synergy developing in time. Their temporal structure enables quicker or slower recovery of the local goal elbow-angle value.

Thus, compensatory movements and related adjustments are produced in order to intentionally stabilize any motor task during exercise. Specifically, in quasi-isometric exercises, these compensatory adjustments aim to correct any deviation from the task goal. Thus, the stabilizing control is reflected in the temporal structure and time variability properties of the coordinative variable under study.

Changes in the temporal variability of coordinative variables can be measured by analytical tools such as Detrended Fluctuation Analysis (DFA) (Delignières et al., 2011). DFA was first introduced by Peng et al. (1994) to determine long-correlations behavior in non-stationary time series. The output of this method is the exponent α, which provides information about the scaling properties of the signal. According to Eke et al. (2000), two general families of processes can be differentiated by the value of the α exponent: fractional Gaussian noises (fGn) and fractional Brownian motions (fBm). For $0.5 < \alpha \leq 1$ the time series are generated with increments which are, on average, positively correlated in time, meaning that a positive trend in the past will more likely be followed by a positive trend in future; this is called persistent fGn. Its cumulative sum results in persistent or super-diffusive fBm with $1.5 < \alpha < 2$. For $1 < \alpha < 1.5$ an anti-persistent or sub-diffusive fBm process occurs in which increments are negatively correlated, that is, a positive trend in the past will more likely be followed by a negative trend in the future. The value of the exponent α is conceptually equivalent to other scaling exponent like Hurst's (H) exponent (Bassingthwaighte and Raymond, 1994).

There is some recent evidence to suggest that the effect of fatigue does reduce the structure of variability during some kinds of strenuous exercise (Pethick et al., 2015). For their part, Cashaback et al. (2013) observed a change in variability of the biceps brachii surface electromyography during an exhaustive submaximal isometric elbow flexion exercise. Hristovski et al. (2010) contended that the synergy stabilizing mode of perception-action would correspond to the anti-persistent structure of fluctuations of control in continuous motor tasks. Although isometric contractions exhibit greater stationarity in time series than do rhythmic contractions, the continuous adjustments (i.e., corrections in the coordinative variable) made during perception-action cycles and acting on the control of the movement may be of relevance when it comes to determining changes in the structure of variability.

In the present study we aimed to investigate the effect of time-on-task on fluctuations in the elbow angle (coordinative variable) during a quasi-isometric exercise performed until the FISTP. The main goals were to quantify changes in the temporal structure of fluctuation variability as the performer approaches the FISTP and to test the hypothesis of loss of psychobiological flexibility of motor control at the kinematic level of analysis (Balagué et al., 2014a). We hypothesized that for prolonged intervals on task, and close to the FISTP, the structure of the coordinative variable variability will undergo a shift toward Brownian motion as a consequence of the temporal relation shift in the inhibitory-excitatory processes relation along the psychobiological perception-action axis of performers. Were this hypothesis to be supported, it could lead to novel interpretations of the mechanisms that produce exhaustion in endurance motor tasks.

METHODS

Participants

Seven Caucasian physical education students (males; $M = 22.34$ years old, $SD = 3.47$) with no sport specialization but engaged in a wide range of aerobic activities at least three times a week volunteered to participate in this study. Prior to taking part, they completed a questionnaire to confirm their health status, as well as an informed consent form, which was approved by the Clinical Research Ethics Committee of the Sports Administration of Catalonia.

Procedure

On three different days over a period of 4 weeks, participants performed a quasi– isometric test holding an Olympic bar with an elbow flexion of 90° until the FISTP. (Hristovski and Balagué, 2010). Accordingly, they were asked to maintain intentionally a 90° angle at their elbow joint and to persist as close as possible to it even if the initial elbow angle was lost. One week prior to the test the weight of the bar for each participant was determined as 80% of the one-repetition maximum test (1RM) using an arm-curl exercise. During the trials participants had to sit on an inclined-forward bench in order to prevent possible spinal injuries. A reference cord was placed at the level of the participant's wrist in order to facilitate haptic and visual feedback on the initial position and its loss. To make the task more representative to real-world situations we did not fixed the elbows of participants but they were left to freely vary in all three dimensions. Before starting the test all participants were adjusted to the required position of 90° elbow flexion, with their wrists touching the reference cord. As shown in **Figure 1** the trial was finished when the participant left the bar on its support (i.e., when the FISTP was reached). Variation in the elbow angle during the trials was recorded using an electrogoniometer (Biometrics) and its associated software (Ebiom). The sensors of the electrogoniometer were placed on marked points on the upper arm and forearm for both extremities and were adjusted to the required starting flexion of 90°. The sampling frequency was set at 50 Hz and the amplitude resolution was 0.1° for each extremity.

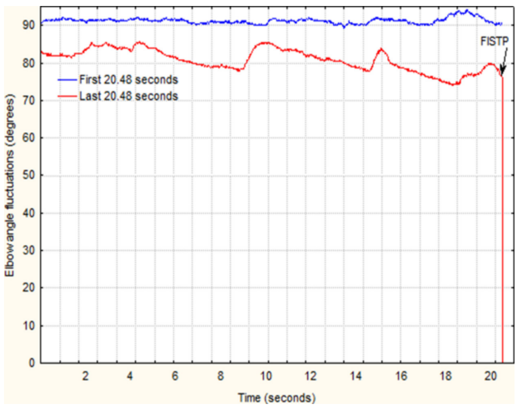

FIGURE 1 | Example of initial and final elbow angle fluctuations.

Data Analysis

To study changes in the time series structure we first determined the FISTP as an abrupt and persistent switch toward negative values in the differentiated time series calculated as $y = x\text{-}x(lag = 1)$ where x denotes the elbow angle, $x(lag = 1)$ the lagged elbow angle for 1 data point and y denotes the angle change (Hristovski and Balagué, 2010). The mean length of the time series was 5878 data points; $SD = 1417$ data points. **Figure 1** shows an example of the initial and final periods of the elbow angle fluctuations. The mean of data points until the FISTP was 5703 data points with $SD = 1409$. A total of 84 time series were analyzed: 7 (participants) × 2 (arms) × 3 (trials) × 2 (time on task periods). The time series analyzed are available as Supplementary Material. Changes in the structure of the variability in each time series were calculated by using the DFA:

Detrended Fluctuation Analysis (DFA)

According to Ihlen's code for Matlab® (Ihlen, 2012). To illustrate briefly the DFA analysis, the total length of elbow angle fluctuations (N) was first integrated by Equation (1).

$$Y(i) \equiv \sum_{k=1}^{i} [x_k - \langle x \rangle] \tag{1}$$

Where x_k is the elbow fluctuation signal and $\langle x \rangle$ is the average elbow fluctuation of the *N* samples. A polynomial function of order 2 was then used to fit the time series in order to calculate the local trend (Ihlen, 2012). The resulting time series were divided into different boxes *n* of equal length (i.e., scales), with the local trend being subtracted in each box. Because the DFA works with power of 2 sample data points the largest time scale that was analyzed contained 1024 data points. For each box the root mean square (RMS) fluctuation was calculated by using Equation (2).

$$RMS = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left[y\left(k\right) - y_n(k)\right]^2} \tag{2}$$

Where the $y(k)$ are the integrated time series and the *yn(k)* is the local trend in each box. The H exponent, obtained as the slope value of the regression line between the scale and local fluctuations on a log-log diffusion plot, was used to determine the structure of the time series fluctuations (see **Figure 2**).

Statistics

Effects of [trial (3) × arm (2) × time on task (2)] on the Hurst exponent values were analyzed by a Three-way fixed design RM ANOVA. Also effects of [Trial (3) × Arm (2) on Time on task (1)] for the initial time series as well as [Trial (3) × Arm (2) on Time on task (1)] for the final time series Hurst exponents was conducted by a Two-way RM ANOVA. The same design was applied for checking effects of [Sampling timescale (7) × Time on Task (2)]. To test for pairwise differences in comparisons where main effects attained significant values Tukey HSD *post-hoc* comparison tests were applied. We additionally performed a correlation analysis between the elbow angle fluctuations of both arms to check for possible shared variance of these sub-systems.

RESULTS

All participants accomplished successfully the requirements of the experiment, reaching the FISTP on average in 122.2 s ($SD = 29.2$).

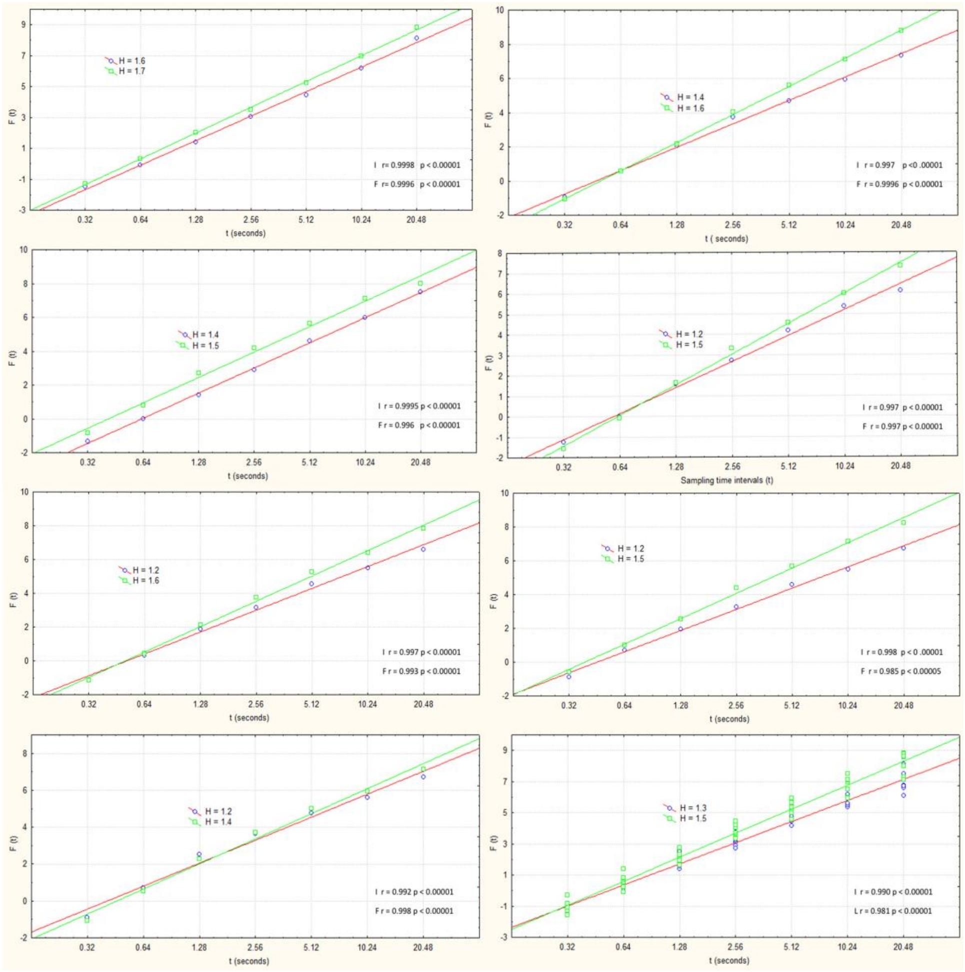

FIGURE 2 | Regression curves and H exponents for the seven participants in the initial (red line) and final (green line) periods of exercise pooled over both arms. In the lower right corner is a regression curve pooled over all participants. r—correlation of linear fit to data; p-significance level. I—initial and F—final time series. Horizontal axis: Time window of sampling; Vertical axis: Fluctuation size is given as log2 RMS.

RM ANOVA

The three-way fixed effects RM ANOVA revealed a main effect of time on task on the Hurst exponent value $F_{(1,\ 36)} = 29.62$; $p < 0.00001$. There were no significant effects of the Trial $F_{(2,\ 36)} = 2.65$; $p < 0.085$; and Arm $F_{(1,\ 36)} = 0.23$; $p < 0.633$ on the mean Hurst exponent values respectively. It also revealed a significant interaction Trial (3) × Time on task (2) $F_{(2,\ 36)} = 4.30$; $p < 0.02$ (**Figure 3**). However, there were no significant three-way [Trial (3) × Arm (2)] × Time on task (2) interactions $F_{(2,36)} = 0.10$; $p < 0.91$, as well as Two-way [Trial (3) × Arm (2)] $F_{(2,\ 36)} = 0.48$; $p < 0.62$, nor [Arm (2) × Time on task (2)] $F_{(1,\ 36)} = 0.31$; $p < 0.58$ interactions. *Post-hoc* comparisons showed a significant difference between the mean Hurst exponent of initial and final period for Trial 1 $p < 0.00001$, but showed no significant differences for Trial 2 $p < 0.09$ and Trial 3 $p < 0.12$ (**Figures 3**, **4**).

The Two-way RM ANOVA for [Trial (3) on Time on task (1)] for the initial time series revealed no significant main effect of trials on the Hurst exponent $F_{(2,\ 36)} = 2.55$; $p < 0.0923$. However, the [Trial (3) on Time on task (1)] revealed a significant main effect $F_{(2,\ 36)} = 4.20$; $p < 0.0230$ for the final time series. *Post-hoc* comparisons revealed a significant difference between the mean Hurst exponents belonging to the first and the second trial $p < 0.022$.

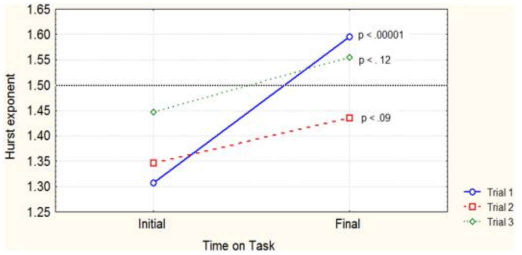

FIGURE 3 | Trial vs. Time on task interaction with associated significance values of mean Hurst exponent differences. The dotted line marks the border between anti-persistent (sub-diffusive) and persistent (super-diffusive) Hurst values.

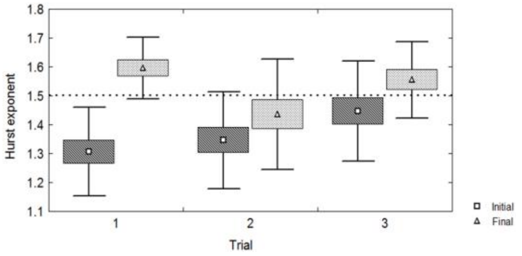

FIGURE 4 | Pair-wise comparisons of Hurst exponent (initial and final) differences vs. Trial number. The dotted line marks the border between anti-persistent (sub-diffusive) and persistent (super-diffusive) Hurst values.

The Two-way RM ANOVA for [Sampling timescale (7) × Time on Task (2)] revealed significant main effect $F_{(1,\ 42)} = 113.06$; $p < 0.00001$ on the fluctuation size differences between initial and final periods, as well as significant two-way interaction $F_{(6,\ 42)} = 5.57$; $p < 0.0003$ (**Figure 5**).

Between Arms Correlations of Hurst Exponents

Significant Pearson correlation coefficients between the right and left arm elbow angle H values were obtained for the initial ($r = 0.772$; $p < 0.0001$) and the final time on task ($r = 0.691$; $p < 0.0005$), but there was no significant difference between correlation coefficients ($z = 0.530$; $p < 0.596$).

DISCUSSION

The main aim of this research was to help clarify the dynamic mechanisms that lead to exhaustion at the action level by extending some preliminary results regarding motor control in time continuous tasks under developing fatigue (Hristovski et al., 2010; Balagué et al., 2014b). In applying the notion of task goal stabilizing synergy (Latash, 2008; Kelso, 2009) to processes spread across time scales we hypothesized that: under the non-fatigue condition it would have to be manifested as a dominantly anti-persistent process. This process would be detectable by time series analytic techniques such as DFA. Contrary to this, when the goal directed synergy is subject to accumulated fatigue then the control of the elbow angle would tend to be of a persistent type. We hypothesized that this is due to the impaired ability of the psychobiological system to make short-term adjustments.

Multi-way RM ANOVA results of the initial period of the task revealed a consistent tendency toward anti-persistent fBm of the elbow angle in both limbs across all three trials. The timescale on which on average the fluctuations in the final part close to FISTP became significantly larger than those in the initial part was close to 1 s. On all timescales larger than this up to the largest one with period of 20.48 s the fluctuations tend to be larger in the final part of the exercise. In almost all 84 cases, however, this was followed in the final period by a change in the slopes of the DFA plot of the

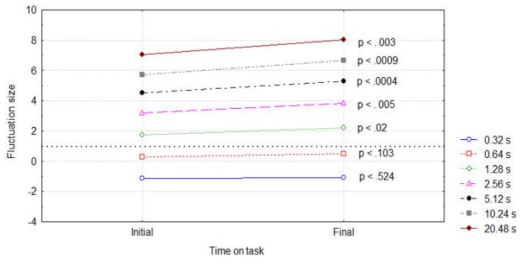

FIGURE 5 | Interaction of the Sampling timescale (right handside legend) and Time on task (horizontal axis) on the Fluctuation size (given as $\log_2$ RMS). The dotted line shows the timescale on which the fluctuation size of final period time series become significantly larger in comparison with initial period time series.

fluctuations, revealing a tendency toward persistent fBm. These observations corroborate the hypothesis that a goal stabilizing synergy that is spread over longer time periods in a non-fatigued system tends to be of anti-persistent type. On the one hand, the anti-persistent fBm is a non-stationary process which serves to regulate the force production around the goal value, but since it is anti-correlated it confines the system close to it. On the other hand, a persistent fBm is a poor strategy for maintaining constant task goals because it creates an overly itinerant behavior which does not attain the task goal if not reduced with time. This shift from anti-persistent to persistent fBm possibly reflects that the dynamics within the system becomes increasingly low dimensional, and that the cooperative and competitive behavior of component processes dwell on longer time intervals. In the initial period of the task the temporal sequences of weak fluctuations signify a potential for more flexible control of the goal variable. By contrast, in the final period the enhanced long-period fluctuations possibly signify an increasingly coherent and, therefore, less flexible control of the ongoing activity. These increasingly coherent yet competitive processes seem to be responsible for the enhanced low-frequency variability close to the FISTP. The significant shared variance of H exponents between both arms, as revealed by the correlation analysis, points to the integrated control by both arms. However, the substantial portion of variance that was not shared bilaterally shows also the existence of autonomy in the control of each arm separately (Kelso, 2012). From a kinematic point of view, the anti-persistent dynamics of the elbow angle consist of weak fluctuations around the goal value of 90°, due to the fine adjustments made. These fine adjustments are psycho-physiologically produced by the intentionally sustained cooperation among the higher control loops (presumably responsible for task specific perception, attention, motivation), down to spinal reflexes and muscular processes which vary on much shorter time scales. It is important to bear in mind that for anti-persistent processes the subsequent increments in fluctuations are negatively correlated, satisfying the definition of a goal stabilizing synergy. The balance of excitation and inhibition is a general mechanism for stabilizing the activity level in neural tissue (Shu et al., 2003; Higley and Contreras, 2006; Shew et al., 2009), and it has also been demonstrated in computational models of neural networks (van Vreeswijk and Sompolinsky, 1996; Brunel, 2000). That said, any positive fluctuation, as a consequence of central excitation, is on average compensated for by a subsequent negative fluctuation that arises as a result of joint coupling between the central inhibition and the pull of gravity. These kinds of negative feedback loops are well-known mechanisms for generating anti-persistent time series (Cuomo et al., 2000). From the results obtained in this research, the anti-persistent type of feedback was possibly implemented by having a greater available number of degrees of freedom, such that a more fine-grained time-amplitude control of the goal variable could be achieved. In other words, the inhibition-excitation control processes were competing on short time scales. For kinematic fluctuations in isometric exercises, this would mean that different articulatory degrees of freedom are served by different but anti-correlated neural networks. In order to account for the DFA results, networks must be initially sufficiently distinct such that neural activity in one network is only weakly coupled to activity in other networks (e.g., only partially overlapping). At the beginning of the exercise these anti-correlated distinct networks are able to provide more independent and, therefore, fine-grained time-amplitude control of the goal coordination variable. Through competition on short time scales (e.g., unconscious reflexes), the anti-persistent fBm is characterized by relatively balanced high to low frequency fluctuation amplitudes. As the task continues and fatigue develops, however, this fine-grained control, based on short-time competition, loses its grip and the competition shifts toward longer term intervals. In our opinion this effect is underpinned by the protective behavioral inhibition, consisting of processes that encompass the neural and muscular changes (e.g., neuromuscular tension; Gandevia, 2001) that result in a delayed possibility of adjustment of the goal variable. The metabolic inhibition might be reflected, for example, by the lower contractile ability of some portion of muscle fibers and provoke a greater inhibition effect.

The increased neurotransmitter levels in some central nervous system synapses (Cotel et al., 2013) may also heighten the inhibitory effects at this level. The accumulated effort enhances the growth of this phase and it becomes increasingly macroscopic. As fatigue, i.e., neuro-metabolic inhibition sets in these networks start to perform more in unison, with the excitatory influence being constrained by longer-term motivational loops. To be able to adjust the goal variable, a highly motivated performer has to intentionally activate an increasingly larger population of motor units to compensate the inhibitory influences.

The competition of these growing coalitions then begins to unfold over longer time scales. In other words, the control becomes coarser with respect to time. Finely-grained, high frequency-low amplitude modes contributions decrease in comparison to the coarse-grained, low frequency-high amplitude modes adjustments generated dominantly by long-term varying attention-motivation loops. The dominant portion of control is thus transferred to conscious, intentional, long-term, coarser grained loops. This means that the motivationally supported excitatory phase also segregates, becoming more coherent in order to counteract the increasing inhibition. Thus, what emerges is a formation of two macroscopic competing coalitions. Because intention-motivation control loops function on longer time scales (Kiebel et al., 2008) than do spinal and subcortical control loops, the adjustment delay shifts to longer time intervals. The competition between the intention to sustain the task and the progressive loss of neuromuscular tension is illustrated by the amplitude increase of long-term fluctuations in goal variable values during the final period of the exercise. This enhancement of low-frequency elbow angle fluctuations precedes the abrupt reduction in the angle which coincides with the FISTP, as manifested by the tendency toward larger H values. Similar results were obtained previously on the basis of analysis of other measures such as SD and the power spectrum profiles of elbow angle fluctuations in participants performing the same task (Hristovski and Balagué, 2010). However, the obtained trial vs. time on task interaction effects pointed to a more involved picture of these processes. There is apparently a long-term, i.e., a week to week, variability of the temporal structure of quasi-isometric control. Although in all three trials there was a tendency of participants to initially engage in an anti-persistent regime of control and in the final part to approach the persistent regime, this effect was most clear only on the first trial. Changes in attention mood, motivation or change in control strategy by engaging/disengaging energy transfer from other parts of body on the resistance system over period of weeks may be responsible for this kind of a nested temporal process. However, from this research we are not able to discuss in more detail about the factors which may be responsible for this variation.

In addition, two main potential methodological limitations should be mentioned here: the scarce number of participants and the lack of taking into account for analysis other biomechanical degrees of freedom of the shoulder and elbow joint system. The later may account for the different strategies that participants used to negotiate the fatigue. In this research, we used only DFA method because we were specifically interested in the time variability structure of quasi-isometric exercises as a supplement to previous research findings. These findings used other measures of variability such as the SD and the power-spectrum shift of elbow-angle fluctuations (Hristovski and Balagué, 2010). The behaviors of both measures were consistent with present findings concerning the enhancement of low-frequency fluctuations with developing fatigue and close to FISTP.

In summary, the path to task disengagement seems to involve, on the coordination level, temporally nested psychobiological changes. At larger time scales, i.e., weeks, there seems to exist a slow process of variation possibly affected by change in personal constraints and in connection to negotiating the fatigue that develops on much shorter timescales during a sole exercise bout. At this timescale there exists a tendency toward a gradual shift from weakly coupled, short-term, anti-correlated activity toward more-strongly coupled, long-term correlated activity of competing psychobiological networks. The final task disengagement event (FISTP) in this scenario may be considered as a giant, i.e., coherent, protective inhibitory fluctuation that causes a temporary abrupt switch to the low energy expenditure level. More generally, this mechanism may be considered as an evolutionary stabilized protective decision-making process. There would appear to be a compelling case to link this understanding of how fatigue manifests on the coordination level with percolation processes and the formation of giant components (Breskin et al., 2006) that are prominent in complex systems, such as human psychobiological networks. In future research it is warranted to examine the viability of this hypothesis on both the experimental and modeling levels so as to contribute further to an understanding of the consequences of exercise-induced fatigue and the identification of the limits of endurance.

AUTHOR CONTRIBUTIONS

PV Conception and design of the experiment. Analysis and interpretation of data. Drafting or revising the article. RH Conception and design of the experiment. Analysis and interpretation of data. Drafting or revising the article. NB Conception. Interpretation of the data. Drafting or revising the article. The authors approved the final version and agree to be accountable for all aspects of the work.

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SUPPLEMENTARY MATERIAL

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REFERENCES

Balagué, N., Hristovski, R., Vainoras, A., Vázquez, P., and Aragonés, D. (2014a). "Psychobiological integration during exercise," in *Complex Systems in Sport*, eds K. Davids, R. Hirsitovski, D. Araújo, N. Balagué, C. Button, and P. Passos (New York, NY: Routedlge), 62–81.

Balagué, N., Hristovski, R., Vázquez, P., and Slapsinskaite, A. (2014b). "Psychobiology of endurance and exhaustion. A nonlinear integrative approach," in The *1st International Scientific Conference. Research in Physical Education, Sport and Health* (Ohrid: Faculty of Physical Education, Sport and Health), 13–22.

Bassingthwaighte, J. B., and Raymond, G. M. (1994). Evaluating rescaled range analysis for time series. *Ann. Biomed. Eng.* 22, 432–444.

Breskin, I., Soriano, J., Moses, E., and Tlusty, T. (2006). Percolation in living neural networks. *Phys. Rev. Lett.* 97:188102. doi: 10.1103/physrevlett.97.188102

Brunel, N. (2000). Dynamics of sparsely connected networks of excitatory and inhibitory neurons. *J. Comput. Neurosci.* 8, 183–208. doi: 10.1023/A:1008925309027

Cashaback, J. G., Cluff, T., and Potvin, J. R. (2013). Muscle fatigue and contraction intensity modulates the complexity of surface electromyography. *J. Electromyogr. Kinesiol.* 23, 78–83. doi: 10.1016/j.jelekin.2012.08.004

Cotel, F., Exley, R., Cragg, S. J., and Perrier, J. F. (2013). Serotonin spillover onto the axon initial segment of motoneurons induces central fatigue by inhibiting action potential initiation. *Proc. Natl. Acad. Sci. U.S.A.* 110, 4774–4779. doi: 10.1073/pnas.1216150110

Cuomo, V., Lanfredi, M., Lapenna, V., Macchiato, M., Ragosta, M., and Telesca, L. (2000). Antipersistent dynamics in short time scale variability of self-potential signals. *Ann. Geophys.* 43, 271–278. doi: 10.4401/ag-3644

Delignières, D., Torre, K., and Bernard, P. L. (2011). Transition from persistent to anti-persistent correlations in postural sway indicates velocity-based control. *PLoS. Comput. Biol.* 7:e1001089. doi: 10.1371/journal.pcbi.1001089

Edelman, G. M., and Gally, J. A. (2001). Degeneracy and complexity in biological systems. *Proc. Natl. Acad. Sci. U.S.A.* 98, 13763–13768. doi: 10.1073/pnas.231499798

Eke, A., Hermán, P., Bassingthwaighte, J. B., Raymond, G. M., Percival, D. B., Cannon, M., et al. (2000). Physiological time series: distinguishing fractal noises from motions. *Pflugers Arch.* 439, 403–415. doi: 10.1007/s004249900135

Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiol. Rev.* 81, 1725–1789.

Glazier, P. S., and Davids, K. (2009). Constraints on the complete optimization of human motion. *Sp. Med.* 39, 15–28. doi: 10.2165/00007256-200939010-00002

Higley, M. J., and Contreras, D. (2006). Balanced excitation and inhibition determine spike timing during frequency adaptation. *J. Neurosci.* 26, 448–457. doi: 10.1523/JNEUROSCI.3506-05.2006

Hristovski, R., and Balagué, N. (2010). Fatigue-induced spontaneous termination point–Nonequilibrium phase transitions and critical behavior in quasi-isometric exertion. *Hum. Mov. Sci.* 29, 483–493. doi: 10.1016/j.humov.2010.05.004

Hristovski, R., Venskaitytë, E., Vainoras, A., Balagué, N., and Vázquez, P. (2010). Constraints-controlled metastable dynamics of exercise-induced psychobiological adaptation. *Medicina (Kaunas)* 46, 447–453.

Ihlen, E. A. F. (2012). Introduction to multifractal detrended fluctuation analysis in Matlab. *Front. Physiol.* 3:141. doi: 10.3389/fphys.2012.00141

Kelso, J. A. S. (2009). "Synergies: atoms of brain and behavior," in *Progress in Motor Control*, ed D. Sternad (New York, NY: Springer Science-Business Media, LLC), 83–91.

Kelso, J. A. S. (2012). Multistability and metastability: understanding dynamic coordination in the brain. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 367, 906–918. doi: 10.1098/rstb.2011.0351

Kiebel, S. J., Daunizeau, J., and Friston, K. J. (2008). A hierarchy of time-scales and the brain. *PLoS. Comput. Biol.* 4:e1000209. doi: 10.1371/journal.pcbi.1000209

Kugler, N. P., Kelso, J. A. S., and Turvey, M. T. (1980). "On the concept of coordinative structures as dissipative structures: I. Theoretical lines of convergence," in *Tutorials in Motor Behavior*, eds G. E. Stelmach and J. Requin (New York, NY: North-Holland), 3–47.

Latash, M. (2008). *Synergy*. New York, NY: Oxford University Press.

Peng, C. K., Buldyrev, S. V., Havlin, S., Simons, M., Stanley, H. E., and Goldberger, A. L. (1994). Mosaic organization of DNA nucleotides. *Phys. Rev. E. Stat. Nonlin. Soft. Matter. Phys.* 49, 1685–1689. doi: 10.1103/PhysRevE.49.1685

Pethick, J., Winter, S. L., and Burnley, M. (2015). Fatigue reduces the complexity of knee extensor torque fluctuations during maximal and submaximal intermittent isometric contractions in man. *J. Physiol.* 593, 2085–2096. doi: 10.1113/jphysiol.2015.284380

Shew, W. L., Yang, H., Petermann, T., Roy, R., and Plenz, D. (2009). Neuronal avalanches imply maximum dynamic range in cortical networks at criticality. *J. Neurosci.* 29, 15595–15600. doi: 10.1523/JNEUROSCI.3864-09.2009

Shu, Y., Hasenstaub, A., and McCormick, D. A. (2003). Turning on and off recurrent balanced cortical activity. *Nature* 423, 288–293. doi: 10.1038/nature01616

Turvey, M. T. (1992). Affordances and prospective control: an outline of the ontology. *Ecol. Psychol.* 4, 173–187. doi: 10.1207/s15326969eco0403_3

van Vreeswijk, C., and Sompolinsky, H. (1996). Chaos in neuronal networks with balanced excitatory and inhibitory activity. *Science* 274, 1724–1726. doi: 10.1126/science.274.5293.1724

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STUDY IV

Hrsitovski, R., Balagué, N., & Vázquez, P., (submitted)
Formation of coherent attitudes in sports fans.

Formation of Coherent Attitudes in Sports Fans

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***Abstract**: The coherent attitude formation of sports fans coupled to a common environmental source of information was used to test empirically a model's consequences based on the dynamical systems approach. Ninety-seven students were given a list of stimuli related to potentially incorrect referee decisions that negatively affected their favorite team. They were then asked to complete 3 questionnaires concerning their opinion, emotional response and preferred action, respectively, in relation to these referee decisions. Results showed an initial increase in fluctuations in social responsiveness, followed by a reduction signifying the onset of coherent attitude layering. Nonlinear regression analysis revealed the emergence of 1, 2 and 4 layers of coherence in the opinion emotional and action space, respectively. Eight attitudinal patterns emerged within the framework of the experiment, ranging from the most extreme (i.e. potentially violent sub-sample) to the least extreme subsample. The principal component analysis revealed a strong formation of collective attitudes and a high degree of integration within and between the opinion, emotional and action spaces. These results confirm the predictions of the tested model and explain how different proto-groups, from violent to moderate, may be formed as a consequence of global coupling to a common source of information.*

KEYWORDS: [Attitudinal coherence, Sports fans proto-group, Star topology model].

INTRODUCTION

The study of aggressive attitudes and violent collective behavior in sport has been growing in the last decades. The main focus of research has been put on better understanding the phenomenon and in implementing efficient intervention and prevention programs (Gimeno, Sáez, Ariño & Aznar, 2007; Gómez, 2007; Javaloy-Mazón, 1996). To date, no formal models have been built to explain the emergence of coherent attitudes among fan supporters.

The emergence of malignant social attitudes is a phenomenon that shares some general properties among systems and some aspects of it have been successfully investigated. Several mathematical models have predicted the emergence of coherent changes in human social systems as a consequence of a nonspecific parameter change (Renfrew & Poston, 1978; Shelling, 1971; Weidlich, 1978; Zeeman, Hall, Harrison, Marriage & Shapland, 1976). These approaches have shown exquisite explanatory power (by means of computer simulations) in relation to the macroscopic effects of inter-individual social interactions, such as the emergence of clustering, attitude polarization, ideologies, beliefs, etc. (Nowak & Latane, 1994; Nowak, Szamrej & Latane, 1990; Vallacher & Nowak, 2007; Nowak, Vallacher, Bui-Wrzosinska & Coleman, 2006; Vallacher, Coleman, Nowak & Bui-Wrzosinska, 2010; Vallacher & Jackson, 2009). Of particular appeal in this body of research is the definition of intractable conflicts as stable attractor states emerging from hidden malignant social attitudes (Coleman, Vallacher, Nowak, Brui-Wrzosinka & Bartoli, 2010; Liebovitch, Vallacher, Nowak, Coleman, Bartoli & Brui-Wrzosinska, 2012; Musallam, Coleman & Nowak, 2010). In addition, the synchronization of internal

> states as a consequence of close relationships is a new and promising research direction that is potentially able to resolve a longstanding issue in the relationship between mind and social context (Vallacher, Nowak & Zochowski, 2007). All these models share the common characteristic of being local models, that is, the coherence within them emerges as a result of local interactions between the social elements. However, coherent states may also emerge when social elements do not interact locally but possess a common coupling with environmental events.
>
> From the dynamical systems perspective, groups start to form from some initial state, evolve and stabilize through mutual interactions, and may eventually dissolve (Vallacher & Nowak, 2007). This initial state, in which members of a social ensemble are still not interacting but nonetheless form coherent attitude layers, is defined as a proto-group state, in other words, it is a ‘group to be formed’. This subtle state can be considered as a critical nucleus, a precursor, which, depending on constraints, may evolve into a group or disintegrate back to a population of independent individuals. This state is especially interesting with respect to the possible induction of hidden malignant social attitudes within the proto-group formed by fans (Coleman et al., 2010).

A star topology model (Hristovski, 1997) (Fig.1), drawing on the mathematical theory of paramagnetism, predicts the onset of non-local coherence in social ensembles consisting of locally non-interacting individuals, coupled globally and unidirectionally only to the events in their environment. In this model the central node activity represents an environmental event (e.g., a referee’s decision – B) that impinges on peripheral nodes (e.g., team supporters). Note that a referee’s decisions have the role of a *non-specific* control parameter which does not impose explicit control *instructions* about team supporters' attitudes. This is a rather different and simpler class of social network interaction to that proposed by the abovementioned models. The fans do not exchange information and the model has exact solutions that can easily be tested experimentally. Furthermore, it predicts the final states of certain social phenomena such as the formation of proto-groups, which have much in common with the local models mentioned above. Note that although there is no immediate and explicit interaction between the members of the social ensemble of fans, they are nonetheless bound together through their common characteristic: they are supporters of the same team and have identical or at least strongly correlated values, namely identification with the team. In this respect, we can speak of a non-local or implicit coupling within the social ensemble of explicitly non-interacting fans.

Insert Figure 1 About Here

Obviously, due to the interaction with the environmental constraint, in this case a referee's decisions, and their shared personal constraints, namely identification with their favorite team, a new set of common properties may be induced in the group in the form of coherent opinions, emotions and preferred actions. These properties may form an additional set of constraints, juxtaposed to and interacting with the previous ones, which together could form another, more complex initial state that may initiate the evolution of the proto-group.

The exact solution of the model (Hristovski, 1997) is the well-known Brillouin function that describes the behavior of a social ensemble under environmental influences *B:*

$$\langle \sigma_J \rangle = A_1 cth(A_1 X) - A_2 cth(A_2 X) \qquad (1)$$

where <*σ*$_J$> is the normalized (from 0 to 1) expected (average) attitudinal intensity per subject, which captures the collective state of the social ensemble. The maximal value <σ_J> = 1 signifies full coherence, that is, an identical collective attitude in the social ensemble. The sign <…> signifies an ensemble average and the sign *cth* refers to the hyperbolic cotangent function; $A_1 = \frac{2J+1}{2J}$ and $A_2 = \frac{1}{2J}$ are constants for a given *J* which plays the role of a personal constraint in the attitudinal space (see Fig. 1). It represents the maximal value (extreme) that could be attained by a fan in each of the attitudinal spaces such as: opinion, emotion and action; $X = KJB$; where, *B* is a running sum (accumulation) of referee's decisions. The single free parameter of the model $K = \frac{C}{Q}$ represents the relationship between the coupling strength (C) of the social ensemble to the environmental events (i.e. its coupling to referee's decisions *B*) and the social ensemble variability (*Q*). We will call *K* a 'coupling to variability ratio'.

The expected (i.e. average) attained attitudinal level per subject <U_J>, is given by Eq. 2:

$$\langle U_J \rangle = CJ\langle \sigma_J \rangle \qquad (2)$$

where *CJ* gives the asymptotic value of the coherent attitude layers which have been formed and <σ_J> is defined by equation (1).

The social susceptibility χ, i.e the social responsiveness to the external stimuli *B* per subject, is defined by Eq. 3 as:

$$\chi = \frac{\langle U_J \rangle}{B} \qquad (3)$$

The condensation of coherent states in the social ensemble appears as a dynamical product of the symmetry breaking mechanism in the space of attitudinal states, in the following way: Let the perception - response structure that experiences the decisions be a bistable one, so that it could be in the state of: 1. Inhibition (the decisions do not excite it, ($C = 0$), so that there is a balance between the spontaneous polar influences); 2. Excitation (the decisions excite it positively or negatively ($\pm C$), so that they are experienced by it as positive or negative with degree of degeneration (resolution) $d = 2J + 1$. When there are no stimuli, or it is insensible to them ($C = 0$), such a structure has nothing to experience, and the state of each member of the ensemble (fan) is undetermined. Such states correspond to a state of antiparallel spins (balance of spontaneous polar influences with minor fluctuations about zero value), therefore they compensate each other, making the state in the structure totally balanced and undetermined. Here, the symmetry among the polar states is total. We can see that on Fig. 2A. Small transversal lines in the middle of the two-way arrows could be considered as mirrors. Then in the system there is symmetry with respect to the mathematic group of transformation with 2 elements $\mathbf{G_2}$. This state is symmetric (invariant) with respect to identical transformation $I = (J \rightarrow J)$, and with respect to operation that generates the cycle of space inversions as well, $I = (J \rightarrow -J)$. From equations (7) - (10) we can see that when the number of experienced decisions is $B = 0$, the expected value of the spin $<s_J>$, i.e the order parameter $<U_J>$ is identically equal to zero.

When the decisions of the referee are experienced and accumulate ($B \neq 0$) the state $<s_J> = 0$ (as well as $< U_J > = 0$) becomes unstable. Depending on the system of fans, new stable state at each of them would take one of total $2J + 1$ possible states, that is it will take a state which is closer to one of the poles. It means that the stimulus would be experienced as a positive or negative and that such an event would produce a certain cognitive, emotional and action state. Under the influence of assimilated stimuli, the spins that have been mutually compensated till now would become in parallel position (they would become decompensated, with same orientation). This state of assimilated stimuli, guided by the common (shearing) pool of information (the same sign of coupling C) of the ensemble, breaks the previous symmetry (see Fig. 2B), that leads to the onset of preferred orientation in the space of attitudinal states of the subjects, so that, in the elements of the social ensemble is being created certain attitude. Then, the expected value of the spin $<s_J>$, that is the attitudinal charge of social ensemble $< U_J >$, becomes different from zero. In this new state, the mathematic group $\mathbf{G_2}$ is not a group of symmetry of the system any more. This mathematical group is now reduced only to the element of trivial identity transformation $\mathbf{I}$. Such symmetry breaking into the attitudinal space of social ensemble, that is the transition $\mathbf{G_2} \rightarrow \mathbf{I}$, characterize the qualitative change from the state of having no attitude (cognitive, emotional or action component) with respect to the events in its environment, into the state with certain attitude about them. In other words, the non - invariance of the new state under the group $\mathbf{G_2}$ amounts to the assumption that in the observed social ensemble are created long - lasting, non - vanishing attitudes.

Insert Figure 2 about Here

From what it is said above it follows that: If the social ensemble is homogeneous in its coupling to the environment, then attitudinal coherence will arise for some value of the external stimulation *B*; If the social ensemble is homogeneous with respect to the internal personal constraint *J*, then a single-layered attitudinal coherence (attractor state) will arise for some value of the external stimulation *B;* If the social ensemble is not homogeneous with respect to the personal constraint *J*, then a multi-layered attitudinal coherence (multistability), proportional to the number of different values of J, will arise for some value of the external stimulation B.

The aim of this study was to detect some of the consequences of the star topology model by examining the attitudinal evolution and responsiveness in the opinion, emotional and action dimensions of sports fans coupled to a common environmental source of information.

METHODS

Participants

A sample of 97 participants (N_{male} = 73, N_{female} = 24; aged 20-24 years) was randomly recruited from a population of Caucasian physical education students. They were informed about the procedures, but were not aware of the purpose of the study.

Interventions and Procedure

Data were gathered by giving participants a list of environmental stimuli (B) and three questionnaires whose purpose were to collect information regarding their opinion, emotion and preferred action responses.

The B contained twelve stimuli in the form of incorrect referee decisions that affected the participants' favorite team. These potentially incorrect decisions were considered to have a moderate influence on the match result (e.g., they were midfield decisions).

The list stated the following:

"*Imagine that you are watching on TV a football match in which your favorite team or the national team of your country is participating. The referee behaves in the following way*:"

The three questionnaires assessing the opinion, emotion and action dimensions were based on scaling the participants' judgments (in a form of probabilistic statements) regarding the referee's decisions. Specifically, each questionnaire was scaled from 0 to 8, where 0 indicated that the participant did not have any opinion, emotion or desire for action in relation to the referee's decisions, and 8 represented total disagreement with the referee's decisions. For each incorrect decision on the *B*, participants had to choose the response option on the corresponding questionnaire. The questionnaires stated the following:

"*Assess the referee's behaviour (1st questionnaire), choose your emotion (2nd questionnaire) and indicate your preferred action (3rd questionnaire) in relation to the referee's decision as described on the list (B), taking into account his/her previous decisions in the match. For each of the decisions on the list (B), please choose the response option that best reflects your opinion/emotion/preferred action."*

Participants were seated sufficiently apart so as to prevent any direct interaction. The *B* and the three scaled questionnaires were then distributed and explained verbally. Some examples were given in order to avoid misunderstandings about the requirements of the experiment.

Data Analysis

The questionnaires showed a high, one week inter-measurement interval, test-retest reliability with inter-item average correlation of r = .98, r = .95 and r = .94 for the opinion, emotion and action scale respectively. The experiment enabled the determination of the J values of the subsamples, while the values of parameter B were defined as the sum of the referee's decisions. The single free parameter K was estimated by applying a nonlinear regression of Eq. 2 to the experimental data, with J_{max}= 15/2. The quasi-Newton method was used to determine the parameter estimation convergence. Goodness of the least-squares fit was tested by the amount of the explained variance R^2. A principal component analysis using the Kaiser-Gutmann criterion to determine the number of significant components was applied to the 12 B-dependent statistical averages of opinion, emotional and action attitudes.

The results for responsiveness (i.e. susceptibility) to the external stimuli were obtained through Eq. 3. The fluctuation intensities were estimated as a standard deviation (SD) of the sample for each B value.

RESULTS

Attitudinal Evolution in the Opinion, Emotional and Action Dimensions

The nonlinear regression according Eq. 2 showed a highly significant relationship between the experimental data and the model predictions of attitudinal evolution.

In the opinion dimension (see Fig. 3a) the regression analysis revealed one layer of coherence. The regression curve for the expected value of $<U_J>_{\text{opinion}}$ (J = 7.5; K = .11, N = 97) showed a high goodness of fit (R^2 = .91; p < .001). In this dimension, coherence emerged for B > 6.

In the emotional dimension (see Fig. 3b) two layers of coherence (J_1 and J_2) were found. The regression curves for the expected value of $<U_J>_{\text{emotional}}$ (J_1 = 7.5, K = .10, N = 71 and J_2 = 6.5, K = .07, N = 26) showed a highly significant relationship between the theoretical curves and the data (R^2_1= .90, p < .001; and R^2_2 = .89, p < .001). In this case, coherence emerged at B > 6 for the first curve (J_1) and at B > 9 for the second (J_2).

In the preferred action dimension (see Fig. 3c) four layers of coherence (J_1, J_2, J_3 and J_4) were found. The regression curves for the expected value of $<U_J>_{\text{action}}$ (J_1 = 7.5, K = .11, N = 24; J_2 = 5.5, K = .10, N = 18; J_3 = 4.5, K = .15, N = 12; and J_4 = 3.5, K = .20, N = 43) showed a high goodness of fit (R^2_1 = .91, p < .001; R^2_2 = .93, p < .001; R^2_3 = .92, p < .001; and R^2_4 = .80, p < .001) with the experimental data. Coherence emerged at B > 6 for J_1, J_2 and J_3, and at B > 5 for J_4. Table 1 shows all the parameters calculated by the model for each dimension.

The residuals were symmetrically distributed around the expected values, which is another corroboration of the high goodness of fit between the theoretical predictions and the experimental data. Fig. 3 show that in most cases (using the criterion J_{max}-1 £ $<U>$), coherence emerged after the 5th and 6th stimulus (B > 5 and B > 6), except in the case of J = 7.5 for the emotional dimension, where coherence emerged for B > 9.

Insert Figure 3 About Here

Attitudinal Responsiveness and Fluctuations in the Opinion, Emotional and Action Dimensions

The responsiveness of the sample attained its maximal values at median values of B=2, whereas fluctuations were maximal at median values of B=3. Fig. 4 (a, b) shows the distributions of data from the opinion dimension for B=3 and B=8, respectively. It can be observed that opinion variability was maximal for B=3, whereas it converged to its lowest variability (i.e. maximal coherence) for B=8.

The enhancement of variability (i.e. fluctuations) and maximal susceptibility was observed in the interval $0 < B < 4$ (see Fig. 5). After this interval, these properties started to decrease slowly, signaling the formation of a new stable state and a condensation of attitudes toward their saturation values. Note that in contrast to fluctuations, susceptibility does not converge to the zero value even for large B values. This is a consequence of the susceptibility definition (see Eq. 3).

Insert Figure 4 about Here

Principal Component Analysis.

Although the Kaiser-Gutmann criterion tends to over extract the number of significant principal components with eigenvalues larger than 1, the analysis revealed one general component that explained 98% of the total variance, with an eigenvalue of $\lambda = 6.95$. All communalities /h^2) were highly significant ($\langle h^2 \rangle = .998$; ± .004), as were the loadings of the variables on the principal component ($\langle q \rangle = .987$; ± .003).

Eight attitudinal patterns (Table 1) emerged within the framework of the experiment, and ranged from the potentially most violent (i.e. most extreme) to the least extreme (i.e. moderate).

Insert Table 1 about here

DISCUSSION

The experimental evidence supports basic predictions 1, 3 and 4 of the star topology model (Hristovski, 1997). The attitudinal layers of coherence do not have to emerge from local interactions (Latane, 1996; Nowak et al., 1990; Vallacher et al., 2010 but may arise as a consequence of the common identification with the favorite team, which forms their common mode of coupling with the external stimuli (i.e. the referee's decisions). To our knowledge, this is the first empirically corroborated formal model of the emergence of coherence and social proto-groups among team supporters, a model that also describes the stratification of their attitudes under the influence of environmental and personal constraints. The experiment demonstrated the existence of equifinality, that is, the property of the social system and of the individuals involved to attain the same final state, despite evolving using various paths. Path variability is an effect of the large number of weakly correlated intrapersonal degrees of freedom on the evolution of individual attitudes. The attitudinal variability weakened as the common coupling with the environmental events became dominant and suppressed the personal degrees of freedom, such that the strongly correlated individual attitudes were, in effect, sucked into a single collective attitude. Moreover, the high goodness of fit for different numbers of participants also supports the robust properties of this model with respect to the cardinality of the observed social system.

The susceptibility (social responsiveness) and fluctuations (response variability) of the ensemble showed non-monotonous behaviour. Shortly after the onset of environmental events they were enhanced, signaling a destabilization of the previous state and a transition towards the formation of a coherent attitude. This means that under global coupling and in relation to referee decisions that fans perceive as moderately offensive, the maximal responsiveness of fan groups and their variability in attitudes would be expected to occur within this range of number of referee's decisions B. Although all the fans reacted in the same direction (i.e. they break the initial symmetry present at B=0), as individuals they differed in other sets of personal constraints and this contributes to the early (i.e. small B values) 'disagreement', in other words, the enhancement of fluctuations. Such unidirectional fluctuations actually push the average social attitude $<U_J>$ towards the final coherence value that is the attractor, which emerges for higher B values. In other words, whereas for the first few referee's decisions the social ensemble is yet attitudinally undifferentiated due to personal differences (some fans need more and some less evidence for changing their attitudes), the subsequent referee's decisions bring about clear formation of coherent social sub-ensembles that share a stable attitude. In this coherent state personal differences are suppressed and the collective attitude dominates. In this case, the referee's decisions have the role of a control parameter which destabilizes the neutral attitudinal state present at B=0, and through fluctuations leads the system into a coherent attractor state. This coherence was evident in the results of the principal component analysis, where seven variables were reduced to only one collective variable (order parameter) accounting for more than 98% of the total variance.

This behaviour constitutes strong evidence for the highly integrated nature of opinion, emotional and action spaces on the individual and social levels. It is also worth noting that the greatest coherence was achieved in the opinion space, whereas the emotional and, particularly, the preferred action space were more segregated. This may be due to the more refined (i.e. heterogeneous) structure of the fan sample in terms of their responses to external events. For example, individuals motivated by excitement (Javaloy-Mazón, 1996), by *eustress* (Gantz & Wener, 1995), a form of positive stress involving excitement and anxiety that often accompanies sport viewing, or by the feeling to belong to a group (Gómez, 2007), may differ from fans who are motivated by economic concerns (Frey, 1992; Gantz et al., 1995), or from those influenced by the entertainment motive (Zillmann, Bryant & Sapolsky, 1989). Such differences may be particularly emphasized in the emotional and preferred action spaces because of their direct saturation by diverse motivational factors affecting the intrapersonal constraint J. This constraint introduced a potential for multistability into the system, that is, a large number of stable, collective, coherent attitudes (attractors) were created by the social system under the impact of external stimuli. This leads to a notion of non-local coherent layering (stratification) after being exposed to equal environmental stimulation for a certain amount of time.

Accordingly, for instance, the violent patterns (see Table 1) could be considered as a formation of potentially violent proto-groups, which might subsequently attain (through local network interactions) all the properties that are characteristic of a violent mob, including spatial clustering and collective violent action (see the previous comment on motivational differences between sports fans). Another important and more general theoretical and practical aspect stems from these findings. The emergence of coherence as a result of the suppression of individual degrees of freedom raises the possibility that a third person or institution, e.g. in politics, might efficiently control and manipulate such social ensembles, because as the majority of personal differences are suppressed the whole ensemble may be treated as a single collective entity controlled by a common body of coherent information. Hence, instead of dealing with a multitude of individual degrees of freedom, that is, individual opinions, emotions and action preferences, one actually has to deal with a single collective coherent person (Balagué & Torrents, 2011). In contrast to the above, the moderate pattern 4 (see Table1) implies a social proto-group that has the potential to evolve into a well-formed group trying to realize its goals through institutional procedures, i.e., a moderate proto-group ($J = 3.5$ level).

If the present results are viewed in the light of those obtained by local models (e.g. Nowak & Vallacher, 1998) one might consider the predicted final states within our model as the initial state of a model with local interactions among its elements. In this regard, it would be particularly interesting to investigate the possibility of change among personal constraints J as a consequence of local interactions among fans. Indeed, the possibility that the J constraint is subject to change under local interactions, such as peer pressure, is quite real. Were these to be the case, then individual fans possessing different J constraints may, under conditions of global coupling with environmental events, change their personal constraints when subject to local interactions.

The way in which groups with common personal constraints are formed from proto-groups could be an interesting topic for future research. The question here would be to determine how growth of interpersonal interactions depends on the common views of environmental events and the action preferences of those involved. This problem is obviously fundamental to group or even team formation processes, where one might investigate the formation of network connections among the elements of the proto-group. Another interesting direction for future research can also be inferred from the results of this study. The least violent coherent layer in the action space, $J = 3.5$ ($<U_J> = 4$), was formed by 79% of the total number of female fans, and hence a further question arises: How do J constraints depend on other social constraints (e.g. the influence of family attitudes toward female and male populations), on peer pressure, and on the possible influence of certain biochemical gender differences, such as testosterone levels? Finally, the behavior of social ensembles under varying neutral, positive and negative referee decisions would constitute yet another direction for future research that might produce somewhat different results to those obtained here.

In conclusion, the experimental data explain how attitudes and responsiveness in the opinion, emotional and action dimensions of sports fans evolve under the influence of global coupling to a common source of information (referee’s decisions) and the diversity of personal constraints. The formation of a number of fan proto-groups that attained attitudinal coherence in the opinion, emotional and, particularly, the preferred action dimensions is observed confirming the predictions of the proposed star topology model.

REFERENCES

Balagué, N. & Torrents, C. (2011). Complejidad y deporte. Barcelona: INDE.

Coleman, P. T., Vallacher, R. R., Nowak, A., Bui-Wrzosinska, L. & Bartoli, A. (2010). Navigating the landscape of conflict: Applications of dynamical systems theory to addressing protracted conflict. In N. Ropers (Ed.), *Systemic thinking and conflict transformation*. Berlin: The Berghoff Foundation for Peace Support.

Frey, J. H. (1992). Gambling on sport: Policy issues. *Journal of Gambling Studies*, 8, 351-360. doi: 10.1007/BF01024122

Gantz, W. & Wenner, L. A. (1995). Fanship and the television sports viewing experience. *Sociology of Sport Journal*, 12(1), 56-74.

Gimeno, F., Sáenz, A., Ariño, J. V., & Aznar, M. (2007). Deportividad y violencia en el fútbol base. Un programa de evaluación y prevención de partidos de riesgo. *Revista de Psicología del Deporte*, 16(1), 103-118.

Gómez, A. (2007). La violencia en el deporte. Un análisis desde la psicología social. *Revista de Psicología Social*, 22, 63-87.

Hristovski, R. (1997). Condensation of coherent states in social groups by the symmetry breaking mechanism. *Proceedings of the 6th International Congress on FIS Communications*, Nish, 279-282.

Javaloy-Mazón, F. (1996). Hinchas violentos y excitación emocional. *Revista de Psicología del Deporte*, 5(2), 93-104.

Latane, B. (1996). Dynamic social impact: Robust predictions from simple theory. In R. Hegselman, U. Mueler, & K. Troitzsch (Eds.), *Modelling and simulating in the* *social sciences from a philosophy of science point of view* (pp. 287-310). Dordrecht: Kluver.

Liebovitch, L. S., *Vallacher, R. R.*, Nowak, A., Coleman, P. T., Bartoli, A., & Bui-Wrzosinska, L. (2012). Mathematical models of the dynamics of conflict. In A. W. Davidson, M. A. Ray, & M. Turkel, M. (Eds.), *Nursing, caring, and complexity science: For human-environment well-being.* New York: Springer.

Musallam, N., Coleman, P. T. & Nowak, A. (2010). Understanding the spread of malignant conflict: A dynamical systems perspective. *Peace and Conflict: Journal of Peace Psychology*, 2, 127-151.

Nowak, A. & Latane, B. (1994). Simulating the emergence of social order from individual behavior. In N. Gilbert & J. Doran (Eds.), *Simulating societies: The computer simulation of social processes* (pp. 257-286). London: University College London Press.

Nowak, A., Szamrej, J. & Latane, B. (1990). From private attitude to public opinion: A dynamic theory of social impact. *Psychological Review*, 97, 362-367.

Nowak, A. & Vallacher, R. R. (1998). Toward computational social psychology: Cellular automata and neural network models of interpersonal Dynamics, In S. J. Reed & L. C. Miller (Eds.), *Connectionist models of social reasoning and social behavior* (pp. 277-311). Mahwah, New Jersey: Erlbaum.

Nowak, A., Vallacher, R. R., Bui-Wrzosinska, L. & Coleman, P. T. (2006). Attracted to Conflict: A Dynamical Perspective on Malignant Social Relations. In A. Golec & K. Skarzynska (Eds.), *Understanding social change: political psychology in Poland* (pp. 1-18). Hauppauge: Nova Science Publishers Ltd.

Renfrew, A. C. & Poston, T. (1978). Discontinuities in the endogenous change of settlement pattern. In K.L. Cooke & C. A. Renfrew (Eds.), *Transformations: Mathematical approaches to culture change* (437-461). New York: Academic Press.

Shelling, T. (1971). Dynamic models of segregation. *Journal Mathematical Sociology,* 1, 143-186.

Vallacher, R. R. & Nowak, A. (2007). Dynamical social psychology: On complexity and coordination in interpersonal relations. In M. Uhl-Bien & R. Marion (Eds.), *Complexity and leadership, Volume 1: Conceptual foundations* (pp. 49-81). Charlotte, NC: Information Age Publishers.

Vallacher, R. R., Coleman, P. T., Nowak, A. & Bui-Wrzosinska, L. (2010). Rethinking intractable conflict: The perspective of dynamical systems. *American Psychologist*, 65, 262-278.

Vallacher, R. R. & Jackson, D. (2009). Thinking inside the box: Dynamical constraints on mind and action. *European Journal of Social Psychology*, 39, 1226-1229.

Vallacher, R. R., Nowak, A., & Zochowski, M. (2007). Dynamics of social coordination: The synchronization of internal states in close relationships. In P. Hauf & F. Forsterling (Eds.), *Making minds: The shaping of human minds through social context* (pp. 31-46). Amsterdam: John Benjamins Publishing Company.

Weidlich, W. (1978). Dynamics of interacting social groups, in Cooperative Effects. In Haken, H. (Ed.), *Progress in synergetics* (pp. 269-282). Amsterdam: North Holland.

Zeeman, E. C., Hall, C., Harrison, P. J., Marriage, H. & Shapland, P. (1976). A model for institutional disturbances. *British Journal of Mathematical & Statistical Psychology*, 29, 66-80.

Zillmann, D., Bryant, J. & Sapolsky, B. S. (1989). Enjoyment from sports spectatorship. In Goldstein, J.H. (Ed.), *Sports, games, and play: Social and psychological viewpoints* (2nd ed., pp. 241-278). Hillsdale, NJ: Erlbaum.

Table 1. Stratified attitude patterns formed in the social ensemble under the impinging referee decisions B. Each row represents one attitude pattern formed in the opinion, emotional and preferred action spaces. Potentially violent and moderate proto-group formation can be detected based on their attained coherent values in the action space (J_{action})

Number of the attitude pattern	$J_{opinion}$	$J_{emotional}$	J_{action}	Proto-group
1	7.5	7.5	7.5	Violent
2	7.5	7.5	5.5	
3	7.5	7.5	4.5	Moderate
4	7.5	7.5	3.5	Moderate
5	7.5	6.5	7.0	Violent
6	7.5	6.5	5.5	
7	7.5	6.5	4.5	Moderate
8	7.5	6.5	3.5	Moderate

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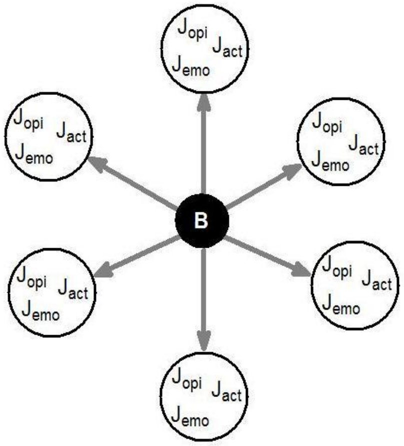

Fig. 1. A star network of a referee-fans system. The decisions B from the central node, i.e. the referee, impinge on peripheral nodes, i.e. the team supporters (fans). Each fan may have different personal constraints, J, in the opinion, emotional and action spaces.

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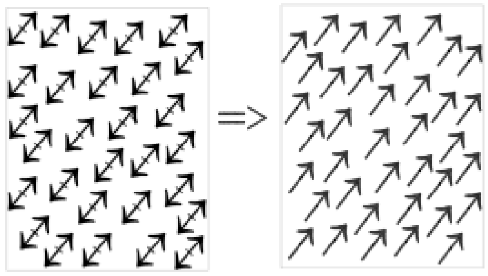

$\langle\sigma_z\rangle=0$ Figure 2A. $\langle\sigma_z\rangle\neq0$ Figure 2B

Fig. 2. Symmetry breaking of the original state without attitude to a state in which attitudes are stabilized.

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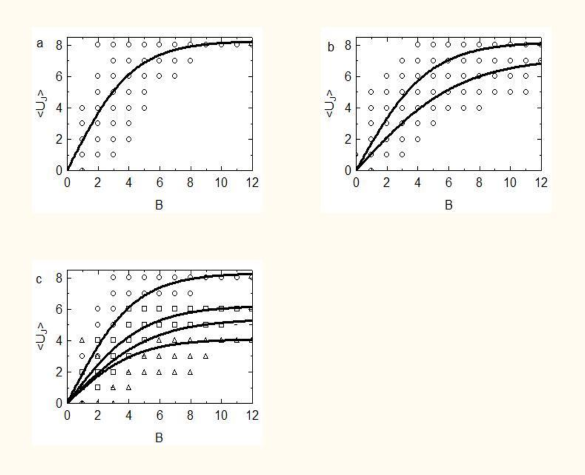

Fig. 3. a) Regression curve for the expected value of the opinion dimension, $<U_J>_{\text{opinion}}$. b) Two regression curves for the expected value of the emotional dimension, $<U_J>_{\text{emotional}}$. c) Four regression curves for the expected value of the preferred action dimension, $<U_J>_{\text{action.}}$ B is a number of referee’s decisions.

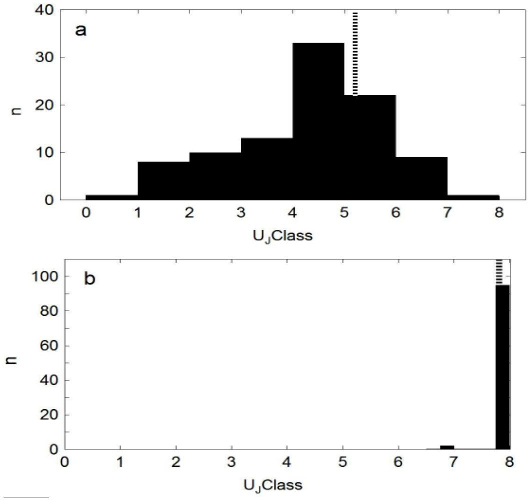

Fig. 4. Example histograms of data distribution in the opinion space (a: B=3; b: B=8). Dotted vertical lines signify the position of the fitted curve (compare with Fig. 2). Vertical axis n = number of observations; horizontal axis U_J Class = attitudinal level class. The coherence of opinions for B=3 is low, while for B=8 it is high.

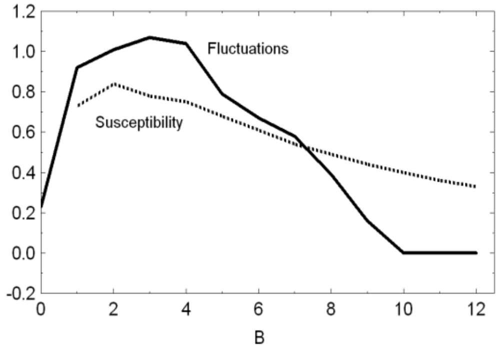

Fig. 5. A typical profile of a point-to-point estimate of the social responsiveness, i.e. susceptibility (χ), from the data (dotted line) and fluctuation estimates from the data (bold line).

GENERAL DISCUSSION AND CONCLUSIONS

This thesis shows how a unified framework, based on general NDST principles and concepts, can be used to study diverse sport-related behavior, usually researched by different disciplines like physiology, psychology and social sciences. Indeed, general NDST concepts such as collective variable, control parameter, stability, instability and nonlinear change were proved to be useful to study apparently unconnected phenomena like the path to exhaustion or the coherent attitudes of sport fans. The results show that different collective variables extracted from different levels (organismic, kinematic, psychological, and social) and operating at different time scales change their dynamics under the influence of control parameters (workload, time on task, and incorrect referee decisions, respectively) following the same general laws.

The results reveal that the coordinative state of the systems under study remains stable only for certain values of the respective control parameter. Beyond such values the system destabilises and, at a critical point, suffers a nonlinear change. This is captured by an abrupt re-organization or qualitative change of the collective variable. This re-organization, which is the result of a self-organizing process, reflects the system adaptability to changing environmental and task constraints. This nonlinear self-organized process of change is exemplified at two different levels: at organismic level, by the formation of new psychobiological synergies that compensate the inhibitory processes produced by effort accumulation, and at social level, by the formation of coherent attitudinal patterns that form under the influence of erroneous referee decisions.

Table 1 summarizes the general findings of all experiments included in this thesis.

Table 1.*Summary of the results obtained testing the dynamic behavior of diverse collective variables under the influence of different control parameters. The same NDST general concepts were used independently of the level of analysis*.

Article	Experiment	Exercise	Collective Variable	Stability	Control Parameter	Instability	Nonlinear change
I	a) Dose-effect relations of training stimuli (modelling)	Any type	Performance level	Overreaching (positive effect of the training stimuli)	Workload	Alteration of performance level evolution	From overreaching to overtraining (negative effect of the training stimuli)
I	b) Dynamics of the elbow angle	Quasi isometric 90º elbow flexion holding an Olympic bar at 80% of 1 RM until exhaustion	Elbow angle	The fluctuation dynamics around 90º elbow flexion	Time on task	Enhancement of the elbow angle fluctuations	From stable 90º elbow flexion to 0º elbow flexion (task disengagement)
I	c) Dynamics of attention focus	Running at 80-90% of the HR max	Attention focus (TUT / TRT)	Keeping the imposed TUT state	Time on task	Increase of non-volitional TRTs	From imposed TUT to stable TRT state
I	d) Dynamics of volition states	Quasi isometric 90º elbow flexion holding an Olympic bar at 80% of 1 RM	Volition state (UP intention / DOWN urges)	UP state	Time on task	Emergence of DOWN urges (UP/DOWN switches)	From UP state to stable DOWN state (task disengagement)
II	Perceived exertion shifts (PES) dynamics	Cycling at 4 different intensities corresponding to initial RPE = 13,15,17,19	Perceived exertion Shifts (PES)	The fluctuating dynamics of PES (increments/decrements)	Time on task	The non-fluctuating dynamics of PES (just increments)	From fluctuating dynamics to non-fluctuating dynamics of PES
III	Variability properties of the elbow angle	Quasi isometric 90º elbow flexion holding an Olympic bar at 80% of 1 RM until exhaustion	Elbow angle	The anti-persistent fluctuation dynamics of the elbow angle	Time on task	The persistent fluctuation dynamics of the elbow angle	From anti-persistent to persistent fluctuation dynamics of the elbow angle
IV	Sport fans coherence	Respond questionnaires	Attitudes at opinion, emotional and action levels	Independent attitudes of fans (before answering the questionnaires)	Number of incorrect referee decisions	The formation of coherent attitude patterns of fans at opinion, emotional and action levels	From independent to coherent collective attitudes of fans

Note. PES = Perceived Exertion Shifts; RPE = Rate of Received Exertion; RM = Repetition Maximum; TUT = Task Unrelated Thoughts; TRT = Task Related Thoughts.

Each system evolves by passing the following three phases: Initial stability, the loss of stability (instability) of the initial state and formation of the new stable phase (which can be further destabilized). In our research the initial stability is manifested in four different ways on the organismic level: by the overreaching state of the performance variable, i.e., a positive effect of the training stimuli (exp. Ia); by the fine adjustments (on short time scales) of the prescribed elbow angle value (exp. Ib) and its anti-persistent variability profile (exp. III); by keeping the intended TUT (exp. Ic) and "UP" state (exp. Id), and by the fluctuating dynamics of PES (exp. II). Finally, the stability is represented by the independent attitude behavior of fans on the opinion, emotion and action dimensions on the social level (exp. IV).

When constraints change beyond certain values, [i.e., workload increases (exp. Ia), time on task enlarges (exp. Ib, Ic, Id, exp. II and exp. III) and the number of referee wrong decisions against the favourite team increases (exp. IV)], there is a loss of stability of the corresponding coordinative variables. The instability on the organismic level manifests through the increase of fluctuations of the performance evolution (exp. Ia), the enhancement of fluctuations of the elbow angle (exp. Ib); the emergence of TRT's and DOWN urges that compete with the initial stable TUT and UP states (exp. Ic and Id), and the non-fluctuating dynamics of PES (exp. II). On the social level, the instability is reflected by the reduction of the variability of the individual responses and the progressive formation of layers of coherence at opinion, emotion and action dimensions (exp. IV). Thus, as the initial coupling among system components weaken, a new cooperation among systems components emerges. On the organismic level this nonlinear change is reflected by a transition from positive (overreaching) to negative (overtraining) effect of training stimulus (exp. Ia), on a kinematic level by a sudden change of the elbow angle from 90º to 0º (exp. Ib), this transition is intimated by a slow transition from anti-persistent to persistent variability profile (exp. III). On the psychological level, by the change from stable TUT to stable TRT state (exp. Ic), from UP to DOWN state (exp. Id), and from fluctuating to non-fluctuating dynamics of PES (exp. II). Finally, on the social level, the nonlinear change is reflected by the transition from independent to coherent attitudes of fans (exp. IV).

The newly attained final stable states are the overtraining state of the performance variable, i.e., a negative effect of the training stimuli (exp. Ia); the rest state of the elbow angle (exp. Ib and exp. III); The TRT (exp. Ic) and "DOWN" state (exp. Id), and the non-fluctuating dynamics of PES (exp. II). The newly stabilized final state in the social group is represented by the presence of coherent attitudes of fans on the opinion, emotion and action dimensions. (exp. IV).

In particular, the experiments where kinematic and psychological variables (attention focus and volition states) were studied during static and dynamic exercises performed until exhaustion delineate 3 effort phases in the path to exhaustion:

- The first phase, at exercise onset, is characterized by a greater stability and flexibility of the system to maintain the initial conditions. This is revealed through the light fluctuations around the 90ºelbow angle and its dominant anti-persistent structure of variability, the ability of the performers to maintain the imposed TUT and UP state, and the fluctuating dynamics of PES.
- The second phase is characterized by a progressive reduction of degrees of freedom and adaptability of the system due to the effects of the accumulated effort. This is observed by the increase of fluctuations of the elbow angle, the metastable dynamics of thoughts (emergence of TRTs competing with TUTs) and volition states (emergence of DOWNs competing with UPs), and the fluctuating dynamics of PES.

- The third phase, close to the task disengagement, is characterized by the persistent fBm structure of variability of the kinematic variable, the stability of TRTs and urges to terminate (DOWNs) and the non-fluctuating dynamics of PES. It is important to note that the change of behavior of the kinematic and psychological variables is a consequence of the competition between the inhibition (i.e. metabolic changes in the muscles) and excitation (i.e. excitation of the central nervous system) forces during the effort (Vázquez, Hristovski & Balagué, 2016). The process suggests a different understanding of the task disengagement phenomenon, which cannot be attributed to any specific site or process but to the general loss of stability mechanism.

In conclusion, the NDST unifying concepts remain valid and stay relevant to explain different types of sport-related phenomena, independently of its level of description and time scale of analysis. Therefore, the NDST framework seems to be a promising way to satisfy the interdisciplinar and transdisciplinar claims of sport science and science in general; and particularly, to serve as a rigorous mathematical theory forming platform where detailed socio-psycho-biological mechanisms would be incorporated in lawful formal relations (Hristovski, 2013). In fact, the NDST concepts and language already in different sciences like physics (from Newton onwards), chemistry (Lehn, 2002; Nicolis & Prigogine, 1977), biology (Barabási & Oltvai, 2004; Chang, Hemberg, Barahona, Ingber & Huang, 2008; Walczak, Sasai &Wolynes, 2005), economics (Foster, 1997; Witt, 1997), psychology (Kelso, 1995; Kohonen, 2012; Van Orden, Holden, & Turvey, 2003) and sociology (Nowak, Vallacher, Tesser, & Borkowski, 2000; Vallacher, Coleman, Nowak, & Bui-Wrzosinska, 2010; Vallacher & Jackson, 2009) among others, have started to extend to sport disciplines as a consequence of science evolution (Balagué et al., 2016). One future challenge for sport science is to enlarge the study of emergent behaviour observed at small scales (individuals, pairs of opponents and teams) (Bourbousson, Sève, & McGarry, 2010) to larger scales, such as pairs of teams, mass-start competitions (Trenchard, 2015) and leagues of competition (Travassos et al., 2010).

As shown in this thesis, the unifying NDST concepts may play a major explanatory role and may contribute to build a unified framework for the study of sport-related phenomena. In this sense, this thesis: a) provides support to integrative and transdisciplinar approaches to sport science (see Balagué et al., 2016), b) contributes to reduce the barriers among scientific disciplines and scientific language, c) improves the communication and transfer of knowledge among scientists. (Hristovski, 2013; Hristovski, Balagué & Vázquez, 2014).

Based on the above-mentioned reasons, the current NDST-based unifying approach may also be useful in academic settings. Contemporary education, based on a fragmented structure of subjects and topics, limits reasoning and critical thinking in students, and brings about a fragmented worldview. Some authors have found qualitative differences between the explanatory patterns of science considered in secondary school and university textbooks and those found in the recent modelling scientific publications, especially in the areas of social and biological sciences (Hristovski et al., 2014). This fact contributes little to the development of the integrative competencies and knowledge considered essential in modern society. In such a context, providing an education in science that could help to integrate knowledge and facilitate the transfer to theoretical explanatory principles among disciplines seems a key point.

REFERENCES

Balagué, N., Hristovski, R., Vainoras, A., Vázquez, P., & Aragonés, D. (2014). Psychobiological integration during exercise. In K. Davids, R. Hristovski, D. Araújo, N. Balagué, C. Button, & P. Passos (Eds.), *Complex systems in sport* (pp. 82–102). London, UK: Routledge.

Balagué, N., Torrents, C., Hristovski, R., Davids, K., & Araújo, D. (2013). Overview of complex systems in sport. *Journal of Systems Science and Complexity*, *26*, 4–13. doi:10.1007/s11424-013-2285-0

Balagué, N., Torrents, C., Hristovski, R., & Kelso, J.A.S. (2016): Sport science integration: An evolutionary synthesis. *European Journal of Sport Science*. Advance on line publication. doi: 10.1080/17461391.2016.1198422

Barabási, A. L., & Oltvai, Z. N. (2004). Network biology: Understanding the cell’s functional organization. *Nature Reviews. Genetics*, *5*, 101–113. doi: 10.1038/nrg1272

Bourbousson, J., Sève, C., & McGarry, T. (2010). Space-time coordination dynamics in basketball: Part 2. The interaction between the two teams. *Journal of Sports Sciences, 28*, 349–358.

Bovier, A., & den Hollander, F. (2015). *Metastability. A potential-theoretic approach*. Heidelberg: Springer.

Bressler, S.L., & Kelso J.A.S. (2001). Cortical coordination dynamics and cognition. *Trends in Cognitive Science, 5*, 26–36. doi: 10.1016/S1364-6613(00)01564-3

Chang, H. H., Hemberg, M., Barahona, M., Ingber, D. E., & Huang, S. (2008). Transcriptome-wide noise controls lineage choice in mammalian progenitor cells. *Nature, 453*, 544–7. doi:10.1038/nature06965

Eissing, T., Kuepfer, L., Becker, C., Block, M., Coboeken, K., Gaub, T., … Lippert, J. (2011). A computational systems biology software platform for multiscale modeling and simulation: Integrating whole-body physiology, disease biology, and molecular reaction networks. *Frontiers in Physiology, 2.* doi: 10.3389/fphys.2011.00004

Foster, J. (1997). The analytical foundations of evolutionary economics: From biological analogy to economic self-organization. *Structural change and economic dynamics, 8,* 427–451. doi: S0954349X97000027

Glansdorff, P., & Prigogine, I. (1971). *Thermodynamics theory of structure, stability and fluctuations*. London: Wiley-Interscience.

Haken, H. (1964). Theory of coherence of laser light. *Physical Review Letters*, *13*, 329-331.

Haken, H. (1987). Synergetics. An approach of self-organization. In F. Eugene Yates (Ed.), *Self-organizing systems. The emergence of order* (pp. 417-434). New York, NY: Plenum Press.

Hristovski, R. (2013). Synthetic thinking in (sports) science: The self-organization of the scientific language. *Research in Physical Education Sport and Health, 2*, 27-34.

Hristovski, R., Aceski, A., Balagué, N., Seifert, L., Tufekcievski, A., & Aguirre, C. (2016). Structure and dynamics of textual contents in European sports science: An analysis of ECSS abstracts (1996-2014). *European Journal of Sport Science.* Advance online publication. doi: 10.1080/17461391.2016.1207709

Hristovski, R., Balagué, N., & Schöllhorn, W. (2014). Basic notions in the science of complex systems and nonlinear dynamics. In K. Davids, R. Hirsitovski, D.Araújo, N. Balagué, C. Button, & P. Passos (Eds.), *Complex systems in sport* (pp. 62-81). London, UK: Routledge.

Hristovski, R., Balagué, N., & Vázquez, P. (2014). Experiential learning of the unifying principles of science through physical activities. In F. Miranda (Ed.), *Systems Theory* (pp. 37-48). New York, NY: NOVA Publishers.

Kelso, J.A.S. (1995). *Dynamic patterns: The self-organization of brain and behavior*. Cambridge: MIT Press.

Kelso, J.A.S. (2009). Synergies: Atoms of brain and behavior. In D. Sternad (Ed.), *Progress in Motor Control* (pp. 83-91). New York, NY: Springer Science-Business Media.

Kelso, J.A.S., Southard, D., & Goodman, D. (1979). On the nature of human interlimb coordination. *Science, 203*, 1029-1031.

Kohonen, T. (2012). *Self-organization and associative memory*. London: Springer-Verlag.

Kugler, P.N., Kelso, J.A.S., & Turvey, M.T. (1980). On the concept of the coordinative structures as dissipative structures: I. Theoretical lines of convergence. *Tutorials in motor behavior, 3*, 3-47.

Landau, L. D. (1969). *Collected Papers*. Moscow: Nauka.

Lehn, J. M. (2002). Toward complex matter: Supramolecular chemistry and self-organization. *Proceedings of the National Sport Academy of Sciences of the United States of America, 99*, 4763–4768.

Maisuradze, G.G., Liwo, A., & Scheraga, H.A. (2009). Principal component analysis for protein holding dynamics. *Journal of Molecular Biology, 385*, 312-329. doi:10.1016/j.jmb.2008.10.018.

Nowak, A., Vallacher, R. R., Tesser, A., & Borkowski, W. (2000). Society of self: The emergence of collective properties in selfstructure. *Psychological Review, 107*, 39–61. doi: I0.1037/W 33-295X.107.1.39

Nicolis, G., & Prigogine, I. (1977). *Self-organization in non-equilibrium systems*. New York, NY: State University of New York Press.

Rabinovich, M.I., Huerta, R., Varona, P., & Afraimovich, V.S. (2008). Transient cognitive dynamics, metastability, and decision making. *PLoS Computational Biology, 4*, 25–30. doi:10.1371/journal.pcbi.1000072

Ric, A., Hristovski, R., Gonçalves, B., Torres, L., Sampaio, J., & Torrents, C. (2016). Time scales for exploratory tactical behaviour in football small-sided games. *Journal of Sport Sciences*, *13*, 1–8. doi: 10.1080/02640414.2015.1136068

Travassos, B., Araújo, D., Correia, V., & Esteves, P. (2010). Ecodynamics approach to the study of team sports performance. *The Open Sports Sciences Journal*, *3*, 56–57. doi:10.2174/1875399X01003010056

Trenchard, H. (2015). The peloton superorganism and protocooperative behavior. *Applied Mathematics and Computation*, *270*, 179–192.

Van Orden, G. C., Holden, J. G., & Turvey, M. T. (2003). Selforganization of cognitive performance. *Journal of Experimental Psychology: General, 132*, 331–350.

Vallacher, R. R., Coleman, P. T., Nowak, A., & Bui-Wrzosinska, L. (2010). Norethinking intractable conflict: The perspective of dynamical systems. *American Psychologist, 65*, 262–278.

Vallacher, R. R., & Jackson, D. (2009). Thinking inside the box: Dynamical constraints on mind and action. *Journal of Social Psychology, 39*, 1226–1229.

Vázquez, P., Hristovski, R., & Balagué, N. (2016). The path to exhaustion. Time-variability properties of coordinative variables during continuous exercise. *Frontiers in Physiology, 7*. doi: 10.3389/fphys.2016.00037

Walczak, A. M., Sasai, M., & Wolynes, P.G. (2005). Self-consistent proteomic field theory of stochastic genes witches. *Biophysical Journal*, *88,* 828–850. doi: 10.1529/biophysj.104050666

Wilson, K.G. (1975). The renormalization group: Critical phenomena and the Kondo problem. *Reviews of Modern Physics*, *47*, 773.

Witt, U. (1997). Self-organization and economics—what is new? *Structural change and economic dynamics*, *8,* 489–507. doi:10.1016/S0954-349X(97)00022-2