UNIVERSITAT DE
BARCELONA

Exercise-Induced Pain. Dynamic Perspective

Agne Slapsinskaite

ADVERTIMENT. La consulta d'aquesta tesi queda condicionada a l'acceptació de les següents condicions d'ús: La difusió d'aquesta tesi per mitjà del servei TDX (**www.tdx.cat**) i a través del Dipòsit Digital de la UB (**diposit.ub.edu**) ha estat autoritzada pels titulars dels drets de propietat intel·lectual únicament per a usos privats emmarcats en activitats d'investigació i docència. No s'autoritza la seva reproducció amb finalitats de lucre ni la seva difusió i posada a disposició des d'un lloc aliè al servei TDX ni al Dipòsit Digital de la UB. No s'autoritza la presentació del seu contingut en una finestra o marc aliè a TDX o al Dipòsit Digital de la UB (framing). Aquesta reserva de drets afecta tant al resum de presentació de la tesi com als seus continguts. En la utilització o cita de parts de la tesi és obligat indicar el nom de la persona autora.

ADVERTENCIA. La consulta de esta tesis queda condicionada a la aceptación de las siguientes condiciones de uso: La difusión de esta tesis por medio del servicio TDR (**www.tdx.cat**) y a través del Repositorio Digital de la UB (**diposit.ub.edu**) ha sido autorizada por los titulares de los derechos de propiedad intelectual únicamente para usos privados enmarcados en actividades de investigación y docencia. No se autoriza su reproducción con finalidades de lucro ni su difusión y puesta a disposición desde un sitio ajeno al servicio TDR o al Repositorio Digital de la UB. No se autoriza la presentación de su contenido en una ventana o marco ajeno a TDR o al Repositorio Digital de la UB (framing). Esta reserva de derechos afecta tanto al resumen de presentación de la tesis como a sus contenidos. En la utilización o cita de partes de la tesis es obligado indicar el nombre de la persona autora.

WARNING. On having consulted this thesis you're accepting the following use conditions: Spreading this thesis by the TDX (**www.tdx.cat**) service and by the UB Digital Repository (**diposit.ub.edu**) has been authorized by the titular of the intellectual property rights only for private uses placed in investigation and teaching activities. Reproduction with lucrative aims is not authorized nor its spreading and availability from a site foreign to the TDX service or to the UB Digital Repository. Introducing its content in a window or frame foreign to the TDX service or to the UB Digital Repository is not authorized (framing). Those rights affect to the presentation summary of the thesis as well as to its contents. In the using or citation of parts of the thesis it's obliged to indicate the name of the author.

AGNE SLAPSINSKAITE

Exercise-Induced Pain. Dynamic Perspective

INEFC
Generalitat de Catalunya
UNIVERSITAT DE BARCELONA

UNIVERSITAT DE BARCELONA

Facultat d'Educació

Institut Nacional d'Educació Física de Catalunya
Centre de Barcelona

Programa de doctorat
Activitat Física, Educació Física i Esport

EXERCISE-INDUCED PAIN. DYNAMIC PERSPECTIVE

Tesi doctoral presentada per:

AGNE SLAPSINSKAITE

Directors:

DRA. NATÀLIA BALAGUÉ SERRE

DR. ROBERT HRISTOVSKI

Tutora:

DRA. NATÀLIA BALAGUÉ SERRE

Per optar al títol de Doctora per la Universitat de Barcelona

BARCELONA, 2017

To my beloved parents *Virginija* and *Bronius* for the life they gave to me,

This thesis was supported by the Institut Nacional d’Educació Física de Catalunya (INEFC) and Generalitat de Catalunya.

ACKNOWLEDGEMENTS

I would like to extend my gratitude to all those who shared their knowledge with me since the congress of Complex Systems in Sports and Medicine held in Kaunas in 2010.

Firstly, very sincere and special thanks to my supervisor Dr. Natalia Balagué for all the continuous challenges and intellectual stimulations she provided me within the course of my PhD studies and toward my personal development in general.

I am also deeply thankful to my advisor Dr. Robert Hristovski who has been so kind to let me pick his brain on a regular basis for data analyses and devoting numerous hours for discussing concepts and ideas related to nonlinear dynamic theory and the nonlinear life.

Besides my advisors, I would like to especially thank Dr. Selen Razon for all the e-mails which we exchanged and all the valuable advises and recommendations she shared with me.

I would also like to thank Dr. Gershon Tenenbaum for a serious of fruitful collaborations together; he was a great asset for our research team.

Countless thank also to the members of our research group “Complex Systems in Sport” for making me feel part of something bigger: Dr. Pablo Vázquez Justes, Dr. Sergi García Retortillo, Dr. Daniel Aragonés, Ángel Ric Diez, Gemma Espigares, Cecilia Aguirre, Alain López, Aleix Giber. Without their insightful comments and encouragements this journey would not be as smooth and easygoing.

Last but not the least, I would like to thank to INEFC who provided me with the opportunity to be a part of their institution by awarding me with their highly honorable pre-doctoral scholarship. Additional thanks to our Research department including Maribel Pérez, Carmen Suarez and Dr. Joan Cadefau for your time and support during these three years. To that end, I am also very grateful to a number of people who made me feel like a local: all the members of our “yoga” team, pre-doctoral students already doctors: Dr. Priscila Torado Pineda, Dr. Diego Chaverri Jové, Dr. Gerard Carmona Dalmases, Dr. Jairo Vázquez, Dr. Pedrona Serra Payeras, Dr. Víctor Labrador, Dr. Rafael Tarragó García, Dr. Mari Mahmud as well as the one’s still on the road: Blai Ferrer Uris, Victor Illera Domínguez, Sergi Nuell, Joan Babí Lladós, Ingrid Hinojosa Alcalde, Jorge Castizo, Bruno Fernandez-Valdes Villa, Clara Teixido Batlle. It has been a pleasure for me to share time and space with you all.

Above all, I am deeply thankful and grateful to my wonderful family who supported me from very long distances – my beloved parents Bronius and Virginija, my brother OP. Mindaugas and my twin sister Indrė. Without their endless support, and encouragements I could not be where I am right now.

Take into account that great *love* and great achievements involve great *risk*.

-DALAI LAMA-

TABLE OF CONTENTS

ABBREVIATIONS

APS - American Pain Society

DST – Dynamical System Theory

hPCA – hierarchical Principal Component Analysis

IASP - International Association for the Study of Pain

NDST - Nonlinear Dynamical System Theory

PC – Principal Component

PE – Perceived Exertion

PES – Perceived Exertion Shifts

RPE - Rating of Perceived Exertion

TRT – Task Related Thoughts

TRT-E - External Task Related Thoughts

TRT-I – Internal Task Related Thoughts

TUT– Task Unrelated Thoughts

TUT-E- External Task Unrelated Thoughts

TUT-I - Internal Task Unrelated Thoughts

SUMMARY

This present document includes a doctoral thesis prepared at the University of Barcelona. This thesis was developed as a compendium of publications resulting from the accomplishments of the 3-year pre-doctoral studies. It consists of seven chapters. Chapter 1 includes two sections: a general one which delineates the history and most relevant scientific queries related to pain induced by exercise (sections 1.1, 1.2, 1.3) and a second one which focuses on a nonlinear dynamic approach to pain and attention under the framework of the psychobiological model of exercise-induced fatigue (section 1.4). The Chapters 2, 3, 4 and 5 include four research examples related to the topic. Chapter 6 discusses main research findings. Finally Chapter 7 provides conclusions and future lines of the research on the development of a Nonlinear psychobiological model of exercise-induced fatigue from a standpoint of the NDST.

Exercising above certain intensity and duration elicits feelings of discomfort and pain. As pain is related to exercise tolerance and task disengagement previous studies have focused on pain intensity measurements but have not payed attention on its locations *dynamics*. Pain location dynamics provide a possibility to explore how fatigue spreads throughout the body, to identify pain distribution and its individual patterns as well as to search the temporal organization of subjective experiences (qualia), which remain largely understudied up until now. The psychobiological model of exercise induced fatigue has highlighted the presence of nonlinear features studying the dynamics of thoughts and perceived exertion in the course of constant and incremental exercises performed until exhaustion. In order to understand better the psychobiological mechanisms of exercise-induced fatigue and design adequate interventions to increase the exercise tolerance, this thesis proposes considering the study of pain dynamics and attention in alternative settings with the following objectives in mind: a) to delineate the pain and discomfort location dynamics during constant cycling and running performed until exhaustion, b) to detect individual pain patterns during these tasks, c) to examine the potential presence of nested metastable pain-attention dynamics during incremental cycling performed until exhaustion, d) to compare the effects of indoor and outdoor environments on attention focus and cycling endurance.

For the purpose of this thesis, all participants were tested while cycling and/or running at constant or incremental power until exhaustion. Pain and discomfort locations were self-monitored and reported every 15s using a 50-item pain body map. Self-caught measurements and self-selected key words were used together with an experimenter-classified method to monitor the attention focus in indoor and outdoor conditions.

Present results revealed that: a) the number of body locations with perceived pain increased throughout the effort expenditure, b) three consistent pain dynamic patterns were identified during constant cycling and running (i.e., adders, adders/jumpers and jumpers), c) pain-attention dynamics during incremental exercise was metastable and temporarily nested, d) outdoor environment compared to indoor, improved endurance and increased the use of external thoughts.

In conclusion, the thesis highlights the metastable dynamics of the body-mind-environment interaction during constant and incremental exercises performed until exhaustion and reinforces the presence of the nonlinear features pointed by the psychobiological model of exercise induced fatigue. The pain-attention temporal nestedness and the proposed taxonomy based on attention-driven mechanisms may be a fruitful avenue to pursue for future investigation. Moreover, the dynamic approach may help practitioners to design adequate interventions to increase exercise endurance and tolerance within different settings and can be used for studying alternative clinical/medical pain presentations.

RESUM

L'exercici intens i durador provoca sensació de malestar i dolor. Com el dolor està relacionat amb la tolerància a l'esforç, els estudis previs han centrat l'atenció en mesurar la intensitat de dolor sense considerar la seva evolució espai temporal. La dinàmica de localització del dolor possibilita estudiar com la fatiga s'estén en el cos, els patrons individuals de distribució d'aquest dolor, i l'organització temporal de les experiències subjectives ("qualia"), inexplorada fins ara. El model psicobiològic de la fatiga induïda per l'exercici destaca la presència de no linealitat en la dinàmica dels pensaments i de la percepció de l'esforç durant exercicis realitzats fins l'esgotament. Aquesta tesi vol explorar el dolor i l'atenció en diferents entorns amb els següents objectius: a) delimitar la dinàmica de localització del dolor durant l'exercici, b) detectar patrons individuals d'aquest dolor, c) examinar la potencial presència d'una dinàmica metastable niada de la relació dolor-atenció, d) comparar els efectes d'ambients oberts i tancats en el focus d'atenció i la resistència.

Tots els participants van realitzar proves de pedaleig o carrera a intensitat constant o incremental fins l'esgotament. La localització del dolor va ser auto-monitoritzada i informada cada 15s a través d'un mapa del cos de 50-elements. Mesures "self-caught" i paraules clau auto-seleccionades es van utilitzar per monitoritzar els pensaments en entorns oberts i tancats.

El resultats obtinguts van mostrar que a) el nombre de llocs dolorosos augmenta amb l'acumulació d'esforç, b) la dinàmica de localitzacions del dolor permet identificar tres tipus de patrons individuals consistents durant el pedaleig i la carrera continus ("adders", "adder/jumpers" i "jumpers", c) la dinàmica de la relació dolor-atenció durant l'exercici incremental es metastable i temporalment niada, i d) en entorns oberts, respecte als tancats, millora la resistència i augmenta l'ús de pensaments externs. En conclusió, la tesi destaca la dinàmica d'interacció metastable entre cos, ment i ambient durant l'exercici constant i incremental realitzat fins l'esgotament. Els resultats poden ajudar a dissenyar intervencions dirigides a augmentar la resistència i a regular l'exercici en diferents entorns. També poden ser utilitzats per estudiar altres tipus de dolor clínicament rellevants.

This Thesis is based on Four Research Articles:

1. Slapsinskaite, A., Razon, S., Balagué Serre, N., Hristovski, R., & Tenenbaum, G. (2015). Local pain dynamics during constant exhaustive exercise. *Plos One*, *10*(9), e0137895. http://doi.org/10.1371/journal.pone.0137895

2. Slapsinskaite A., Selen R., Balagué Serre N., Ščiupokas A., Hristovski R., Tenenbaum G. Idiosyncratic Pain Patterns during Exhaustive Exercise. Scandinavian Journal of Pain. (Under review).

3. Slapsinskaite, A., Hristovski, R., Razon, S., Balagué, N., & Tenenbaum, G. (2017). Metastable pain-attention dynamics during incremental exhaustive exercise. *Frontiers in Psychology, 7*(January), 1–9. http://doi.org/10.3389/fpsyg.2016.02054

4. Slapsinskaite, A., García, S., Razon, S., Balagué, N., Hristovski, R., & Tenenbaum, G. (2016). Cycling outdoors facilitates external thoughts and endurance. *Psychology of Sport and Exercise*, *27*, 78–84. http://doi.org/10.1016/j.psychsport.2016.08.002

CHAPTER ONE

INTRODUCTION

This introduction is divided into two main sections: a general one that delineates the history and most relevant scientific queries related to pain induced by exercise (sections 1.1, 1.2, 1.3) and a second one that focuses on the nonlinear dynamic approach to pain that justifies this thesis and relates the conducted research (section 1.4).

1.1.PAIN

> "*Study the past if you would define the future*"
> — Confucius—

A brief overview of history. The concept '*pain*' was mentioned for the first time in an ancient traditional Chinese medicine book more than 3,000 years ago (Pfaff, 2013). In Greek mythology pain suffering is seen as a revenge of goddess Poine to punish the mortals. Later on, Latin word 'poena' preceded the English word 'pain'. In ancient times philosophers were trying to comprehend the nature of pain and the Greek philosopher Aristotle (382-322 B.C.), for instance, postulated that the *heart* was the seat of all sensations (i.e., hearing, vision, smell, taste, and pain), emotions, and even mental functions. Much later, the French philosopher Rene´ Descartes (1596–1650) suggested that brain plays a major role in the experience of pain and marked a major milestone in the study of pain. Descartes was the first one who described a detailed somatosensory pathway in humans and argued that noxious stimulus would activate the brain and a signal of pain would then be processed in a single line-labelled way. For most part of the 19th century pain research and conceptualization remained within the framework of "specificity theory". In the 20th century, the notion of nociception (1906) was proposed by Sir Charles Scott Sherrington (1857–1952) and the emphasis of the pain experience was placed upon the tissue injury. To date, scientific fields that study and describe pain are not yet complete, even though recent investigations have removed many ancient mysteries and inaccuracy surrounding the nature of pain. Consequently, the following sections outline the scientific achievements to understand pain and this thesis includes a purely exploratory design.

Pain definitions. There are many different definitions to pain. One of the most agreed upon definition refers to the one of International Association for the Study of Pain (IASP) and the American Pain Society (APS). IASP and APS define pain as an unpleasant sensory and emotional experience associated with an actual or potential tissue damage, or described in terms of such damage (Linblom, Mersky, & Mumford, 1986). Another previous definition coined by McCaffery, has also described pain as "whatever the experiencing person says it is, whenever the experiencing person says it is" (McCaffery, 1968). This definition is important in that it highlights the subjective feature of reporting pain which is unique to human-beings. In 1994 and 2008, even though the taxonomy of pain underwent changes, the definition of pain remained the same (Loeser & Treede, 2008). Nevertheless, these universally accepted ways to define pain still did not satisfy some, hence, a newer definition of the term was warranted. In 2016, a more polished definition defined pain as *a "distressing experience associated with actual or potential tissue damage with sensory, cognitive, emotional, and social components"* (Williams & Craig, 2016). This new definition describes the essential subjectivity of pain experience differentiating it from physiological processes while keeping in mind the biological mechanisms that govern the pain experience itself. As such, this definition indeed embeds the fundamental notion of sensory input modulation through a broad range of biological and psychosocial factors.

From pain matrixes to pain connectome. The complexity of the pain system however was not adequately accounted by any of the existing pain theories including the: 1) specificity theory, 2) intensity theory, 3) pattern theory and, 4) gate-control theory (Pfaff, 2013). Nevertheless, brain imaging studies in both human and animal subjects helped endorse theoretical notions of neuromatrix (Casey & Bushnell, 2000; Price, 1999). It is known that noxious stimuli caused by tissue or nerve damage and processed by an extensively distributed, hierarchically interconnected neural network was termed "pain matrix" by Melzack (Casey & Bushnell, 2000; Melzack, 2005). In Melzack's words, "the neuromatrix for the physical self generates the neuro signature pattern for pain" (Melzack & Wall, 1967). The peripheral and central neurons comprised neuromatrix, which have been shown to be involved in the *dynamical* response and adaptation to noxious stimulus that caused acute and chronic pain states (Khalsa, 2004). The regions included in the neuromatrix system were named as: the primary and secondary somatosensory cortices, insula, anterior cingulate cortex, prefrontal cortex, amygdala, and several nuclei of the thalamus (Raja, Hoot, & Dougherty, 2011).

Recently, however, the notion of "pain matrix" was criticized, and the brain was characterized as a "*dynome*" (Kopell, Gritton, Whittington, & Kramer, 2014). This new characterization put the emphasis on the role of a *dynamic* communication within and between networks in the shaping of the behavior and cognition. Because pain is generated by neural processing in the brain, in fact select neural architectures (i.e., arrangements of pools or clusters of neurons) and circuits (i.e., connections between these clusters) are necessary for the appropriate perception of the nociceptive stimuli (Key, 2016). Additionally, the dynamic pain connectome (i.e., full description of anatomical connections in the brain) states that it is about time to consider pain as an intrinsically dynamic experience and process encoded by the "pain connectome" - a spatiotemporal signature of brain network communication that represents the integration of cognitive, affective and sensorimotor aspects of pain (Kucyi & Davis, 2015).

Pain pathway: from nociception to perception. The term "nociception" proposed by Sir Charles Scott Sherrington (1857-1952) is derived from the Latin word "*nocere*" which means "to injure." This physiological term is still used in science to describe the neural processes of encoding and processing noxious stimulus (Loeser & Treede, 2008). During the nociception process, the neural information related to an actual or potential tissue damage is detected, transduced, encoded, and transmitted from the site of origin to the higher brain centers where pain sensation is modulated and perceived. For instance, when a noxious stimulus is applied to the toes, it may seem like the resultant pain is localized in these appendages, however, the feeling of pain is actually generated in the brain (Key, 2016). As such, the string of processes resulting in a noxious stimulus-inducing pain include: *transduction*, *transmission*, *modulation,* and *perception* (Raja et al., 2011). In the transduction stage, all the information available to the nervous system about noxious stimulus must be encoded by the primary afferent neurons (Prescott, Ma, & De Koninck, 2014). However, perception of pain does not relay on transmission of a pristine, untransformed neural representation of the original stimulus (Prescott et al., 2014). The representation is modulated through the spinal cord, thalamus, and the cortex. It undergoes transformations that ultimately produce a neural representation which underlies the induced perception. Within this framework, transformations depend on local microcircuit and factors, such as the descending modulation that influences the microcircuit function (Prescott et al., 2014). It is not surprising, that pain sometimes is referred as a highly subjective sensation with a complex and often non-linear relationship between nociceptive input and pain perception (Wiech, Ploner, & Tracey, 2008). Therefore, one can argue that the experience of pain is not exclusively driven by the noxious input but in turn is highly contingent on modulation (Wiech et al., 2008). Even nociception that is typically the cause of pain is neither necessary nor sufficient and is very often not even linearly related to the resulting sensation of pain (Tracey, 2010). The subjectivity of a painful experience is not mutually exclusive with its objective quantification, and remains one of the reliable indicators to consider in the observation of perceived pain.

1.2. PAIN IN EXERCISE

'Know your pain and gain'

(Moseley & Butler, 2015)

History and definitions. Exercising above certain intensity levels and durations elicits feelings of discomfort and pain. To our knowledge, the first attempt to study pain in exercise settings date back to 1930s. Back then, the nature of forearm muscle pain was examined during hand contractions performed while blood flow to the hand and forearm was occluded (Katz, Lindner, & Landt, 1935). Later, pain intensity was first recorded in 1966 during an isometric endurance task (Caldwell & Smith, 1966). Scientist used different terms to determine the pain experienced during exercise. As such previous literature has used the term *naturally occurring pain* (Cook, O'Connor, Eubanks, Smith, & Lee, 1997; Cook, O'Connor, Oliver, & Lee, 1998; O'Connor & Cook, 2001). Currently, the term is used interchangeably with: *discomfort* (Tenenbaum et al., 1999), *transient pain* (Morton & Callister, 2014; Morton, Richards, & Callister, 2005)*, spontaneous pain or soreness* (Cazzola et al., 2009)*, exertive pain* (Razon et al., 2010)*, exercise- induced pain* (Angius, Hopker, Marcora, & Mauger, 2015)*, activity induced pain* (Larsson et al., 2015), and *exercise related pain* (Dannecker & Koltyn, 2014). Given more than 75 years of research on the topic of exercise and pain, it is interesting to note that relatively few studies tried to broaden the understanding of neurobiological mechanisms and *dynamics* that underlie exertive pain. Therefore, a recent topic of inquiry refers to how many exercise professionals and health care providers regularly and appropriately measure exercise-related pain (both components: induction and reduction) in their exercise prescriptions and recommendations (Dannecker & Koltyn, 2014).

Theories and mechanisms. To date, scientific theories of pain hardly tackle some of the really difficult questions about exertive pain. Specifically, even though pain is set to be an integral part of exercise and sport settings, there is still a gap of knowledge about the dynamics of exertive pain (O'Connor & Cook, 1999). Likewise, although muscle pain experienced during exercise is common, it is in fact seldom investigated (Cook et al., 1998). As a result, today still, the mechanisms of exercise-induced muscle pain are not fully understood. With regards to the mechanism of the exertive pain, the literature is equivocal as to whether the increased pain response in these conditions is due to heightened *peripheral nociceptive* sensitivity or to an increased *central processing* of the same sensory input (Chen et al., 2008). The peripheral nociceptive sensitivity during a high intensity exercise is commonly believed to be a consequence of accumulation of a variety of noxious biochemical elements (e.g., serotonin, H+, potassium, lactate, histamine and prostaglandins) (O'Connor & Cook, 1999). Later on, it was proposed that pain arising from an intense, repetitive and rhythmical movement, which is consentient with endurance exercise likely results from a combination of increased intramuscular pressure, release of noxious metabolites, and deformation of tissue associated with muscular contractions (Ellingson, Koltyn, Kim, & Cook, 2014). However, further elaborations on the theory and more comprehensive understanding of the exertive pain mechanism were warranted.

Peripheral input. Typically, the experience of pain directly relates to tissues including perhaps tissue inflammation or tissues that are just unfit or underused. Skeletal muscles include type III and IV afferents also termed *A-delta* and *C fibers* that transmit the nociceptive signals. These skeletal muscle nociceptors are located along the walls of arterioles surrounding the connective tissue. This location of skeletal muscle nociceptors is ideal for receiving algetic substances released from a damaged or active skeletal muscle (O'Connor & Cook, 1999). Furthermore, under ischemic conditions which are predominant under prolonged muscular contractions occur as a response to a subgroup of *C fibers* nociceptors. This subgroup can be activated when *naturally occurring muscle pain is perceived* for instance during intense exercise (Cook et al., 1997). However, the role of peripheral nociception for pain is still debated (Leknes, 2011). It is well known, that the peripheral afferent input ascends via the dorsal columns to project to various cortical and subcortical brain regions, such as the somatosensory cortex and ventroposterior lateral nucleus of the thalamus (Almeida, Roizenblatt, & Tufik, 2004), where conscious pain sensation is produced. It is difficult to uncouple afferent feedback and pain, as both travel through type III and IV afferents, this may be explained by a limited number of studies focusing solely on changes in pain during exercise. In general, it is important to consider that the perception of pain is the end product of peripheral and central inhibitory-facilitator mechanisms from exercise induced mechanical, thermal, and chemical stress.

Central processing. The conscious experience of a sensory event is derived from a complex convolution of afferent information arising from peripheral sensory transducers with cognitive information about the present context, past history, and future implications of the stimulus (Coghill, McHaffie, & Yen, 2003). On one hand, it would be advised not to forget that the brain makes the final decision as to whether or not the peripheral input should be consciously perceived as pain. On the other hand, understanding the spinal cord and the brain processes behind the pain experience can provide with a significant control of the experience. To that end, it is known that from the spinal cord, nociceptive information is transmitted to the brain by the projection neurons that constitute three major pathways: the spinothalamic, spinoreticular, and pinomesencephalic tracts (O'Connor & Cook, 1999). As such, acute or transient pain activates a large set of brain regions, including thalamus, primary and secondary somatosensory areas, insula, anterior cingulate cortex, and periaqueductal gray matter, areas with variable activation of striatum (dorsal and ventral), amygdala, and medial and dorsolateral prefrontal cortex. The nociceptive areas via top-down, bottom-up projections can be modified. For instance, the modulation of vegetative reactions and internal feelings via anterior insular networks; the attentional modulation of sensory gain by top-down and bottom-up transactions; and the access of nociceptive information to declarative consciousness (Garcia-Larrea & Peyron, 2013).

Exertive pain dimensions: intensity, location. The biggest attempts in the study of pain during exercise was made by Cook and O'Connor (Cook et al., 1997, 1998; O'Connor & Cook, 1999). Given that the cycle ergometer testing has been consistently documented to induce naturally occurring muscle pain it is not surprising that majority of investigations are performed while cycling. At the beginning of the investigations of naturally occurring pain, the scientist wanted to observe changes in *pain intensity* defined as the intensity of hurt that the subjects feel in their legs while cycling (Cook et al., 1998). These attempts have revealed that pain increases as a function of exercise intensity (Cook et al., 1998). Jameson and Ring (2000) also observed elevated muscle and knee pain ratings across elevated cycling work rates, but the highest pain ratings occurred during the slowest pedaling cadence providing somewhat counter logical results. These past research concerning pain induced by muscle contractions were limited to experiments in which pain was measured by asking the subjects to self-report their perceived muscle pain. With regards to the self-report approach, the method is commonly pointed as a limitation of these studies, many additional studies have suggested the objectivity of subjective data. Consequently, it is important to understand that even if the investigations of pain within exercise settings started with the evaluation of pain intensity, other dimensions of pain can also be captured for instance its location or unpleasantness. The location of pain can be measured since exercise can be painful in diverse muscle groups. As such, it was found that subjects free of injury and pathology consistently report experiencing quadriceps muscle pain during moderate- and high-intensity cycle ergometry (Motl, Gliottoni, & Scott, 2007; O'Connor & Cook, 2001). Investigations of exercise-related pain should not focus solely on muscles because as described previously, Jameson and Ring (2000) detected not only muscle, but also knee pain during cycling. Likewise, Brown et al.'s (Brown, Miller, Posthumus, Schwellnus, & Collins, 2011) survey of 1,285 female marathon runners found that 54% of women recalled breast pain during moderate physical activity and 64% recalled breast pain during vigorous activity (Dannecker & Koltyn, 2014). Even if the observed number of muscles (locations) was very narrow, the primary aim in these studies was to understand the topology of pain and its intensity during exercise task.

Exertive pain threshold. An algetic response is promoted for the assessment of pain thresholds. This is generally done through thermal, pressure, and electrical stimuli application (Ellingson, Shields, Stegner, & Cook, 2012; Janal, Glusman, Kuhl, & Clark, 1994; Naugle, Naugle, Fillingim, & Riley, 2013; Ruble et al., 2005). The prevailing practice to use thermal, pressure, and electrical stimuli in exercise settings may have misrepresented the importance of exertive pain. Specifically, because the pathway between nociception to pain perception is an extremely complex one, using thermal pressure may not adequately stimulate exertive pain (Astokorki & Mauger, 2016). It has been previously suggested that the tolerance of exertive pain is an important prerequisite for endurance performance (Mauger, 2013). In recent investigations, the tolerance of exercise-induced pain explained a significantly larger variance in cycling task termination, than pain threshold and tolerance did through algometry and cold pressure tests (Astokorki & Mauger, 2016). These traditional pain measures explain some of the variance in endurance performance (compared to the tolerance of exertive pain). This also suggests that the importance of high pain tolerance to endurance performance may have been previously underestimated. The latter is also important because the traditional measures of pain tolerance and threshold (such as algometry and the cold pressure test) are often used to inform about the tolerance of the pain arising from an intense exercise. In turn, avoiding the use of thermal, pressure, and electrical stimuli induced pain in the assessment of exertive pain phenomenon remains a key recommendation for future research (Astokorki & Mauger, 2016).

1.3.PAIN MODULATION

"If you are distressed by anything external, the pain is not due to the thing itself, but to your estimate of it; and this you have the power to revoke at any moment."

— Marcus Aurelius —

Modulation of perception in pain experience. To underpin variations in pain perception it is important to understand the modulation of pain. Recent work in cognitive science and neuroscience is leading us to a better understanding of modulation of the pain perception. However, the study of pain within physical exercise is a daunting task owing to the difficulty of dissenting out the pain modulation from the pain perception. It is generally agreed upon that the experience of pain occurs at the convergence of biological, psychological and sociological, as well as sensory, cognitive, emotional, and social components (Williams & Craig, 2016). Hence, there is a need to take a closer look at brain to help us understand how these modulators contribute to the experience of pain.

Pain modulatory system. The descending pain modulatory system exerts influences on nociceptive input from the spinal cord. This network of cortical, subcortical, and brainstem structures includes prefrontal cortex, anterior cingulate cortex, insula, amygdala, hypothalamus, periaqueductal grey, rostral ventromedial medulla, and dorsolateral pons (Tracey & Mantyh, 2007). The coordinated activity of brain network modulates nociceptive signals via descending projections to the spinal dorsal horn. By virtue of these descending connections, the central nervous system can selectively control signal transmission from specific parts of the body (Garland, 2013). The network is dynamic and it treats cortical function as arising from the coordination dynamics within and between cortical regions (Bressler & Kelso, 2016). This is also why pain is highly subjective and at the same time subject to influences and interactions of ongoing synchronous neural activity and organized patterns of spontaneous brain networks. By means of metastable coordination dynamics, relative coordination gives cognition the capacity for rapid and fluid change, without the coordinated network ever needing to relax into a stable state (Bressler & Kelso, 2016).

Sensory modulation. The nervous system is highly adaptable and accommodates most demands. When impulses from inflamed, scarred, weak or acidic tissues arrive at the synapse in the dorsal horn, or when neurons from the brain release excitatory chemicals, the neuron in the spinal cord adapts to meet the demand. In the short term, the neuron can increase sensitivity to the incoming excitatory chemicals (Butler & Moseley, 2013). The sensitivity to the incoming excitatory chemicals can be modulated by *age* and *gender*. Gender differences in experimental pain sensitivity have been widely investigated in experimental pressure pain threshold (Chesterton, Barlas, Foster, Baxter, & Wright, 2003; Naugle et al., 2013), as well as thermal pain threshold (Fillingim, Maixner, Kincaid, & Silva, 1998; Naugle et al., 2013). Results indicate that females exhibit greater sensitivity to noxious stimuli than males. However, in the case of naturally occurring pain, the threshold showed a high variability (Cook et al., 1998). Pain threshold for females occurred at an absolute power output that ranged from 25 to 232 watts from 66 to 322 watts for males (Cook et al., 1998). These results confirmed higher sensitivity to pain in females within exercise settings. The pain sensitivity was shown to be dependent on age and ranged from increased to decreased sensitivity to no change (Schludermann & Zubek, 1962; Yezierski, 2012). Pain sensitivity have also been suggested to result from age-related anatomical, physiological, and biochemical changes as well as compensatory changes in homeostatic mechanisms and intrinsic plasticity of somatosensory pathways involved in the processing and perception of pain. Thus, other factors that may contribute to the impact of age on pain sensitivity include dysregulation of the hypothalamic-pituitary-adrenal axis and changes in autonomic function that occur with advancing age (Yezierski, 2012).

Cognitive modulation. Attention, expectation, and beliefs also contribute to the cognitive modulation of pain. Historical theories of pain are based primarily on nociceptive processes and do not or not sufficiently account for the interactions and dynamics between cognitive-attentional processes (Moayedi & Davis, 2012). In the last few decades, interest in the nature of painful experience has drawn extensively on the cognitive science methodologies (Sullivan, 2008), especially with the realms of attentional modulation (Eccleston & Crombez, 1999).

Attention. Pain attracts attention and it can rarely be ignored. In functional coupling between key brains regions during pain processing attentional resources allocated toward pain increase. Attentional modulation through descending modulatory system is extensively examined (Wiech et al., 2008). Furthermore, attention modulates perception and cognition by allocating processing resources to relevant external and internal events. This unique attention-demanding quality orients humans away from other environmental stimuli, ongoing thoughts and emotions. Attention and pain also mutually influence one another (Brooks, Nurmikko, Bimson, Singh, & Roberts, 2002; Dunckley et al., 2007; Seminowicz & Davis, 2007) even though, attention is believed to support defensive behavior by prioritizing threat-relevant information (Legrain et al., 2009). On the other hand, pain responses are influenced by spontaneous trial-by trial fluctuations in pre-stimulus activity. Neural communication across the whole brain-wide network 'connectome' -including pain-attention related circuits- is intrinsically dynamic and spontaneously fluctuates on multiple time-scales (Deco, Jirsa, & McIntosh, 2013; Kucyi & Davis, 2015). The high prevalence of such fluctuations, their intrinsic nature, and their importance to subjective experience, such as pain, are exemplified by evidence from studies of spontaneous brain dynamics, the impact of pre-existing brain state on subsequent perception. Previously, it was thought that these fluctuations could be linked to attentional shifts that subjects are aware of or intrinsic dynamics of neural activity that are below the level of consciousness (Viane, Crombez, Eccleston, Devulder, & De Corte, 2004). But later on, it was shown that the individual's attentional state may wax and wane spontaneously, even in the presence of unchanging nociceptive input and regardless of on-going task demands (Peters & Crombez, 2007). Attentional fluctuations away from non-painful modalities and their neural mechanisms can be described as "*perception decoupling*" or "*disengagement of attention*" from perception. Spontaneous attentional fluctuations towards and away from pain and the individual differences in regards to this behavior are represented in brain network structure and dynamics. The link among spontaneous fluctuations, brain networks dynamics and the neural processing of pain may be essential in the perception of pain. Furthermore, focusing attention to specific location increases the chance that changes are detected and perceived (Van Hulle, Van Damme, Spence, Crombez, & Gallace, 2013). One might, for example, expect that in a situation in which a person is performing a potential pain-inducing movement, the subject scans his/her body and perceives the occurring changes.

Reappraisal. Pain has a warning character and is therefore commonly perceived as threatening. The degree of threat was shown to depend upon the belief of the subjects in their own coping resources (Lazarus & Folkman, 1984) and perceived control over pain (Salomons, Johnstone, Backonja, & Davidson, 2004). If coping resources are sufficient, pain can be perceived as controllable. To that end, people who perceive a high degree of control try to initiate action and persist more successfully in the face of failure. For instance, positive thoughts, beliefs and even dispositional optimism affect pain processing to provide further means by which these effects are amplified, reduced, habituated or sustained over time (Petrovic, Petersson, Ghatan, Stone-Elander, & Ingvar, 2000).

Expectations. Negative and positive expectations are powerful modulating factors that influence pain perception (Tracey, 2010). Expectations enable an organism to prepare for the upcoming sensory input, so it is vital to study expected and perceived features of pain. Ploghaus et al. (2003) were the first to identify brain activation consistent with the violation of expectations. The aim of this approach was to provide insights into 'how' the brain learns about pain over time by considering the history of successful (i.e., confirmed) and unsuccessful (i.e., violated) learning trials. Furthermore, expectations from multiple sources were shown to influence pain physiology independent of reinforcement (Koban & Wager, 2016). Finally, it is worth to understand that our brain prioritizes somatosensory input at body locations where pain is expected (Van Hulle et al., 2013). Surprisingly, mediated factors that fall into the cognitive domain may also account for significant portions of inter-individual differences in the subjective experience of pain. For example, expectations about a stimulus and previous experience have a marked influence on the subjective experience of pain. Thus, it presented some of the reasoning behind the phenomenon of placebo, nocebo and reappraisal effects work in humans in pain perception (Tracey, 2010).

Emotional modulations. It is generally agreed upon that emotional states modulate the experience of pain. For instance, fear was shown to be one of the most important emotion in the modulation of pain and is connected with pain catastrophizing (Moseley & Butler, 2015). Moderate levels of fear seem to increase attention to salient events such as pain, thereby augmenting its perceived intensity (Meagher, Arnau, & Rhudy, 2001). Moreover, high levels of fear may become more salient than pain. Salience is defined by the extension to which a stimulus contrasts in one or more perceptual features with surrounding competing stimuli (Yantis, 2008). Also salient are novel stimuli, consisting of events that were never presented before (i.e., new stimuli) or infrequently occurring events (i.e., deviant stimuli).

Social modulation. To date, the modulation of pain by social factors has received far less experimental and neuroscientific attention. There is evidence pointing to associations between pain and the social context in which it occurs. For instance, positive verbal and non-verbal interactions or positive interpersonally relevant primed interactions are known to reduce pain, while negative, mixed valence, or ambiguous interactions increase it (Krahé, Springer, Weinman, & Fotopoulou, 2013). Additionally, experience of pain depends on one's cultural background (Atkins, Uskul, & Cooper, 2016), upbringing (Van Dijk, Vervoort, Van Wijck, Kalkman, & Schuurmans, 2016) and personal values (Branstetter-Rost, Cushing, & Douleh, 2009). Intuitively however it is thought that humans share similarly functioning nervous systems and relatively similar pain reactions hence have a high like hood to feel comparably vis-a-vis of pain.

1.4.INTERRELATION BETWEEN THE RESEARCH ARTICLES

The illiterate of the 21^{st} century will not be those who cannot read & write, but those who cannot learn, unlearn, and relearn.

(Alvin Toffler, American writer and futurist)

1.4.1. Psychobiological Model

Nonlinear psychobiological model of exercise-induced fatigue. Within the present thesis exertive pain has been studied under the framework of the Nonlinear psychobiological model of exercise-induced fatigue (Balagué, Hristovski et al. 2014). In contrast to other models like the Central governor model (Noakes, St Clair Gibson, & Lambert, 2005) and the Psychobiological model of endurance (Marcora & Staiano, 2010), the Nonlinear psychobiological model assigns a different role to the conscious intention to the task disengagement or exhaustion point. While Marcora's model states that the performer has the conscious intention to disengage from the task and the Central governor model sustains this notion while stating that the moment at which exercise terminates is determined by central nervous system (CNS), the Nonlinear psychobiological model points towards the spontaneous disengagement from the task as a consequence of the destabilized intention to continue. The spontaneous nature of the task disengagement has been corroborated by experimental evidence to confirm two generic predictions of NDST models, the so called critical phenomena (Kelso, 1997): a) the enhancement of fluctuations as the system approaches the critical point (Hristovski & Balagué, 2010) and, b) the critical slowing down, as measured by increased correlation in the kinematic time series (Scheffer et al., 2009; Vázquez, Hristovski, & Balagué, 2016) as well as the metastability or flickering behavior (Balagué, Aragonés, Hristovski, García, & Tenenbaum, 2014; Balagué, Hristovski, Aragonés, & Tenenbaum, 2012; Garcia, Balagué, Razon, Hristovski, & Tenenbaum, 2015; Scheffer et al., 2009). No extant model is able neither to predict these effects nor offer an ad hoc explanation for this type of behavior.

Nonlinear dynamic integration of brain, periphery and environment. Psychobiological behavior during endurance exercise could be conceptualized as the result of a self-organized process that emerges from the interaction between three main components: *brain*, *periphery* and *environment* (Balagué, Hristovski, Vázquez, & Slapsinskaite, 2014; Hristovski & Balagué, 2010). Under fatiguing exertion the coupling among aforementioned components of the movement system is likely to be nonlinear. In previous studies the nonlinearity has revealed itself in the evolution of different variables that transited between stable and unstable states. It is important to consider that for a system where a first order phase transition occurs the two phases (stability, instability) can coexist. While one phase (phase 1) can be a stable state the second phase (phase 2) can be metastable or they can swap places, i.e., the first phase can be metastable while the second phase is stable. Thus, it is conceived that effort accumulation and fatigue lead to phase transitions. Within this context, metastability offers the capacity of the spontaneous switching. Therefore, the metastable state can exist for a very long time, but finally the system tends to relax into the stable state.

The critical phenomena have been previously tested while using different kinematic (Hristovski & Balagué, 2010; Vázquez et al., 2016) and psychological variables such as thoughts (Balagué, Hristovski, Garcia, et al., 2015; Balagué et al., 2012; Garcia et al., 2015) or perceived exertion (Aragonés et al., 2013, Balagué et al., 2015) during constant and incremental exercises performed until exhaustion. Two of these variables i.e., perception and attention focus are closely related with pain sensation. Firstly, perceived exertion dynamics in all subjects showed a clear fluctuating dynamics during the moderate and heavy intensity exercises that changed towards a non-fluctuating dynamics when approaching the volitional exhaustion point (Aragonés et al., 2013). It was emphasized that the fluctuation dynamics of perceived exertion helped to recognize the stability or instability of the performed task and was useful to detect the critical volumes of exercise or effort phases. Secondly, attention focus dynamics revealed that the intentionally imposed task unrelated thought (TUT) was stable at the beginning of the test, switched spontaneously to task related thought (TRT) with accumulated effort, competing with TUT and showing metastability, until a final stable TRT state. This observed phenomena pointed towards a nonlinear dynamic self-regulation of attention focus during accumulated effort (Balagué, Hristovski, Garcia, et al., 2015; Balagué et al., 2012; Garcia et al., 2015). In what follows, we summarize that critical phenomena arise when a system is close to its so-called critical points or so called the points of phase transition and could be observed through different psychological or kinematic variables.

Drawing from the very concept of self-organization all cited work within this thesis place a special emphasis upon mind-body and performer-environment interactions. Particularly, the mediating effects of the interaction between the performer and the environment are expounded within the research article IV (see Chapter 5). These integrative and dynamical characteristic may indeed shed further light on the question why other accounts based on separate local sites, failed to elucidate physiological limitations in the occurrence of fatigue and task disengagement within endurance settings (Balagué, Hristovski, et al., 2014).

1.4.2. Common Aspects of Research Articles

The interrelation among the four research articles of this thesis may be better understood on the basis of *four* shared common aspects derived from the NDST approach summarized in Table 1.

1. *Dynamic integration* (i.e., coupling, decoupling) among brain-periphery-environment components are key features to understand short-term integration between continuously interplaying components or to understand long-term coordinated behavior of the system. For instance, in order to illustrate how environmental cues lead towards different kind of interaction laboratory settings could be presented. Laboratory per se limits the access to external information, priming internal information and constraining the interaction among components, especially in comparison to the field. The changed type of interaction is somehow one of the reasons why ecological validity of systems behavior is biased under laboratory conditions. Both environmental cues and accumulated effort can modify the interactions (i.e., strengthening or weakening) among systems' components and in

return may influence coordinated behavior during endurance of exercise. This type of mediating effect of body-periphery-environment components interactions are essential to detect while prescribing endurance activities or studying behavior of the system.

2. *Collective variables* also referred as "order parameters" or "coordinative variables" capture best the dynamic products of these interactions (Bressler & Kelso, 2001). The collective variables also help to recognize the formation of and govern complex systems dynamics and allow to delineate the *qualitative* changes within the system (Haken, 1983). Specifically, taken together, collective variables can capture the linear, proportional or monostable solution and nonlinear, non-proportional regime of the coordinated behavior of the system's component processes. In these four research articles we used two different psychobiological collective variables (i.e., pain locations and thoughts). In addition, research articles depict *macroscopic* effects of collective variables. Since the macroscopic effects are the result of the interaction between the actions of a vast number of component processes, collective variables capture the dynamic products of undergoing interactions on microscopic and mesoscopic levels. To that end, the proposed integration perspective previously helped the scientists to bridge this gap while using different types of psychobiological collective variables such as the volition states, thought processes and perceived exertion during exercise (Aragonés et al., 2013; Balagué, Aragonés, et al., 2014; Balagué et al., 2012; Hristovski & Balagué, 2010).
3. *Control parameters.* In order to study the dynamic of different collective variables (i.e., thoughts and pain locations) three research articles of this thesis manipulated normalized (dimensionless) time on task (TT) or time to exhaustion as the main *control parameter* and one research article manipulated workload. It is important to consider that c*ontrol parameters* generate the changes of state (i.e., stability and instability) within the system. For instance, if control parameters change and attain some critical value, the system is forced to leave the initial state and spontaneously form a new state. When the collective variable becomes unstable, the system starts seeking new task solutions (underpinned by interactions, new couplings between subsystems on microscopic and mesoscopic

levels), ones that involve discovering new psychobiological synergies and reconfiguring the available degrees of freedom during endurance performance (Balagué, Hristovski, et al., 2014).

4. Finally, *metastability* is a key element that connects all research articles within this thesis. The idea of metastability, i.e., the existence and evolution of systems through transient and semi-transient states is an old one dating, at least, from the beginning and mid 20-th century (Eyring, 1935; Nicolis & Prigogine, 1977). Underpinned by these basic notions, the idea of the spatiotemporal organization of brain dynamic activity through transient, metastable states emerged more than 20 years ago (Kelso, 1995), but it has been only recently experimentally researched and detected as such at phenomenological level (Aragonés et al., 2013; Balagué, Hristovski, García, et al., 2015; Balagué et al., 2012). Metastable behavior typically arises when there are many weakly stable or weakly unstable system's states that switch spontaneously among various cooperative configurations within their degrees of freedom. We invoke the notion of metastability to refer to a dynamical state emerging from body-mind-environmental network possessing the properties as defined in Bovier and den Hollander (2016): at short time-scales, the system appears to be in equilibrium, but in fact, explores only a limited part of its available states (e.g., one type of attention focus or attention-pain pattern). At longer timescales, however, it undergoes transitions between numbers of metastable states (different attention-pain states). At the level of brain metastable transient dynamics represent a balance between the segregation of focused cognitive processing and the flexible integration of distributed brain areas (Bressler & Kelso, 2001; Rabinovich, Varona, Tristan, & Afraimovich, 2014). On the phenomenological level, irreducible to neural processes, however, metastability is defined as a flexible integration and segregation among attentional and perceptual degrees of freedom, i.e., the degrees of freedom that form the *experiential states* of performers. Therefore, the perception process requires a short-term *integration* between continuously interplaying components including the environment, the periphery and the brain itself (Rabinovich, Tristan, & Varona, 2015), and requires a *segregation* that is becoming autonomous of some brain regions or degrees of freedom, before they integrate differently. Investigation of this

very shifting provides a platform for understanding coupling and decoupling dynamics of complex goal-directed systems.

1.4.3. Rationale of the Research Process

The interest for conducting the study of pain in the framework of the Nonlinear psychobiological model of exercise-induced fatigue was based on three main aspects:

a) Pain as a subjective experience offers unique possibilities to explore how fatigue spreads on body locations and helps study the dynamics and individual patterns inherent in this sensation.
b) There is a close interrelation between pain and attention and of both with endurance and task disengagement.
c) Furthermore, the location dynamics of pain has not been studied before. Hence, the contribution towards better understanding of attention driven pain mechanisms as well as the development of effective strategies for its management.

This thesis started exploring the pain location dynamics during constant exercise in research article I- Local Pain Dynamics during Constant Exhaustive Exercise. Drawing upon the detection of individual pain dynamic patterns in this article, research article II- Idiosyncratic Pain Patterns during Exhaustive Exercise was elaborated. Next, given the recognition of a nested-type of integration of the attention-pain dynamics in the previous research, in article III- Metastable Pain-Attention Dynamics during Incremental Exercise- emerged. Finally, the need to investigate the effects of the environment on the dynamics of attention and endurance gave rise to research article IV- Cycling Outdoors Facilitates External Thoughts and Endurance.

Objectives of the thesis:

1. To delineate the pain and discomfort location dynamics during constant cycling and running performed until exhaustion.
2. To detect pain patterns during constant exercise performed until exhaustion.
3. To examine the potential presence of nested metastable pain-attention dynamics during incremental cycling performed until exhaustion.
4. To compare the effects of indoor and outdoor environments on attention focus and cycling endurance.

Hypotheses of the thesis:

1. The number of body locations with discomfort and pain will increase while performing constant cycling and running tasks.
2. Instead of generalized patterns, idiosyncratic pain patterns will emerge during constant cycling and running tasks.
3. Pain-attention patterns during incremental cycling will display hierarchical or nested metastable dynamics.
4. The environment type will constraint the attention focus dynamics during constant cycling exercise.
5. Task disengagement will be delayed in the outdoor environment compared to the indoor environment.

Table 1. General common aspects of the four studies presented in this thesis.

Article	Experiment	Aim of the Experiment	Exercise	Collective Variable	Control Parameter	Metastable switching dynamics
1	Dynamics of pain topological distribution	To delineate the topological dynamics of pain and discomfort	Constant power cycling and running exercise	Number and configuration of pain body locations	Time/exhaustion time	(pain/no pain)
2	Patterns of pain topological dynamics	To detect pain patterns	Constant power cycling and running exercise	Principal components of pain body locations	Time/exhaustion time	(pain/no pain)
3	Pain-attention dynamics	To examine the potential presence of nested metastable pain-attention dynamics	Incremental cycling	Principal components of pain body locations	Workload	(pain/no pain)
4	Environmental influence on attention focus dynamics	To compare the effects of indoor and outdoor environments	Constant power cycling exercise (indoor and outdoor)	Attention focus (task-related/task-unrelated thoughts)	Time/exhaustion time	(task-related/task-unrelated thoughts)

CHAPTER TWO

RESEARCH ARTICLE I

PLOS | ONE

RESEARCH ARTICLE

Local Pain Dynamics during Constant Exhaustive Exercise

Agne Slapsinskaite[1☯*], Selen Razon[2☯], Natàlia Balagué Serre[1☯], Robert Hristovski[3‡], Gershon Tenenbaum[4‡]

1 Department of Health and Applied Science, INEFC University of Barcelona, Barcelona, Spain, **2** Department of Physical Education, Ball State University, Muncie, Indiana, United States of America, **3** Department of Physical Education, Sport and Health, Ss. Cyril and Methodius University, Skopje, Macedonia, **4** Department of Educational Psychology and Learning Systems, Florida State University, Tallahassee, Florida, United States of America

☯ These authors contributed equally to this work.
‡ These authors also contributed equally to this work.
* agneslapsinskaite@gmail.com

Abstract

The purpose of this study was to delineate the topological dynamics of pain and discomfort during constant exercise performed until volitional exhaustion. Eleven physical education students were tested while cycling and running at a "hard" intensity level (e.g., corresponding to Borg's RPE (6–20) = 15). During the tests, participants reported their discomfort and pain on a body map every 15s. "Time on task" for each participant was divided into five equal non-overlapping temporal windows within which their ratings were considered for analysis. The analyses revealed that the number of body locations with perceived pain and discomfort increased throughout the five temporal windows until reaching the mean (± SE) values of 4.2 ± 0.7 and 4.1 ± 0.6 in cycling and running, respectively. The dominant locations included the quadriceps and hamstrings during cycling and quadriceps and chest during running. In conclusion, pain seemed to spread throughout the body during constant cycling and running performed up to volitional exhaustion with differences between cycling and running in the upper body but not in the lower body dynamics.

Introduction

People experience local discomfort and exertive pain during intense endurance exercise [1,2]. Previous studies have focused on the impact of exertive pain on effort perception, and time to volitional exhaustion [3,4], and investigated the dynamics of its intensity over extended bouts of exercise [5,6]. Nevertheless, no studies have explored the evolution of exertive pain and its spatiotemporal topology dynamics during exercise.

Exertive pain is defined as a subjective state or feeling associated with tiredness, soreness and numbness [7]. Exertive pain is different from perceived exertion in that the latter is the subjective feeling of heaviness and strain, which stems from physical effort [8]. Athletes competing in aerobic activities refer to "discomfort" in relation to symptoms emanating from legs, respiratory system, proprioceptive system, head, and abdomen [9]. Others have also referred to discomfort in exercising peripheral skeletal muscles as a common limit to different strenuous

Citation: Slapsinskaite A, Razon S, Balagué Serre N, Hristovski R, Tenenbaum G (2015) Local Pain Dynamics during Constant Exhaustive Exercise. PLoS ONE 10(9): e0137895. doi:10.1371/journal.pone.0137895

Editor: Hemachandra Reddy, Texas Tech University Health Science Centers, UNITED STATES

Received: June 5, 2015

Accepted: August 24, 2015

Published: September 30, 2015

Data Availability Statement: All files are available from the datadryad database (doi: http://dx.doi.org/10.5061/dryad.f37d0).

Funding: This study was supported by the Institut Nacional d'Educació Física de Catalunya (INEFC), the Generalitat de Catalunya and Secretaria General de l'Esport i Departament d'Innovació Universitats i Empresa. Agnė Slapšinskaitė is the recipient of a predoctoral fellowship from the Agency for the Management of University and Research Grants (AGAUR). We would like to thank TECNO SPORT for the technical support. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

tasks [10,11] or as a limiting factor to exercise in forms of breathlessness and leg fatigue [3]. The latter is consistent with the notion that there are differentiated rating of perceived exertion (RPE) for legs (RPE-Legs) and chest (RPE-Chest) [12]. Specifically, during a cycling ramp type protocol, RPE-Legs and RPE-Chest have shown to contribute equally to the RPE-Overall, and thus to the whole-body sensory integration process [13].

The perception of discomfort and pain vary inter-individually [14,15]. However, gender differences across all pain modalities have not been supported during exercise [16]. Interestingly, individuals with similar patterns of activation of the primary somatosensory cortex (SI), anterior cingulate cortex (ACC), and prefrontal cortex (PFC) provide similar subjective reports of pain magnitude [17]. This implies that an individual's conscious experience of pain can be accurately captured via introspection [17]. The correlations between brain imaging and pain ratings also provide some external validation of self-report for pain monitoring [18].

A number of introspective methods are used to measure perceived exertion (e.g., RPE (6–20) Borg scale), pain intensity (e.g., numerical pain rating scales) and pain location (e.g., pain drawings, body maps, or manikins) [19]. Of these, pain drawings have been used to measure widespread pain in static conditions of self-report in long-term intervals (e.g., 6 weeks, 6 months, or 1 year) [19,20]. Nevertheless, the evaluation of dynamical changes at short-term intervals is yet to be considered. To date, only the intensity of exertive pain, but not its spatiotemporal topology and spreading patterns, has been studied. Consequently, there is a lack of knowledge about the dynamics of pain and discomfort during constant exercise performed until volitional exhaustion. Additionally, exercise protocols up to date have been either incremental [5] or self-paced [21], but not constant. Consequently, a constant exercise protocol with continuous and steady effort output requirements may be particularly beneficial for investigating the dynamics of pain spread across the body.

The nonlinear dynamical systems theory (NDST) along with the self-monitoring and self-reporting procedures were used for studying the dynamics of perceived exertion and attention allocation during constant running and cycling tasks performed until volitional exhaustion [22–24]. Findings from these studies revealed a non-proportional effect of effort accumulation on thought dynamics and perceived exertion shifts (PES). Moreover, previous accounts of exertive pain and discomfort have neither considered nominal changes in locations of topologically defined body locations nor have they entirely detailed their effect on volitional exhaustion [25]. The purpose of the present study was to delineate the spatiotemporal topology dynamics of pain and discomfort during constant exercise performed until volitional exhaustion. Specifically, we hypothesized that the number of body locations with discomfort and pain would increase while performing running and cycling tasks as a function of "time on task" and that the lower and upper body dynamics would depend on the type of exercise task.

Method

Participants

To determine the sample size for this study a power analysis was conducted using G*Power 3.1 [26]. In similar studies of thought processes larger effect sizes have been reported [23]. Thus, using an effect size of $d = 1.0$, $\alpha < 0.05$, power $(1—\beta) = 0.80$, a sample size of $N = 10$ emerged. Accordingly, eleven European descent physical education students (7 males and 4 females, M = 20.83 years old, SE = ± 1.33, and BMI = 22.94, SE = ± 2.03) were recruited for this study. Participants had no sport specialization but were engaged in a wide range of aerobic activities at least three times a week. Inclusion criterion for the study was the absence of chronic pain and injuries.

Intervention and Procedure

One week prior to the experiment, participants completed a baseline incremental cycling and running test to determine the workload and velocity corresponding to their individual RPE (6–20 Borg's scale) = 15 (i.e., hard) [8]. During this visit, participants were also familiarized with the use of body map and the reporting procedures (see familiarization). In the second and third weeks, participants performed the experimental constant-power cycling and constant velocity running tasks, respectively, in a counter-balanced order. Participants signed an informed consent prior to taking part in the study. All experimental procedures were approved by the local ethics committee of Catalan Sport Council of Catalonia (Consell Català de l'Esport de la Generalitat de Catalunya, Comitè d'ètica registration number 072015CEICEGC) and were carried out according to the Helsinki Declaration.

Discomfort and pain monitoring. Throughout the exercise protocol, every 15s, upon the researcher's prompt, participants reported body locations with discomfort and pain, using a body map (see Fig 1) [27]. The rational for selecting this reporting strategy was to provide ample data points and limiting the potentially deleterious effects of reporting somatic sensations while constantly keeping an internal focus of attention [28]. For the purposes of this assessment, the instructions given to the participants were as follows:

> *"When prompted, we ask you to report the locations of discomfort and pain (if you feel it, independently of its magnitude) using the numbers on the body map placed in front of you."*

Familiarization procedures and baseline tests. All the participants have been previously familiarized with the RPE (6–20) Borg scale and have used it during incremental exercises at least two times during the last two months. The RPE (6–20) Borg scale and its original rating

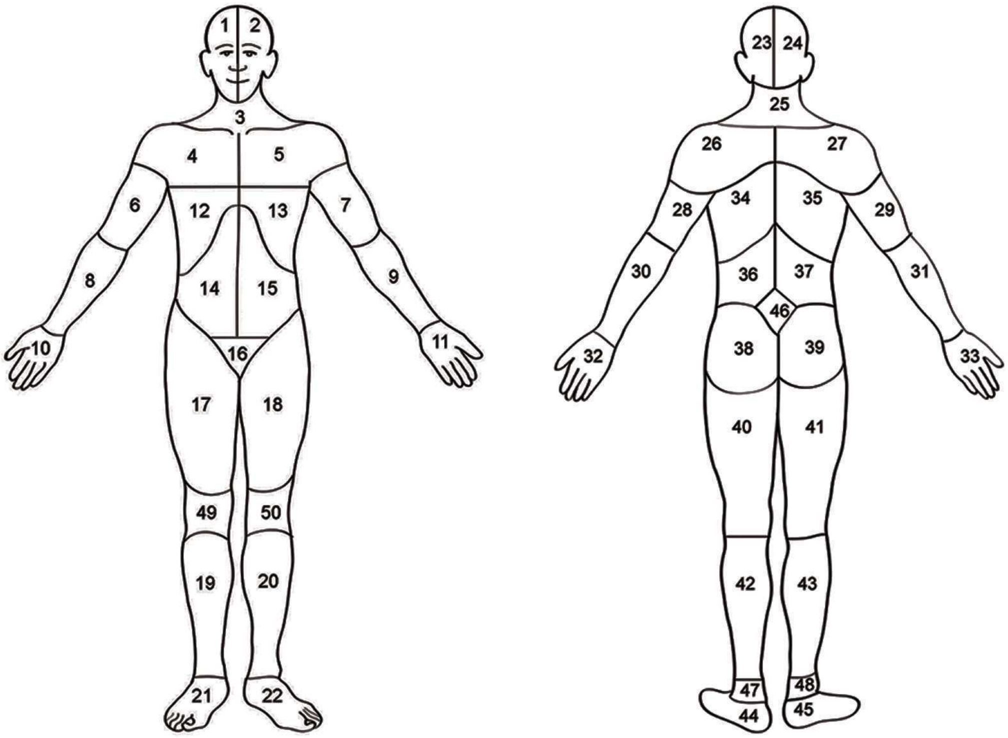


Fig 1. Body map. Head (area 1, 2, 23, or 24); neck (area 3 or 25), shoulders (area 4, 5, 26, 27); arms (area 6, 7, 8, 9, 28, 29, 30 or 31); hand (area 10, 11, 32, 33); ribs or chest (area 12 or 13); abdomen (area 14 or 15), back (area 34, 35, 36, 37), buttocks or hips (area 38 or 39); genitalia (area 16), legs (area 17, 18, 19, 20, 40, 41, 42 or 43); feet (area 21, 22, 44 or 45). Adapted from Margolis, Tait, & Krause (1986).

doi:10.1371/journal.pone.0137895.g001

instructions [8], as well as the body map were handed out and verbally explained to participants prior to the baseline test and experimental procedures.

The baseline incremental cycling test and the constant-power cycling task were performed on a cycle ergometer (Sport Excalibur 925900) with saddle and handlebar specifications adjusted to fit the preference of each participant. The cycling test started with a 2min rest following an initial load of 20W (for females) and 25W (for males). The load was increased by 20W/min (for females) and 25W/min (for males) until participants reported RPE = 15 keeping the required cadence (70rpm). At this intensity (RPE = 15) participants kept pedalling for 2min while reporting their discomfort and pain (see above). During the last 10s of every imposed workload increment, participants were asked to self-monitor and report verbally their RPE on the RPE (6–20) Borg scale with the corresponding anchors placed in front of them at eye level. The workload values corresponding to RPE = 15 were recorded for each participant. If an identical RPE value was reported over two consecutive increments the highest workload value was registered. When the clamped value of RPE = 15 was not reported the value corresponding to the same Borg's RPE (6–20 anchor RPE = 14) was recorded.

The baseline incremental running test (HP Cosmos treadmill) consisted of an initial velocity of 5km/h followed by increases of 1km/h per minute (for males) and 0.5km/h per minute (for females) until they reached a velocity corresponding to RPE = 15. At this intensity participants kept running for 2min while reporting locations with pain and discomfort (see above). Identical self-monitoring and RPE reporting and recording procedures were followed as the cycling protocol.

Constant-power cycling task. The task included two consecutive parts. An initial incremental warm-up (same procedure as in the corresponding baseline test) and a constant-power cycling task were performed up to volitional exhaustion. The constant-power cycling began when participants reached RPE = 15 during the incremental warm-up and lasted up to volitional exhaustion when participants could no longer maintain the fixed pedalling cadence for 5 consecutive seconds while in the sitting position. The RPE (6–20) Borg scale was placed in front of the participants at eye level during the warm up phase and was replaced by the body map during the constant protocol phase. Only the data from participants reporting RPE = 15 at the same target workload obtained during the baseline incremental cycling test were included in the analysis.

Constant velocity running task. The task included two consecutive parts: an incremental warm-up (same procedure as in the corresponding baseline test) and a constant velocity run performed up to volitional exhaustion. The constant velocity run began when participants reached RPE = 15 during the incremental warm-up and lasted up to volitional exhaustion when they could no longer maintain the imposed velocity. The RPE (6–20) Borg scale was placed in front of the participants at eye level during the warming up and was replaced by the body map during the constant protocol. Only the data from participants reporting RPE = 15 at the target velocity obtained during the baseline incremental running test were included in the analysis.

Once the test began, participants performed the cycling/running tasks without any additional communication except for the researcher's prompts for reporting locations. All trials were video recorded to cross validate the accuracy of the collected data. Upon task completion, using a 11 point Likert-type scale with anchors ranging from 0 (*not at all*) to 10 (*greatly*), participants answered two questions to report their adherence to: (a) the cycling/running task (i.e., "*Have you pedalled/ran as long as you can, achieving your exhaustion point*?"), and (b) the self-monitoring and reporting procedure (i.e., "*Have you reported all the changes in your discomfort and pain locations when required*?").

Data Analysis

The reported number of locations with pain and discomfort while performing the tasks were plotted for each participant and the locations were anatomically grouped for lower and upper body areas. Each time series was divided into five non-overlapping temporal windows (time to volitional exhaustion of the participant/5). Mean value of the number of locations with discomfort and pain in total was computed for each time window. The probability of each pain location (according to the body map) was computed for each temporal window. A Friedman ANOVA was used to analyse the number of locations variance over time. Effect sizes (Cohen's d) were calculated to determine means' differences at $p < 0.05$. Mann Whitney U matched pairs test was used to contrast the pain dynamics in lower and upper body during both tasks.

Results

Time to exhaustion during constant cycling at 195 ± 14.3W was 915 ± 62s and constant running at 15.36 ± 0.7km/h was 738 ± 52s. The number of locations with pain and discomfort increased throughout the five temporal windows until reaching the values of 4.2 ± 0.7 for cycling and 4.1 ± 0.6 for running. The Friedman ANOVA revealed a significant effect of time for the total number of locations with discomfort and pain χ^2 (11,4) = 14.08, p = 0.007 in cycling, and χ^2 (11,4) = 26.15 $p < 0.001$ in running. Cohen's d coefficients between the time windows were as follows: 1st and 3th (-2.95 and -2.19), 1st and 5th (-4.13 and -2.2).

Fig 2 illustrates the frequencies of body locations with pain over time; the darker regions show higher frequencies. The dominant locations of pain and discomfort during both tasks were the quadriceps muscle. At the termination of the exercise task, the dominant locations included the quadriceps and hamstrings in cycling and the quadriceps and chest in running.

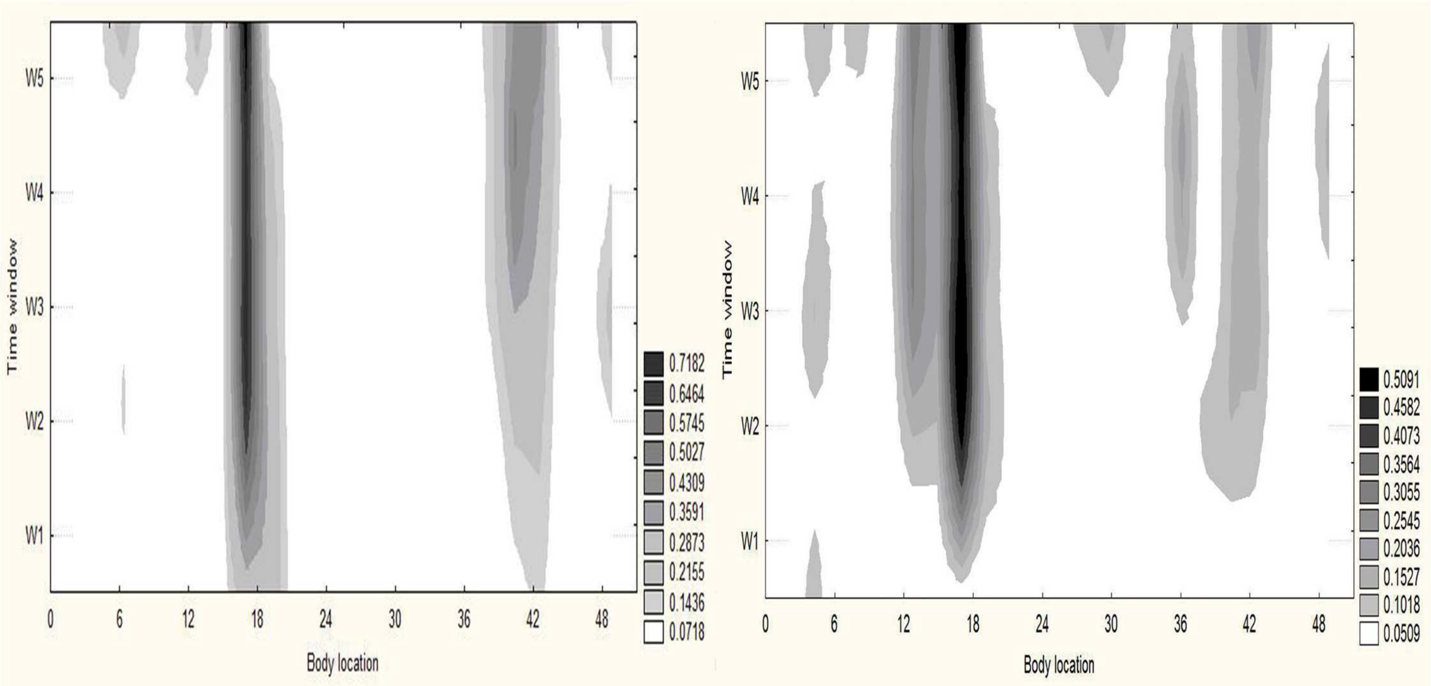


Fig 2. Locations with pain and/or discomfort. The group pulled probabilities of locations with pain or discomfort during cycling (left) and running (right) tasks in 5 temporal windows in a given sample (n = 11). As time on task increases (vertical axis) the number of locations and the probability of experiencing pain and discomfort at selective locations also increase (darker shades of grey) on average. Legend: the probability of experiencing discomfort and pain.

doi:10.1371/journal.pone.0137895.g002

The Mann Whitney U test indicated a significant difference only for the upper body locations between the cycling and running tasks in the 2nd (U(20) = 20, p = 0.003), 3rd (U(20) = 25, p = 0.016) and 4th (U(20) = 28.5, p = 0.026) temporal windows.

Discussion

The main finding of this study revealed that the number of body locations where discomfort and pain are reported during constant cycling and running tasks until volitional exhaustion increased over time. While the lower-body locations increased significantly during both cycling and running, upper-body locations increased significantly only during running.

These findings are consistent with previous research related to the discomfort and exertive pain intensity during incremental and self-paced exhaustive exercise. A linear co-variation between the muscle pain intensity and power output in cycling has been found with lowest pain ratings at the lowest exercise intensity and highest pain ratings at the highest exercise intensity [5]. Increasing ratings have been also indicated in self-paced cycling [21]. Importantly, the present findings also suggest that not only the pain intensity [29] but also the number of pain locations and their frequencies raised while approaching volitional exhaustion. It is evident that the pain threshold (i.e., the point at which an individual perceives a stimulus to be painful), and the pain tolerance (i.e., the point at which an individual is not willing to endure further noxious stimuli) change with the time on task and effort accumulation [30]. However, further research is needed to define the relationship between exercise workload and topology of exertive pain, and extend our findings by exploring the spread patterns of the pain locations. As local pain is task-dependent it will be particularly interesting to test the pain dynamics in incremental or graded exercise protocols. In this study a constant-power instead of incremental-power exercise was chosen a) to prevent from faster task disengagement, especially in less fit participants; b) to avoid changes of the afferent sensory information due to power intensity changes.

Previous studies examining the dynamics of attention focus and effort perception during constant cycling and running until volitional exhaustion have also revealed an effect of time on task (i.e., effort accumulation) on attention allocation and perceived exertion [22–24]. Results from these studies suggested qualitative changes from dissociative to dominantly associative focus of attention, and from fluctuating to non-fluctuating perceived exertion shifts while cycling continuously at RPE = 15 and while running at 80% of maximal heart rate [22–24]. The current findings indicate that as a result of the increased effort output, pain spreads throughout the body. Some have attributed these phenomena to the progressive global instability occurring over the neuromuscular axis that characterizes the exercise-induced fatigue. Specifically, this instability, involving attention and motivational control loops was thought to ultimately lead to task disengagement [31]. Additional inquiries need to discern if the spread patterns of exertive pain and discomfort are subject to qualitative changes, i.e., whether the number of locations increases by adding new locations ("and" logic), shifting between existing locations ("or" logic) or a combination of both. Understanding these qualitative dynamics can facilitate a higher fit between the present results and those previously related to attention focus and the PES.

To better interpret these findings, two limitations should be considered, in the present study: (a) the intensity of discomfort and exertive pain were not measured, and (b) the sample was limited to physically active individuals. Hence, the current findings do not speak to the intensity of pain and/or its dynamics throughout exercise. Additionally, the implications associated with these findings may not hold true for those who are sedentary or highly trained. In conclusion, although different local patterns are observed in cycling and running, pain appears to spread throughout the body as the effort output and time on task increase. These results are pioneer in that they offer an initial account of the spatiotemporal topology of pain spread during constant exhaustive exercise and thereby respond to calls for further studying exertive pain and its tolerance, as well as performance and regulation of exercise in 'normal' samples [29,32].

Author Contributions

Conceived and designed the experiments: AS NBS RH. Performed the experiments: AS NBS. Analyzed the data: AS NBS RH GT. Contributed reagents/materials/analysis tools: AS NBS RH SR GT. Wrote the paper: AS NBS RH SR GT.

References

1. Kress J, & Statler T. A naturalistic investigation of former Olympic cyclists' cognitive strategies for coping with exertion pain during performance. J Sport Behav. 2007; 30(4):428–452.
2. Morton DP, Richards D, Callister R. Epidemiology of exercise-related transient abdominal pain at the Sydney City to Surf community run. J Sci Med Sport. 2005; 8(2):152–162. PMID: 16075775
3. Borg E, Borg G, Larsson K, Letzter M, Sundblad BM. An index for breathlessness and leg fatigue. Scand J Med Sci Sport. 2010; 20(4):644–650.
4. Marcora SM, Staiano W. The limit to exercise tolerance in humans: Mind over muscle? Eur J Appl Physiol. 2010; 109(4):763–770. doi: 10.1007/s00421-010-1418-6 PMID: 20221773
5. Cook DB, O'connor PJ, Eubanks SA, Smith JC, Lee M. Naturally occurring muscle pain during exercise: assessment and experimental evidence. Med Sci Sport Exerc. 1997; 29(8):999–1012.
6. Motl RW, O'Connor PJ, Dishman RK. Effect of caffeine on perceptions of leg muscle pain during moderate intensity cycling exercise. J Pain. Elsevier; 2003; 4(6):316–321. PMID: 14622688
7. Richard LG. On the psychology of passenger comfort. In: Oborne DJ and Levis JA, editor. Human Factors in Transport Research. Academic P. London; 1980. p. 356–364.
8. Borg GA. Borg's perceived exertion and pain scales. Champaign, Illinois, IL: Human Kinetics; 1998.
9. Tenenbaum G, Fogarty G, Stewart E, Calcagnini N, Kirker B, Thorne G, et al. Perceived discomfort in running: Scale development and theoretical considerations. J Sports Sci. Routledge; 1999; 17(3):183–196.
10. Stendardi L, Grazzini M, Gigliotti F, Lotti P, Scano G. Dyspnea and leg effort during exercise. Respir Med. 2005; 99(8):933–942. PMID: 15950133
11. Ueda T, Kurokawa T, Kikkawa K, Choi T. Contribution of differentiated ratings of perceived exertion to overall exertion in women while swimming. Eur J Appl Physiol Occup Physiol. 1993; 66(3):196–201. PMID: 8477673
12. Robertson RJ, Goss FL, Dubé J, Rutkowski J, Dupain M, Brennan C, et al. Validation of the Adult OMNI Scale of Ergometer Exercise. Med Sci Sports Exerc. 2004; 36(1):102–108. PMID: 14707775
13. Zamunér AR, Moreno MA, Camargo TM, Graetz JP, Rebelo ACS, Tamburús NY, et al. Assessment of subjective perceived exertion at the anaerobic threshold with the Borg CR-10 scale. J Sport Sci Med. 2011; 10(1):130–136.
14. Lau WY, Muthalib M, Nosaka K. Visual analog scale and pressure pain threshold for delayed onset muscle soreness assessment. J Musculoskelet Pain. 2013; 21(4):320–326.
15. Nielsen CS, Staud R, Price DD. Individual differences in pain sensitivity: measurement, causation, and consequences. J Pain. 2009; 10(3):231–237. doi: 10.1016/j.jpain.2008.09.010 PMID: 19185545
16. Racine M, Tousignant-Laflamme Y, Kloda LA, Dion D, Dupuis G, Choinire M. A systematic literature review of 10 years of research on sex/gender and pain perception—Part 2: Do biopsychosocial factors alter pain sensitivity differently in women and men? Pain. 2012; 153(3):619–635. doi: 10.1016/j.pain.2011.11.026 PMID: 22236999
17. Coghill RC, McHaffie JG, Yen Y-F. Neural correlates of interindividual differences in the subjective experience of pain. Proc Natl Acad Sci USA. 2003; 100(14):8538–8542. PMID: 12824463
18. Robinson ME, Staud R, Price DD. Pain measurement and brain activity: Will neuroimages replace pain ratings? J Pain. 2013; 14(4):323–327. doi: 10.1016/j.jpain.2012.05.007 PMID: 23548484
19. Williamson A, Hoggart B. Pain: A review of three commonly used pain rating scales. J Clin Nurs. 2005; 14(7):798–804. PMID: 16000093

20. Graven-Nielsen T, Arendt-Nielsen L. Assessment of mechanisms in localized and widespread musculoskeletal pain. Nat Rev Rheumatol. 2010; 6(10):599–606. doi: 10.1038/nrrheum.2010.107 PMID: 20664523

21. Micalos PS, Marino FE, Kay D. Reduced muscle pain intensity rating during repeated cycling trials. J Sport Sci Med. 2004; 3(2):70–75.

22. Aragonés D, Balagué N, Hristovski R, Pol R, Tenenbaum G. Fluctuating dynamics of perceived exertion in constant-power exercise. Psychol Sport Exerc. 2013; 14(6):796–803.

23. Balagué N, Hristovski R, Garcia S, Aragonés D, Razon S, Tenenbaum G. Intentional thought dynamics during exercise performed until volitional exhaustion. J Sports Sci. 2014; 33(1):48–57. doi: 10.1080/02640414.2014.921833 PMID: 24870059

24. Balagué N, Hristovski R, Aragonés D, Tenenbaum G. Nonlinear model of attention focus during accumulated effort. Psychol Sport Exerc. 2012; 13(5):591–597.

25. Mauger AR. Fatigue is a pain-the use of novel neurophysiological techniques to understand the fatigue-pain relationship. Front Physiol. 2013; 104(4):1–4.

26. Faul F, Erdfelder E, Lang A-G, Buchner A. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007; 39(2):175–191. PMID: 17695343

27. Margolis RB, Tait RC, & Krause SJ. A rating system for use with patient pain drawings. Pain. 1986; 24 (1):57–65. PMID: 2937007

28. Villemure C, Bushnell MC. Cognitive modulation of pain: How do attention and emotion influence pain processing? Pain. 2002; 95(3):195–199. PMID: 11839418

29. Haile L, Gallagher M Jr., R J. Robertson. Exercise-Induced Muscle Pain. Perceived Exertion Laboratory Manual SE—3. Springer New York; 2015. p. 21–27.

30. Koltyn KF. Exercise-induced hypoalgesia and intensity of exercise. Sports Med. 2002; 32(8):477–487. PMID: 12076175

31. Hristovski R, Balagué N. Fatigue-induced spontaneous termination point—Nonequilibrium phase transitions and critical behavior in quasi-isometric exertion. Hum Mov Sci. Elsevier B.V.; 2010; 29(4):483–493.

32. Mauger AR, Hopker J. The pain of exercise–insights in to the role of pain on exercise regulation and performance. J Sports Med Doping Stud. 2012; 2(4):1–2.

CHAPTER THREE

RESEARCH ARTICLE II

Idiosyncratic Pain Patterns during Exhaustive Exercise

Agne Slapsinskaite*[1], Selen Razon[2], Natàlia Balagué Serre[1], Arūnas Ščiupokas[3], Robert Hristovski[4], Gershon Tenenbaum[5]

[1]Complex Systems in Sport Research Group, INEFC Barcelona University, Avda. De l'Estadi, 12-22, 08038 Barcelona, Spain
[2]Department of Physical Education, West Chester University, 700 S. High St, West Chester, PA 19382, USA
[3]Department of Neurology, Lithuanian University of Health Sciences, Eivenių g. 2, LT-50009 Kaunas, Lithuania
[4]Department of Physical Education, Sport and Health, Ss. Cyril and Methodius University, Zeleznicka BB, 1000 Skopje, Macedonia
[5]Department of Educational Psychology and Learning Systems, Florida State University, 600 W. College Avenue, Tallahassee, FL 32306, USA

* Corresponding author: *Tel*. (+34) 93 425 54 45/*Fax* (+34) 93 426 36 17/E-Mail: agneslapsinskaite@gmail.com

Idiosyncratic Pain Distribution Patterns during Exhaustive Exercise

Abstract: The purpose of this experimental study was to examine dynamical distribution of pain during constant cycling and running performed up to exhaustion. Ten participants (M = 20.8 years old, SD = ± 1.03) ran and cycled at a "hard" intensity level (e.g., Borg's RPE (6–20) = 15). During task performance, participants reported their pain on a body map every 15s. Three distinct and consistent pain distribution patterns emerged: *adders* who added pain locations, *jumpers* who switched among pain locations, and *adders-jumpers* who both added and switched among pain locations throughout the effort. These distribution patterns had a significant effect ($p < 0.001$) on pain stability (i.e., the time spent within the same pain location) and on total number of changes in pain locations ($p < 0.04$); jumpers reported more changes compared to the adders ($p < 0.035$). Task endurance was associated with the total number of changes of pain locations ($r = 0.46$, $p < 0.04$). Finally, a significant effect of time on the number of symmetric locations χ^2 (10,4) = 16.17, $p < 0.003$ emerged in running. Idiosyncratic pain distribution patterns with more switching among pain locations throughout effort seemed to increase time on task. Further scientific evidence is needed for confirming the extent to which idiosyncratic pain distribution patterns account for and/or help pain management within clinical settings.

Perspective

Sensory discriminative dimension of pain was measured during exercise performed until exhaustion. Idiosyncratic pain distribution patterns related to exercise endurance were identified. Closer inspection of the idiosyncratic pain patterns may have practical implications for exercise adherence in effort settings as well as for widespread pain management within clinical settings.

Key words: pain location, pain dynamics, idiosyncratic patterns, cycling, running, endurance, pain management.

INTRODUCTION

In the course of endurance activities, people experience exertive pain[11] or exercise-related discomfort. Exertive pain is associated with aversive sensations emanating mainly from the legs, respiratory system, proprioceptive systems, head, and abdomen.[16] The term perceived exertion (PE) typically represents a mix of painful sensations, heaviness of breathing during exercise, and fatigue which results from the physical effort. However, researhcers have called for the study of exertive pain as a distinct perceptual marker .[4,7] To that end, exertive pain during exercise has been measured via pain intensity scales,[3] numeric rating scales, visual analog scales[17], as well as pain mapping procedures for identifying painful locations.[9,14]

A taxonomy for complex spatial pain patterns was developed following multi-site pain identifications, which revealed 475 spatial pain patterns, grouped into seven categories.[12] This method emphasizes the importance of spatial patterns, not only for quantifying the painful body sites as an indicator of pain severity,[6] but also for observing the distribution of pain for each person. As a result, further investigation of both static and dynamic pain patterns were warranted.[15] Indeed, defining idiosyncratic pain distribution patterns during exercise can help in the operational definition of perceived pain dynamics that can otherwise be missed by use of other approaches.

Delineating idiosyncratic pain distribution patterns during exercise can prove beneficial in that exertive and clinical pain can at least partly share common mechanisms. In exercise settings pain typically occurs in diverse muscle groups.[4] Somewhat similarly, in clinical settings the experience of multisite pain is common.[8] In fact, in clinical contexts, persistent widespread musculoskeletal pain remains an essential feature of chronic pain syndromes.

The purpose of the present study was to examine the dynamical distribution of pain during constant cycling and running performed up to exhaustion. We hypothesized that instead of generalized patterns, idiosyncratic dynamics of exertive pain would emerge. Consequently, we expected that the results of this study would help advance the understanding of pain dynamics in effort settings. We also considered that due to the potentially common grounds shared between exertive and medical pain distribution, these findings would contribute to the understanding of medical pain dynamics within clinical settings.

MATERIALS AND METHODS

Participants

Sample size was determined using the G*Power 3.1 program.[5] Drawing upon similar studies with large effect sizes[1], an effect size of $d = 1.0$, $\alpha < 0.05$, power $(1 - \beta) = 0.80$ required 10 participants. Ten Caucasian students (4 females and 6 males, Mage = 20.8 years, SD = ± 1.03, Range 19–24) majoring in physical education were recruited. All the participants were healthy and injury-free with no counter indication for exercise testing. Participants were physically active and familiar with cycling and running at high intensities for extended durations.

Intervention and Procedure

Completion of this study took three sessions, each lasting approximately 30 minutes, separated by one-week intervals. At week one, participants completed baseline incremental cycling and running tests to determine the workload and velocity values corresponding to their RPE (6-20 Borg’s scale) = 15 (i.e., heavy).[2] At this time, participants were familiarized with the use of body maps and reporting procedures (see familiarization). At the 2nd and 3rd week, participants completed the constant-power cycling and constant velocity running tasks, respectively, in a counter-balanced assigned order. Prior to the onset of the study, participants completed a health history questionnaire, and an informed consent form. All the experimental procedures were approved by the Clinical Research Ethics Committee of the Sports Administration of Catalonia and were carried out according to the Helsinki Declaration.

Monitoring for Pain. Throughout the exercise protocol, every 15s, upon the researcher's prompt, participants reported body locations with discomfort and pain, using a body map (see Fig 1).[9] The rational for selecting this reporting strategy was to provide ample data points and limiting the potentially deleterious effects of reporting somatic sensations while constantly keeping an internal focus of attention.[18] For the purposes of this assessment, the instructions given to the participants were as following:

"When prompted, please report the locations of discomfort and pain (if you feel it, independently of its magnitude) using the numbers on the body map placed in front of you."

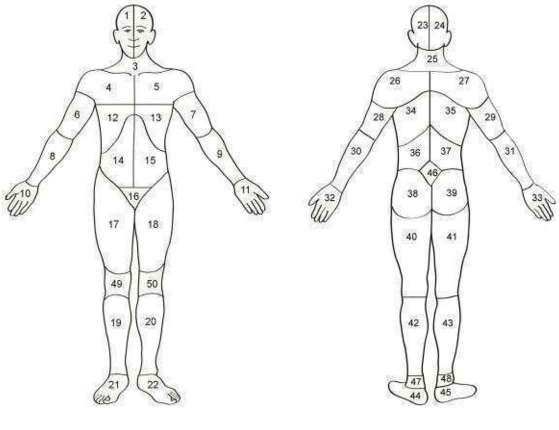


Fig 1. **Body map.** Head (area 1, 2, 23, or 24); neck (area 3 or 25), shoulders (area 4, 5, 26, 27); arms (area 6, 7, 8, 9, 28, 29, 30 or 31); hand (area 10, 11, 32, 33); ribs or chest (area 12 or 13); abdomen (area 14 or 15), back (area 34, 35, 36, 37), buttocks or hips (area 38 or 39); genitalia (area 16), legs (area 17, 18, 19, 20, 40, 41, 42 or 43); feet (area 21, 22, 44 or 45). Adapted from Margolis, Tait, & Krause (1986).

Familiarization and Baseline Tests. Both the RPE scale and body map were verbally explained to the participants prior to the baseline test. The baseline incremental cycling test and the constant-power cycling task were performed on a cycle ergometer (Sport Excalibur 925900) with saddle and handlebar specifications adjusted to the preference of each participant. The cycling test started with a 2min rest. Next, participants cycled at a cadence of 70rpm with an initial load of 20W (for females) and 25W (for males) with increase of 20W per minute (for females) and 25W per minute (for males) until reporting RPE = 15. At this point, participants kept cycling for 2min and reported on the pain scales (see above). During the last 10s of every imposed workload increment, participants reported their RPE. The workload values corresponding to RPE = 15 were recorded for each participant.

The baseline incremental running test was performed on a treadmill (HP Cosmos treadmill). The running test started with a 2min rest. Next, participants ran at an initial velocity of 5km/h with increases of 0.5km/h each minute (for females) and 1km/h each minute (for males) until RPE = 15. At this intensity, participants kept running for 2min and reported on the pain scales (see above). During the last 10s of every imposed workload increment, participants reported their RPE. The workload values corresponding to RPE = 15, were recorded for each participant.

Constant-power Cycling Task. The task included two consecutive parts: an initial incremental warm-up session (identical to the cycling baseline test) and a constant-power cycling task performed up to volitional exhaustion. The constant-power cycling began when participants reported RPE = 15 during the incremental warm-up and lasted up to volitional exhaustion when they could no longer cycle at the fixed cadence for five consecutive seconds at the sitting position. The RPE (6–20) Borg scale was placed in front of the participants at eye level during the warm up phase and was replaced by the body map during the constant protocol phase. Only the data from participants reporting RPE = 15 at the same target workload obtained during the baseline incremental cycling test were included in the analysis.

Constant-velocity Running Task. The task included an incremental warm-up (identical to the running baseline test) and a constant velocity run performed up to volitional exhaustion. The constant velocity run began when participants reported RPE = 15 during the incremental warm-up and lasted up to volitional exhaustion when they could no longer maintain the imposed velocity. The RPE (6–20) Borg scale was placed in front of the participants at eye level during the warming up and was replaced by the body map during the constant protocol. Only the data from participants reporting RPE = 15 at the target velocity obtained during the baseline incremental running test were included in the analysis.

Participants performed the cycling and running tasks without verbal communication except for the researcher's prompts for pain locations. The trials were video recorded to cross validate the accuracy of the data. Upon task completion, on an 11-point Likert-type scale with anchors ranging from 0 (*not at all*) to 10 (*greatly*), participants responded to two prompts that measured their task commitment: (a) "*Have you pedaled/ran as long as you can, up to your exhaustion point?*" and, commitment to the protocol (b) "*Have you reported all the changes in your discomfort and pain locations?"*

Data Analysis

Once recorded, all the locations for each participant were transformed to binary vectors, where 1 meant presence of pain, and 0 – no pain, to obtain the time series with topological configuration of the perceived pain regions while performing the constant cycling and running tasks. To determine the pain dynamic patterns, the binary vectors time series were analyzed with "and" and "or" logical segments.

Principal component analysis (PCA) was used to reduce the dimensionality of the local pain data (obtained from the 50-item pain map). The PCA method was used to extract the components and to obtain a maximal dimensional reduction of the data. The number of components to retain was determined through the number of salient PCs of the first order by applying Kaiser-Guttman criterion (eigenvalue $\lambda \geq 1$)[23] and by the visual inspection of a scree-plot. The parsimonious PC structure was obtained by use of the normalized Varimax criterion.

A Wilcoxon matched pairs test was used to contrast between cycling and running conditions for total number of changes in pain locations and pain stability (i.e., the time spent within the same pain location). Effect of pain distribution patterns on the total number of changes in pain locations and pain stability were subjected to one-way analysis of variance (ANOVA) followed by Tukey's HSD tests for post hoc comparisons. To assess possible relations between the pain dynamics and task endurance, a Pearson correlation was computed.

The reported number of locations with pain while performing the tasks were plotted for each participant. The symmetric pain (i.e., axial distribution of the same locations in right and left sides of the body) were calculated for each participant separately. Each time series was divided into five non-overlapping temporal windows (time to volitional exhaustion of the participant/5) for cycling and running tasks. The probability to experience symmetric pain was computed for each temporal window and took into account only the reported pain. A Friedman ANOVA was used to analyze the number of locations variance over time. Effect sizes (Cohen's d) were calculated to determine means' differences at $p < 0.05$. Data analysis was completed using SPSS version 20.0 (SPSS Inc, Chicago, IL). The level of statistical significance was set at $p < 0.05$.

RESULTS

Idiosyncratic Pain Distribution Patterns

Three groups of participants were identified based on the distribution pattern of pain during cycling and running. Of the 10 participants, 20% reported an increasing amount of locations without losing any previous locations. These participants were termed *adders* as their reporting pattern matched the logic “and”. Next 20% of the participants shifted in between locations without adding any new locations. These participants were termed *jumpers* since they matched the logic “or”. Finally, 60% of participants combined both patterns of reporting and they were termed *adder-jumpers* since their reporting pattern matched a logic of both “and” and “or”.

Principle Component Analysis (PCA) of Pain Data Series

The Kaiser-Guttmann procedure, which relied on the pain distribution pattern, revealed 3 principle components (PCs) and 4 PCs in adders, 7 PCs and 9 PCs in jumpers, and 5 PCs and 6 PCs in adders-jumpers in cycling and running tasks, respectively. On average, adders accounted for 95.02% and 97.47% of the variance in cycling and in running, respectively. Jumpers accounted for 92.12% of the variance in cycling and 94.00% in running. Finally, adders-jumpers accounted for 95.09% of the variance in cycling and 96.96% of variance in running. On average, in the cycling task the first PC accounted for 62.02%, 49.92% and 63.98%, of the total variance in adders, jumpers and adder-jumpers, respectively. In the course of the running task the first PC on average accounted for 64.02%, 52.92% and 58.82%, of the total variance in adders, jumpers and adder-jumpers, respectively. The remaining PCs contributed substantially less to the accounted variance (See Table I). The accounted variances per configuration by the whole system of PCs (commonalities) in both task were $h^2 = 0.95 \pm 0.007$.

Table I. *Principal Components Analysis (PCA) revealing principal components and accounted variance for the original pain data in cycling and running.*

	Cycling						Running				
	Average		SD				Average		SD		
PC	λ	Cum % Var	λ	Cum % Var	n	PC	λ	Cum % Var	λ	Cum % Var	n
1	28.15	58.64	11.96	14.05	10	1	20.76	57.59	7.11	11.33	10
2	7.8	72.52	3.53	11.84	10	2	7.42	78.01	3.54	8.26	10
3	1.53	85.5	2.19	10.15	10	3	3.89	88.14	2.31	7.2	10
4	2.03	89.61	1.63	9.55	9	4	1.85	92.08	1.16	5.13	9
5	1.75	92.57	1.12	9.18	8	5	1.24	95.71	0.97	4.32	8
6	1.31	94.4	1.17	7.96	6	6	1.09	97.25	1.15	3.13	7
7	0.61	99.98	0.09	0.03	2	7	0.76	97.71	0.67	2.14	5
8	0.03	100			1	8	0.69	98.47	0.49	1.27	4
						9	0.56	99.05	0.14	0.9	3
						10	0.32	99.63	0.22	0.64	3
						11	0.09	99.75			1
						12	0.03	100			1

Figure 2 illustrates how different communities of painful zones formed and decayed in time by the shifting projections on the extracted PCs. The dark regions show high values of projections of zones on given PCs corresponding to larger projection values of vectors defining reported body pain sets. They represent formation of a correlated community of pain locations which is only temporarily stable. Each community eventually decayed and left space to another community to be formed.

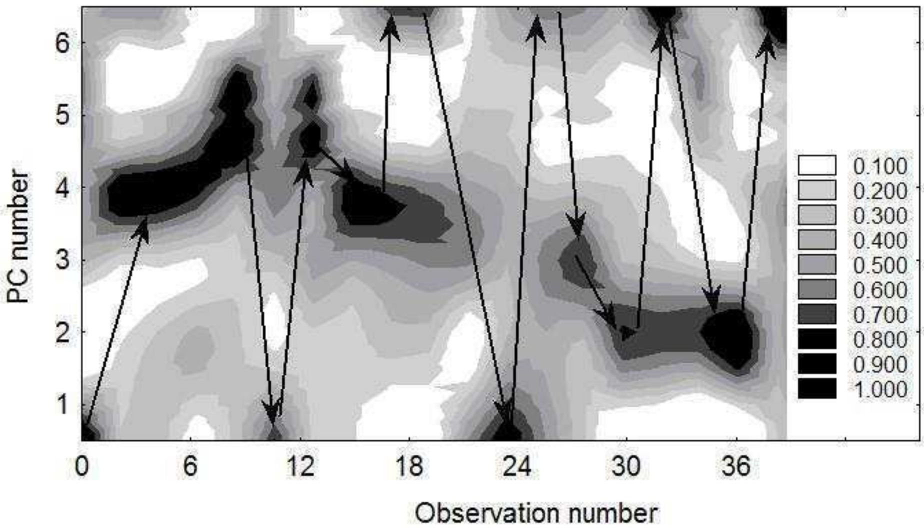


Fig. 2 **Transient communities of painful zones**. The dark regions show high values of projections of zones on given PCs corresponding to larger projection values of vectors defining reported body pain sets.

Pain distribution patterns by exercise mode (e.g., cycling vs. running) failed to significantly affect the total number of changes in pain locations (Z = -0.18, p = 0.86, d = 0.11, 95% CI: (-6.16, 5.21)) and pain stability (Z = -1.78, p = 0.07, d = 0.56, 95% CI: (-33.4, 21.93)).

The pain distribution patterns significantly affected the total number of changes in pain locations F(2, 19) = 4.03; p < 0.04. Tukey post hoc comparisons resulted in a significant difference between adders' and jumpers' patterns, p < 0.035, d = 1.88, 95% CI: (-2.84, 3.39)). Adders, jumpers, and adders-jumpers, respectively, reported 6 ± 2.45, 21.25 ± 11.35 and 16.08 ± 7.61 changes (Figure 3).

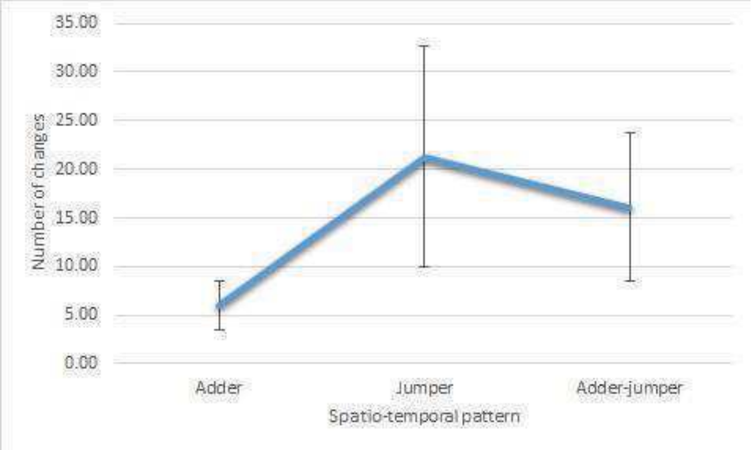


Fig.3 **Changes.** The total number of changes in pain locations within different spatio-temporal patterns. Data are presents as mean ± SD.

The pain distribution patterns affected pain stability (i.e., the time spent in the same pain location/s), F(2, 19) = 10.81; p < 0.001. Adders, jumpers, and adders-jumpers, respectively, were stable in pain lasting an average duration of 143.45s ± 59.7, 51.78s ± 10.11, and 62.28s ± 25.11, respectively (see, Figure 4). Tukey post hoc analyses revealed significant differences between adders and jumpers p < 0.003, d = 2.26, 95% CI: (-34.74, 8.52); specifically between adders and adder-jumpers patterns $p < 0.001$, d = 2.24, 95% CI:(-34.76, 17.8). Finally, task endurance was associated with total amount of changes in pain locations (r = 0.46, p = 0.04).

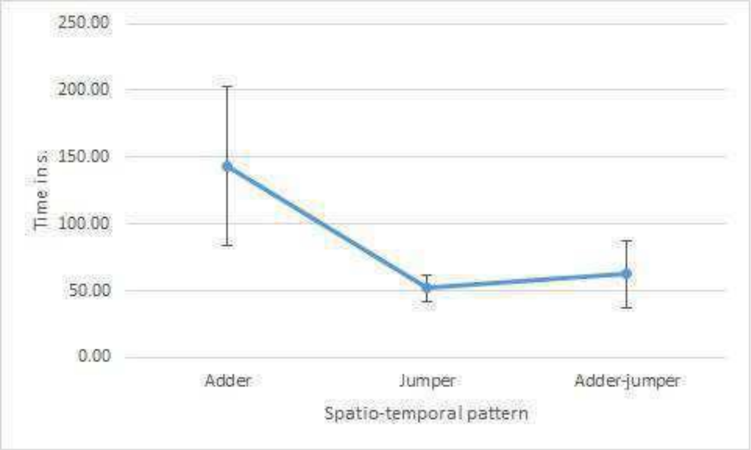


Fig. 4. **Pain stability.** The time spent within the same pain location within different spatio-temporal patterns. Data are presents as mean ± SD.

The results also indicated that the symmetric pain (i.e., the type of axial distribution of the same locations in right and left sides of the body) reached its highest values in the mid-point (73.8% of pain was symmetric) of cycling and at the end (70.7%) of running. The Friedman ANOVA revealed a significant effect of time on number of symmetric pain locations χ^2 (10,4) = 16.17 p = 0.003 in running, but not in cycling χ^2 (10,4) = 7.7, p = 0.1. Cohen's d values between the temporal windows were as follows: 1st and 5th (p = 0.01; d = 1.13, 95% CI:(0.23, 2.02)), 2nd and 4th (p = 0.03; d = 0.62, 95% CI:(0.33, 1.37)), 3rd and 5th (p = 0.02; d = 0.78, 95% CI:(0.2, 1.52)) in running.

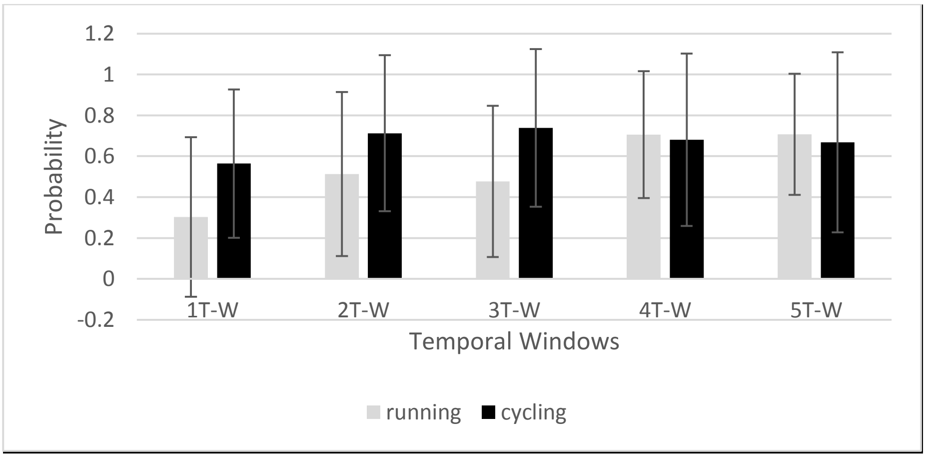


Fig. 5. **Probability of symmetric pain.** The group pulled probabilities of locations with pain during cycling and running tasks in 5 temporal windows in a given sample (n = 10). Data are presents as mean ± SD.

DISCUSSION

The purpose of the present study was to examine the dynamical distribution of pain during constant cycling and running performed up to voluntary exhaustion. Our main findings revealed three idiosyncratic pain distribution patterns during both cycling and running tasks: (1) adders, (2) jumpers and, (3) adder-jumpers. These idiosyncratic distribution pain patterns were kept in both tasks even though the specific pain locations differed within and between the tasks. These results are consistent with previous ones attesting to the importance of identification of idiosyncratic distribution patterns[13] and idiosyncratic differences.[19] The present participants showed idiosyncratic differences in the amount of changes in perceived pain locations (i.e., jumper vs adder), and the increased reports of changes in perceived painful locations were associated with increased task endurance. As such, the jumper pattern for instance seemed to have a positive influence on task endurance. For the adder pattern on the other hand, individuals repeatedly reported the same locations with the exception of a few changes thereby suggesting higher rigidity and stability of painful zones. This said, it is also plausible that given the consistency of their reported locations, adders may have experienced greater pain intensity throughout the task.

In contrast to the group pulled data, evaluation of the idiosyncratic data/dynamics within the present framework did not only help distinguish idiosyncratic pain distribution patterns, but also revealed that the number of painful locations may not increase with time spent on task (i.e., jumpers), and this is important to consider. It is therefore highly plausible that the pain distributed within the body during running and cycling has some indirect links with accumulated effort. The later means that different distribution patterns of pain might result from the interconnection of diverse internal influences of ever-changing variables during exhaustive exercise.

With regards to a novel taxonomy of pain, the literature includes several previous attempts related to complex spatial pain patterns.[12] This said, there is a consensus that although the common focus on single body sites is important, greater emphasis should be placed upon the investigation of the multisite pain.[8] The later in part explains the use of the 19 multisite location scale in clinical practice,[21] as well as the use of the 50-item pain scale within the current framework - to allow a more precise measurement of the newly arising sites throughout the exhaustive exercise. Within the exercise science, no established taxonomy exists for specific pain distribution patterns and, to our knowledge, this is the first attempt to define idiosyncratic pain distribution patterns during exercise. From a measurement standpoint, it is also important to note that although the perception of pain differs from typical perceptual processes as is localized within the body, thus pain is a highly subjective experience. The subjectivity of a painful experience is not however mutually exclusive with its objective quantification, and (subjective observation of pain) remains one of its most reliable indicator. This said, idiosyncratic pain in the same body sites may characterize pain groups with highly different characteristics (e.g., back pain as a single site has only a prevalence of 5% of the cases). Within the current study the use of the 50-item pain scale together with the dynamic approach facilitated a focus on the idiosyncratic data and helped delineate idiosyncratic pain distribution patterns.

Taken all together, these result suggest that the model of exhaustive exercises seems to attest to the changing dynamics of signaling processes of pain. To that end, an interesting follow up could include the exploration of potential similarities between the spatiotemporal distributions of exertive pain and select chronic pain presentations. In the case of Fibromyalgia (FM) for instance, the chronic pain distributes within an axial distribution in the upper and lower quadrants, and the right and left sides of the body.[22] In further similarity to chronic pain presentations, the present data suggested a symmetric distribution of pain locations independently of the idiosyncratic distribution pattern. Specifically, herein, we have not only identified a multisite pain location phenomenon but also revealed a symmetrical distribution of pain in the right and left sides of the body. Consequently, further investigation of these potential common grounds shared between exercise-related pain and chronic pain presentations can further deepen the understanding of the pain experience in general.

The contributions of the present study come in three fold. First, this study provides a novel framework for examining the dynamics of topologically defined areas of body pain during constant power exercise, and thereby further adds to the understanding of pain perception in general. Second, in the absence of a currently established taxonomy, the results from this study help advance an initial taxonomy for pain distribution patterns: adder, jumper and adder-jumper, applicable toward both research and practical realms. Third, the present results reveal an association between exercise endurance and the number of switches among painful locations during exercise. This finding is particularly relevant for the realm of performance science where task endurance is a central topic of interest. Future research is warranted to test the potential link between the idiosyncratic fitness levels and the reported pain distribution patterns. Specifically, it could be beneficial to investigate whether highly trained individuals would present particular distribution patterns over less trained individuals. This tentative assumption is drawn from the current results that suggest that the total number of reported changes is related to task endurance. To that end, jumper could possibly be the prevailing pattern among highly trained individuals and delineating such linkages could prove useful. In addition, exploring the potential translational implications of these results into other clinical settings-specifically toward the management of chronic widespread pain presentations could be particularly valuable.

Potential limitations of the present study come in two-fold. First, in the present study neither the intensity nor the quality of pain was measured; hence, we cannot confirm that pain intensity was higher in adders than in jumpers. Second, the idiosyncratic expectations about the painful locations were not evaluated. This is important in that expectations of pain are known to alter the strength of spinal nociceptive responses in humans.[10] As such, participants could have perceived painful what they initially expected to be painful.

As a word of conclusion, this study remains pioneer in delineating the idiosyncratic distribution patterns of pain during exhaustive exercise. While more research is needed to expand on these findings, exercise practitioners could make use of these results to optimize pain management and performance outcomes in exercise settings. Additionally, medical professionals may find value in the potential translations of this preliminary results toward a more effective and efficient management of an otherwise particularly complex phenomenon such as pain.[20]

ACKNOWLEDGMENTS

This study was supported by the Institut Nacional d’Educació Física de Catalunya (INEFC), the Generalitat de Catalunya. Agnė Slapšinskaitė is the recipient of a predoctoral fellowship from the Institut Nacional d’Educació Física de Catalunya (INEFC).

ETHICAL ISSUES

Participants completed an informed consent form. All the experimental procedures were approved by the Clinical Research Ethics Committee of the Sports Administration of Catalonia and were carried out according to the Helsinki Declaration. Registration: ClinicalTrials.gov ID: NCT02876705

REFERENCES

1. Balagué N, Hristovski R, Garcia S, Aragonés D, Razon S, Tenenbaum G: Intentional thought dynamics during exercise performed until volitional exhaustion. J Sports Sci [Internet] Taylor & Francis; 33:48–57, 2015. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24870059
2. Borg GA: Borg's perceived exertion and pain scales. Champaign, Illinois, IL: Human Kinetics; 1998.
3. Cook DB, O'Connor PJ, Oliver SE, Lee Y: Sex differences in naturally occurring leg muscle pain and exertion during maximal cycle ergometry. Int J Neurosci 95:183–202, 1998.
4. Dannecker EA, Koltyn KF: Pain during and within hours after exercise in healthy adults. Sport Med 44:921–42, 2014.
5. Faul F, Erdfelder E, Lang A-G, Buchner A: G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods [Internet] 39:175–91, 2007. Available from: http://dx.doi.org/10.3758/BF03193146
6. Graven-Nielsen T, Arendt-Nielsen L: Assessment of mechanisms in localized and widespread musculoskeletal pain. Nat Rev Rheumatol [Internet] 6:599–606, 2010. Available from: http://dx.doi.org/10.1038/nrrheum.2010.107
7. Haile L, Gallagher Jr. M, J. Robertson R: Exercise-Induced Muscle Pain. Perceived Exertion Lab Man SE - 3 [Internet] Springer New York; page 21–72015. Available from: http://dx.doi.org/10.1007/978-1-4939-1917-8_3
8. Leveille SG, Bean J, Ngo L, McMullen W, Guralnik JM: The pathway from musculoskeletal pain to mobility difficulty in older disabled women. Pain Elsevier; 128:69–77, 2007.
9. Margolis, R. B., Tait, R. C., & Krause SJ: A rating system for use with patient pain drawings. Pain 24:57–65, 1986.
10. Pfaff DW: Neuroscience in the 21st century: From basic to clinical. Neurosci. 21st Century From Basic to Clin. 2013.
11. Razon S, Basevitch I, Filho E, Land W, Thompson B, Biermann M, Tenenbaum G: Associative and Dissociative Imagery Effects on Perceived Exertion and Task Duration. J Imag Res Sport Phys Act 5:, 2010.
12. Schmidt CO, Baymeister SE: Simple patterns behind complex spatial pain reporting? Assessing a classification of multisite pain reporting in the general population. PAIN® 113:174–82, 2007.
13. Schöllhorn W: Coordination dynamics and its consequences on sports. Int J Comput Sci Sport 2:40–6, 2003.
14. Slapsinskaite A, Razon S, Balagué Serre N, Hristovski R, Tenenbaum G: Local Pain Dynamics during Constant Exhaustive Exercise. PLoS One [Internet] 10:e0137895, 2015. Available from: http://dx.plos.org/10.1371/journal.pone.0137895
15. Tarr J, Thomas H: Mapping embodiment: methodologies for representing pain and injury. Qual Res [Internet] 11:141–57, 2011. Available from: http://eprints.lse.ac.uk/36229/
16. Tenenbaum G, Fogarty G, Stewart E, Calcagnini N, Kirker B, Thorne G, Christensen S: Perceived discomfort in running: Scale development and theoretical considerations. J Sports Sci [Internet] Routledge; 17:183–96, 1999. Available from: http://dx.doi.org/10.1080/026404199366082
17. Tripathi L, Kumar P: Challenges in pain assessment: Pain intensity scales. Indian J Pain [Internet] 28:61–70, 2014. Available from: http://www.indianjpain.org/text.asp?2014/28/2/61/132841
18. Villemure C, Bushnell MC: Cognitive modulation of pain: How do attention and emotion influence pain processing? Pain 95:195–9, 2002.

19. Wiech K, Ploner M, Tracey I: Neurocognitive aspects of pain perception. Trends Cogn Sci 12:306–13, 2008.

20. Williams AC, Craig KD: Updating the definition of pain. Pain LWW; , 2016.

21. Wolfe F, Clauw DJ, Fitzcharles M-A, Goldenberg DL, Häuser W, Katz RS, Mease P, Russell AS, Russell IJ, Winfield JB: Fibromyalgia criteria and severity scales for clinical and epidemiological studies: a modification of the ACR Preliminary Diagnostic Criteria for Fibromyalgia. J Rheumatol The Journal of Rheumatology; 38:1113–22, 2011.

22. Wolfe F, Smythe HA, Yunus MB, Bennett RM, Bombardier C, Goldenberg DL, Tugwell P, Campbell SM, Abeles M, Clark P: The American College of Rheumatology 1990 criteria for the classification of fibromyalgia. Arthritis Rheum Wiley Online Library; 33:160–72, 1990.

23. Yeomans AK, Golder AP: The Guttman-Kaiser criterion as a predictor of the number of common factors. J R Stat Soc Ser B 3:221–229, 1982.

CHAPTER FOUR

RESEARCH ARTICLE III

frontiers
in Psychology

ORIGINAL RESEARCH
published: 06 January 2017
doi: 10.3389/fpsyg.2016.02054

Metastable Pain-Attention Dynamics during Incremental Exhaustive Exercise

Agnė Slapšinskaitė[1], Robert Hristovski[2], Selen Razon[3], Natàlia Balagué[1] and Gershon Tenenbaum[4]*

[1] Complex Systems in Sport Research Group, INEFC Barcelona University, Barcelona, Spain, [2] Saints Cyril and Methodius University of Skopje, Skopje, Macedonia, [3] West Chester University, West Chester, PA, USA, [4] Florida State University, Tallahassee, FL, USA

Background: Pain attracts attention on the bodily regions. Attentional allocation toward pain results from the neural communication across the brain-wide network "connectome" *which consists of pain-attention related circuits*. Connectome is intrinsically dynamic and spontaneously fluctuating on multiple time-scales. The present study delineates the pain-attention dynamics during incremental cycling performed until volitional exhaustion and investigates the potential presence of nested metastable dynamics.

Method: Fifteen young and physically active adults completed a progressive incremental cycling test and reported their discomfort and pain on a body map every 15 s.

Results: The analyses revealed that the number of body locations with perceived pain and discomfort increased throughout five temporal windows reaching an average of 4.26 ± 0.59 locations per participant. A total of 37 different locations were reported and marked as painful for all participants throughout the cycling task. Significant differences in entropy were observed between all temporal windows except the fourth and fifth windows. Transient dynamics of bodily locations with perceived discomfort and pain were spanned by three principal components. The metastable dynamics of the body pain locations groupings over time were discerned by three time scales: (1) the time scale of shifts (15 s); (2) the time scale of metastable configurations (100 s), and (3) the observational time scale (1000 s).

Conclusion: The results of this study indicate that body locations perceived as painful increase throughout the incremental cycling task following a switching metastable and nested dynamics. These findings support the view that human brain is intrinsically organized into active, mutually interacting complex and nested functional networks, and that subjective experiences inherent in pain perception depict identical dynamical principles to the neural tissue in the brain.

Keywords: non-linear dynamics, pain, attention, accumulated effort, exercise, metastability

Edited by:
Tadhg Eoghan MacIntyre,
University of Limerick, Ireland

Reviewed by:
John Toner,
University of Hull, UK
Noel E. Brick,
Ulster University, Ireland

****Correspondence:***
Agnė Slapšinskaitė
agneslapsinskaite@gmail.com

Specialty section:
This article was submitted to Movement Science and Sport Psychology, a section of the journal Frontiers in Psychology

Received: *31 October 2016*
Accepted: *19 December 2016*
Published: *06 January 2017*

Citation:
Slapšinskaitė A, Hristovski R, Razon S, Balagué N and Tenenbaum G (2017) Metastable Pain-Attention Dynamics during Incremental Exhaustive Exercise. Front. Psychol. 7:2054. doi: 10.3389/fpsyg.2016.02054

INTRODUCTION

Humans have the capacity to distract from and also differentiate between various sensations related to physical exercise such as exercise-related effort and pain (O'Connor and Cook, 2001; Pageaux, 2016). Perception of effort is defined as "the conscious sensation of how hard, heavy, and strenuous a physical task is" (Marcora, 2010). Perception of pain on the other hand is defined as the perception of a distressing experience associated with actual or potential tissue damage that entails sensory, cognitive, emotional, and social components (Williams and Craig, 2016). From a standpoint of measurement accuracy within self-report settings, the instructions provided by the test administrator play an important role for distinguishing between perception of effort and pain (Pageaux, 2016).

Of specific interest herein, perception of pain typically requires attentional allocation. To that end, attention focus is a key cognitive mechanism for increasing or decreasing the perception of pain (Legrain et al., 2009; Slapsinskaite et al., 2015). Even in the presence of unchanging nociceptive input and regardless of on-going task demands the attentional state seems waxing and waning spontaneously (Peters and Crombez, 2007). Consequently, shifting of attention could be due to the pain-attention related processes that are intrinsically dynamic and spontaneously fluctuating on multiple time-scales (Bressler and Kelso, 2001, 2016; Deco et al., 2013). Pervasiveness of such attentional fluctuations, their intrinsic nature, and their relevance to subjective experience, such as pain, are further supported by the evidence provided from studies of spontaneous brain dynamics and the impact of pre-existing brain state on subsequent perception (Kucyi and Davis, 2015). Within such a framework, attentional fluctuations away from non-painful modalities and their neural mechanisms can be termed "perception decoupling" or "disengagement of attention" from perception (Schooler et al., 2011). Spontaneous attentional fluctuations toward and "away from pain" and individual differences in this regard are represented in the very brain network structure and dynamics.

The dynamical system theory (DST) is a sub field of mathematics that aims at understanding and describing the dynamical changes that occur over time. Specifically, DST establishes a series of principles that govern the system's dynamical changes. In the last few decades, DST has demonstrated that painful experiences are emergent phenomena resulting from self-organized processes, and that pain-attention interaction can be understood as a virtue of such dynamics (Lutz et al., 2008). To that end, it is known that non-linear dynamic mechanisms are involved in the modulation of attentional focus during physical activity (Balagué et al., 2012; Slapsinskaite et al., 2016). Indeed, the DST framework that captures pain in terms of spatiotemporal trajectories of neural activity emerging from complex non-linear neural interactions, provides a novel approach to the study of pain-attention dynamics (Freeman, 1992).

With regards to the perception of painful sensations also known as nociception (Pfaff, 2013), the brain is intrinsically organized into active, mutually interacting complex and functional networks. There is also a consensus that the pain experience is both highly subjective and top-down modulated (Garland, 2013). To that end, evidence indicates that non-linear dynamical processes form the basis of a number of neural (Izhikevich, 2010) and higher order processes. Specifically, non-linear processes are defined as those with non-proportionality between the input and the output and with occasional reduction to linear processes (Kelso, 1997).

Findings from research that focused on subjective experiences have revealed fluctuating and metastable dynamics inherent to effort perception and within different types of exercise setting (Balagué et al., 2012, 2015; Aragonés et al., 2013; Garcia et al., 2015; Slapsinskaite et al., 2016). Metastability can be seen as a property related to the existence of multiple separated timescales (Bovier and Den Hollander, 2016). At short time-scales, the system appears to be in equilibrium, but in fact, explores only a limited part of its available state space. At longer timescales, it undergoes transitions between numbers of metastable states.

From a broader standpoint, overall cognition is also facilitated through the dynamical phenomenon of chunking (i.e., larger sequence of information is managed into its smaller units). Indeed, chunking has been shown to be involved in a range of perception and cognition-related processes in humans (Gobet et al., 2001; Rabinovich et al., 2014). Thus, the notion that mental function is based on the dynamical and ongoing interaction of a number of neural and bodily parts that produce complex patterns has gained acceptance (Thompson and Varela, 2001; Rabinovich et al., 2008; Rabinovich and Muezzinoglu, 2010).

To date, it is known that brain exhibit periods of stability and instability in both behavioral and neural levels. The transition from stable to unstable patterns comes as a response to the changes in control parameters as those govern the system's properties (stability and instability) (Haken, 1987). The neural dynamics of the brain, based upon metastability and dwelling on different time scales, flexibly reorganize pain-attention on a moment to moment basis. Consequently, the processes that are more stable dwell over longer time scales and naturally tend to correlate with the pain-attention configurations that emerge over shorter time scales. These dynamics, in turn, are reflected in the sequential switching in between the temporally and structurally nested metastable states during trials (Rabinovich and Varona, 2011).

Of specific interest herein, the link among the dynamic principles of spontaneous attention fluctuations, brain networks dynamics and the neural processing of pain observed through subjective experiences of pain may be essential for the understanding of attentional modulation and its involvement in the perception of pain. To that end, exercise settings can provide a particularly adequate context because during exercise the sensory, cognitive, emotional, and physical conditions change continuously. On a practical note, capturing pain-attention interaction dynamics through subjective experiences can also contribute to designing non-invasive approaches to ultimately control pain during exercise or beyond. The purpose of this study was to delineate the pain-attention dynamics during incremental cycling performed until volitional exhaustion. Specifically, drawing upon a DST approach, we hypothesized that pain-attention relationship during exercise would display hierarchically or nested metastable dynamics.

MATERIALS AND METHODS

Study Design and Participants

Fifteen young and physically active adults (10 women, 5 men, $Mage = 22.5$ years, $SEM = 0.43$, age range: 20–25 years, and $BMI = 22.84$, $SEM = \pm 0.77$) who engaged in a wide range of aerobic activities (e.g., jogging, swimming, dancing) at least three times a week, participated in this study. None of the participants had previous history of chronic pain or musculoskeletal injuries at the time of the study. Prior to the onset of the study, participants completed a health history questionnaire, as well as an informed consent form, which was approved by the Clinical Research Ethics Committee of the Sports Administration of Catalonia (registration number 072015CEICEGC). This study was carried out in accordance with the Declaration of Helsinki.

Discomfort and Pain Monitoring

To detect pain dynamics and corresponding bodily regions, a body map (see **Figure 1**) was verbally explained to participants prior to the baseline test and experimental tasks. Using the map, every 15 s during exercise, upon the researcher's prompts, participants reported bodily regions with discomfort and pain. The instructions provided to the participants included the following:

> *"When prompted, we ask you to report the locations of discomfort and pain (if you feel it, independently of its magnitude) using the numbers on the body map placed in front of you."*

Familiarization Procedures

All participants were already familiar with cycle ergometer testing. One week prior to the tests, they received instructions on how to use the body map during the tests. To ensure their competence, they practiced a submaximal version of the incremental cycling test (see below) and using the body map, reported bodily regions with pain every 15 s upon the researcher's prompts. All participants displayed adequate competence of the study protocols following one single trial.

Incremental Cycling Test

Following a 2 min rest period, participants performed a progressive incremental test on a cycle ergometer (Sport Excalibur 925900) with saddle and handlebar specifications adjusted to their preference. For the purposes of the test, they were instructed to pedal at 60 rpm with an initial load of 30 W and increases of 25 W/min for female and 30 W/min for male, until they could no longer maintain the pedaling rate for five consecutive seconds while in the sitting position. Participants performed the test with no verbal communication except for indicating bodily locations with pain after the researcher's prompts. Heart rate was continuously monitored (Polar RS 400) to assure that participants reached at least 170 beats/min at the point of exhaustion. Upon task completion, using an 11-point

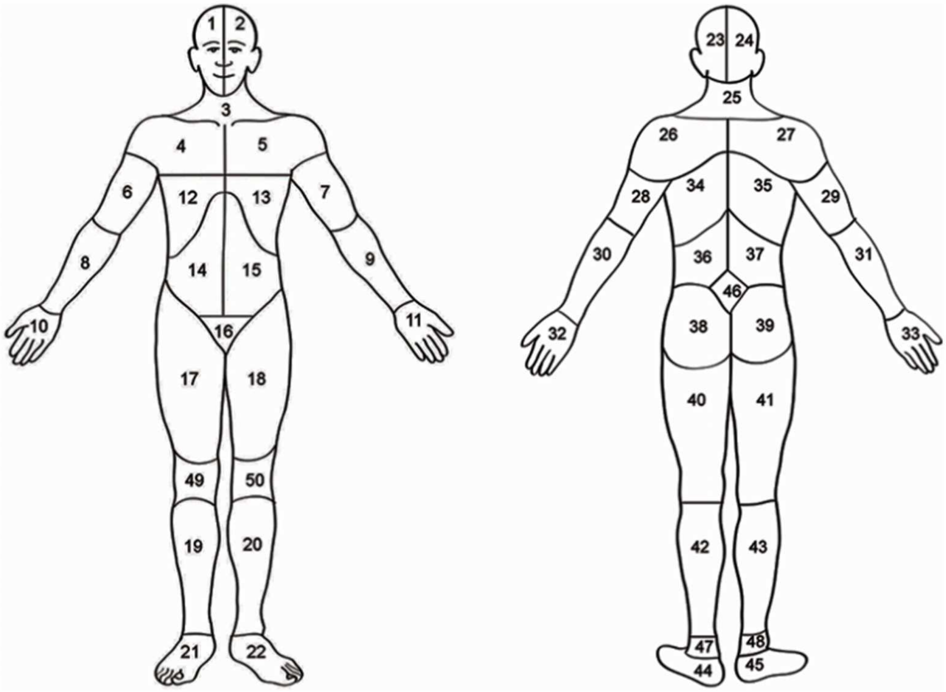


FIGURE 1 | Body map. Head (areas 1, 2, 23, or 24); neck (areas 3 or 25), shoulders (areas 4, 5, 26, 27); arms (areas 6, 7, 8, 9, 28, 29, 30, or 31); hand (areas 10, 11, 32, 33); ribs or chest (areas 12 or 13); abdomen (areas 14 or 15), back (areas 34, 35, 36, 37), buttocks or hips (areas 38 or 39); genitalia (area 16), legs (areas 17, 18, 19, 20, 40, 41, 42, or 43); feet (areas 21, 22, 44, or 45). Adapted from Margolis et al. (1986).

Likert-type scale with anchors ranging from 0 (*not at all*) to 10 (*greatly*), participants answered two questions to measure task commitment: (a) "*Have you pedaled as long as you can, achieving your exhaustion point?*" and, commitment to the protocol (b) "*Have you reported all the changes in your discomfort and pain-locations when required?*"

Statistical Analysis

The reported number of locations with discomfort and pain during the test were plotted for each participant. Each time series was divided into five non-overlapping temporal windows (time to volitional exhaustion of the participant/5). Mean value of the number of locations with discomfort and pain in total were computed for each time window. The changes of entropy were computed within five temporal windows. A median was calculated for each window from all participants' mean value of the number of locations with discomfort and pain frequencies of painful bodily locations.

These collected data with painful locations obtained from the body maps were then used to form 17 Boolean $m \times n$ data matrices where m signifies the number of body locations and n the number of time samples (Casari et al., 1995; Gogos et al., 2000; Jolliffe, 2014). Visual observation of the structure of the data matrices helped distinguish between two types of reported locations: locations that were persistent throughout the entire exercise bout (i.e., long-term and stable locations), and locations that were inconsistent (i.e., short-term and unstable locations). In other words, the data matrix either depicted long-term bodily locations that were stable on the time scale of 10s of minutes, or other short-term ones that were stable on the time scale of 10s of seconds or minutes.

Collective variables were then determined by means of a principal component analysis (PCA) (Jirsa et al., 1994). The Kaiser-Guttmann criterion (eigenvalue $\lambda \geq 1$) was used to define the number of salient PCs of the first order (Yeomans and Golder, 1982). The hierarchical analysis of oblique principal components (hPCA) (Fabrigar et al., 1999) was subsequently used to check for the presence of collective variables of higher order, and to obtain a maximal dimensional reduction of the data. For the purposes of the hPCA analysis, the software package Statistica 5.0 was used.

The null hypothesis of a constant median (with no significant differences) over time was tested using non-parametric repeated-measures Friedman ANOVA. Effect sizes (Cohen's d) were computed to demonstrate the magnitude of standardized differences in medians where effect sizes neared $p < 0.05$ level.

RESULTS

During incremental cycling, the reached maximal load corresponded to 228 ± 17 and 240 ± 30 W for females and males, respectively. On average, participants' heart rate reached 180 ± 9.5 bpm at the exhaustion point. The Friedman ANOVA revealed a significant effect of time for the total number of locations with discomfort and pain, $\chi^2(15,4) = 49.249$, $p < 0.001$, during the incremental cycling test. **Figure 2** depicts the changes in the number of locations with discomfort and pain throughout the five temporal windows. The number of locations resulted in a significant difference between temporal windows: first vs. third time intervals, $Z = -2.97$; $p < 0.05$, $d = 1.59$, 95% CI [0.65, 2.04]); third vs. fifth time intervals, $Z = -3.26$; $p < 0.05$, $d = 0.81$, 95% CI [−0.35, 1.73]), and first vs. fifth time intervals, $Z = -2.17$; $p < 0.05$, $d = 2.27$, 95% CI [1.11, 2.74]).

Figure 3 illustrates the frequencies of locations with discomfort and pain during the incremental cycling test. The number of locations and the probability of experiencing

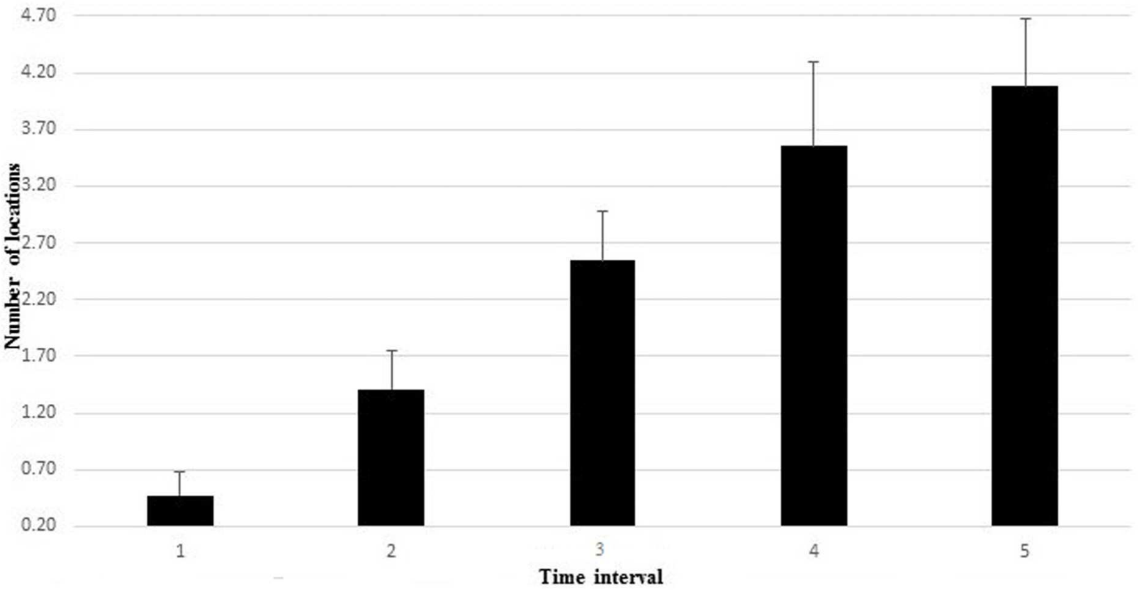


FIGURE 2 | The number of locations with discomfort and pain throughout the five temporal windows.

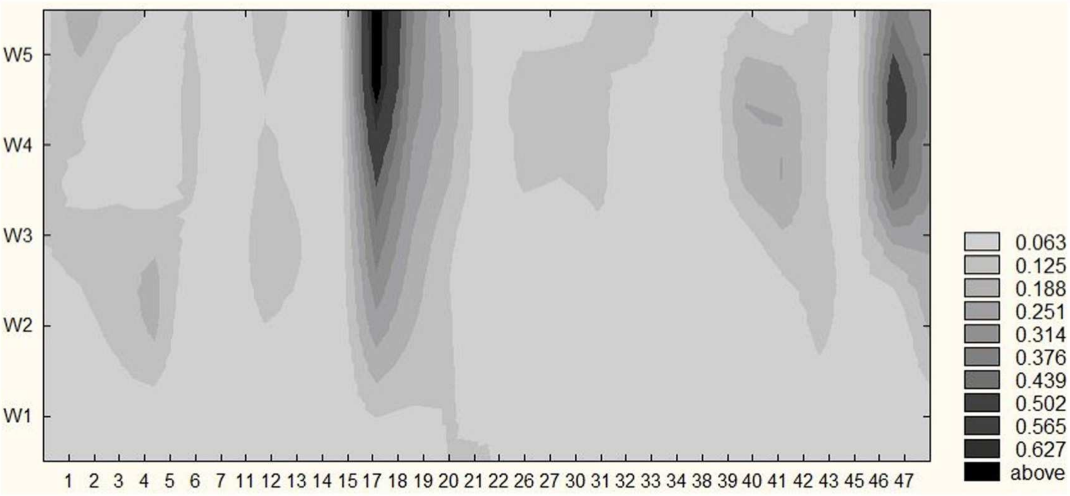


FIGURE 3 | Locations with pain and/or discomfort. The group pulled probabilities of locations with pain or discomfort during cycling tasks in five temporal windows in a given sample ($n = 15$). As time on task increases (vertical axis) the number of locations and the probability of experiencing pain and discomfort at selective locations also increase (darker shades of gray) on average. Legend: the probability of experiencing discomfort and pain.

discomfort and pain at select locations (depicted in darker shades of gray), increased during the test until reaching 4.26 ± 0.59 in the fifth temporal window. The dominant locations with discomfort and pain at exhaustion included left and right quadriceps, lower back and left ankle. Both the waxing and waning experience of pain were also identified. Depicted in shades of gray in **Figure 3**, exertive pain exhibited metastable dynamics, dwelling around select bodily regions for some time to transition into another one quickly after. A total of 37 different areas were reported and marked as painful for all participants throughout the cycling test.

The Friedman ANOVA revealed a significant effect of time for the pain entropy, $\chi^2(15,4) = 49.77$, $p < 0.001$ in incremental cycling (see **Figure 4**). The entropy of exertive pain showed significant difference between all temporal windows except the fourth and fifth windows. first vs. second time intervals, $Z = 2.93$; $p < 0.05$, $d = 1.04$, 95% CI [1.02, 1.05]; first vs. third time intervals, $Z = 3.29$; $p < 0.001$, $d = 2.07$, 95% CI [2.06, 2.08]; first vs. fourth time intervals, $Z = 3.4$; $p < 0.001$, $d = 1.62$, 95% CI [1.61, 1.63]); first vs. fifth time intervals, $Z = 3.4$; $p < 0.001$, $d = 2.44$, 95% CI [2.42, 2.45]; second vs. third time intervals, $Z = 3.17$; $p < 0.001$, $d = 1.04$, 95% CI [1.02, 1.05]; second vs. fourth time intervals, $Z = 3.17$; $p < 0.001$, $d = 0.81$, 95% CI [0.8, 0.82]; second vs. fifth time intervals, $Z = 3.26$; $p < 0.001$, $d = 1.62$, 95% CI [1.61, 1.63]; third vs. fourth time intervals, $Z = 2.07$; $p < 0.05$, $d = 0.00$, 95% CI [−0.01, 0.02]; and third vs. fifth time intervals, $Z = 3.26$; $p < 0.05$, $d = 0.81$, 95% CI [0.8, 0.82]. Kendall's W was equal to 0.83 with an average rank $r = 0.82$. In general, relative to participants who started with low entropy, participants with higher entropy kept and ended with higher entropy.

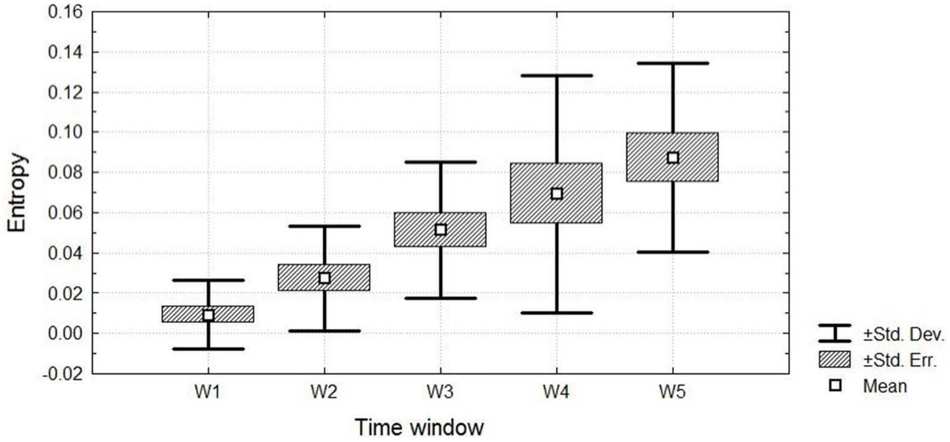


FIGURE 4 | The entropy of exertive pain throughout the five temporal windows.

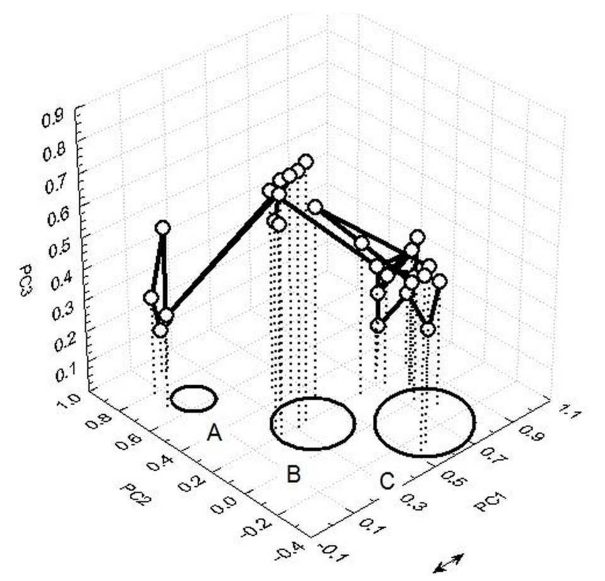


FIGURE 5 | Transient dynamics of bodily locations with perceived pain spanned by three PCs.

Figure 5 depicts an example of transient dynamics of bodily locations with perceived discomfort and pain in the space spanned by three PCs. From a chunk sequence – trajectory within three PCs a dwelling time around select region (e.g., PC1) and a transitional trajectory to another state "temporal winner" PC2 and a final rapid switch to the next metastable state can be identified. This example illustrates a metastability of sensory interactions and integration of information from the painful locations.

Figure 6 presents an integration-segregation picture of exertive pain through three PCs joined hierarchically into one second-order PC. Through hierarchical PC of time series of exertive pain configurations chunks on different time scales can be detected. The trajectory dwells for some time in space then wanes to finally dwell again. The persistent (longest dwell time) painful locations over all time resulted in the emergence of super-chunks. These group-clusters of persistent locations formed a skeleton-like figure on which other less persistent (shorter dwell time) motives join and dissolve following which further short-lived (shortens dwell time) painful locations emerged. The metastable dynamics of the body pain locations groupings over time projected on the secondary PC. The system dwells for some time in one configuration state then quickly shifts to another one. At least three time scales can be discerned: (1) the time scale of shifts (15 s), (2) the time scale of metastable configurations (100 s), and (3) the observational time scale (1000 s).

DISCUSSION

The present findings advance the understanding of generated sequential switching nature of attention-pain dynamics, and further support the view that human brain is intrinsically organized into active, mutually interacting complex and nested functional networks (Rabinovich and Varona, 2011). Surprisingly, our results draw attention to a potential link between pain-attention dynamic states and modeled sequences of two psychological components of effort, namely cognition and emotion (Rabinovich et al., 2010, 2015), as well as the dynamical signatures of several brain functions and mental diseases (Rabinovich and Varona, 2011). This is an important finding in that it demonstrates that the phenomenological subjective experiences, so called *qualia* (Chalmers, 1996), are grounded in identical dynamical principles to the neural tissue, i.e., the brain.

Consequently, perception of pain and attention to pain seem to be multidimensional and interrelated through hierarchical

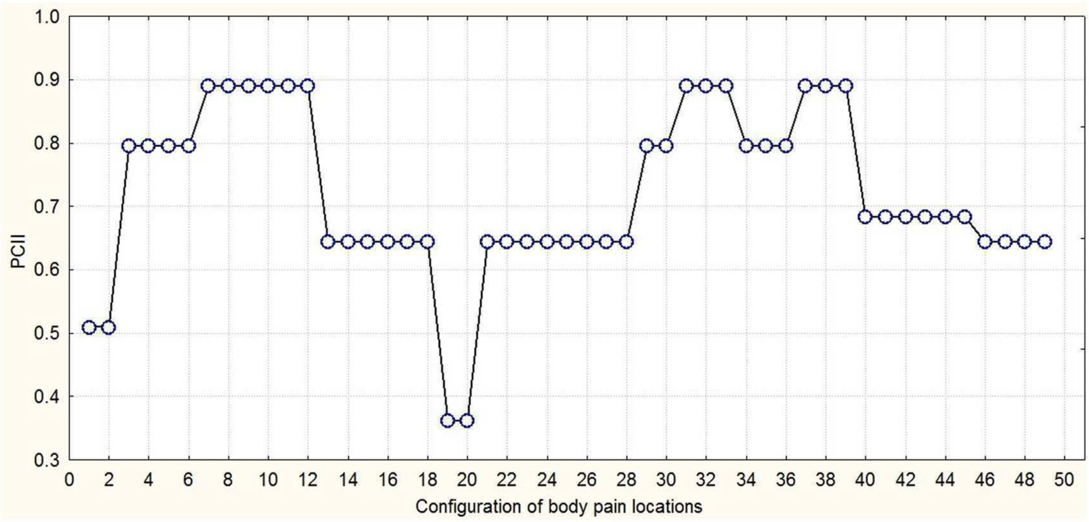


FIGURE 6 | The metastable dynamics of the configuration of body pain locations over time projected on the secondary PC.

dynamical processes that highly depend on sensory cues (i.e., painful locations) (Rabinovich et al., 2015). In the light of these findings, it is important to note that attention does not appear to be a static capacity but rather a process that involves the attentional "reorienting" from one input (i.e., one painful location) or modality (i.e., pain intensity or quality) to another. Therefore, the perception process requires a short-term integration between a number of continuously interplaying components such as the environmental cues, the body and the brain itself (Rabinovich et al., 2015).

The present study focused on the evolving interactions among pain-attention dynamics, where perceived pain throughout a cycling task was considered a bi-product of the mutual interaction between attention and distinct psychophysiological process, and not of select singular mechanisms. In fact, disengagement of attention from perception within ongoing dynamics of pain-attention or so called *perceptual decoupling* could also be responsible for the metastable dynamics observed in this study. Studies on neural mechanisms of spontaneous attentional fluctuations on multiple timescales and pain variability have already underlined the importance of dynamics of pain-attention interactions, and its mutual influence on each other. Upcoming work must consider this phenomenon (Kucyi and Davis, 2015).

The present findings also help detect and confirm the dynamical phenomenon of chunking that the biological-cognitive system uses to manage larger sequence of information into smaller units to facilitate information processing. Indeed, the presence of interconnected pieces that are prevalent over long periods of time supports the notion of a hierarchical organization of neural processing, which is the basis for understanding chunking dynamics (Rabinovich et al., 2014). Specifically, in the present study we observed the produced hierarchical chunking of locations with pain sequences, and to our knowledge for the first time, demonstrated how dynamics of mental hierarchies may be established on component perceptions that dwell over different time scales. Our data suggest that basic functions, such as focusing on the painful locations, and chunking of the information evolve through dynamic and not static interactions. That is, while forming a chunking network individuals tend to transform the chain of metastable states along with transient process to the chain of groups of such states. Therefore, within the present framework, it was considered that the chunks operate on an heteroclinic cycle of metastable states where each metastable state itself is a heteroclinic cycle of basic information items (Rabinovich et al., 2014). Altogether, the set of informational items (i.e., painful locations) can be interpreted as sequences. Consequently, conceptualizing pain and attention-related brain and body network processes from the standpoint of a concurrent activation of sensory cues emanating from the body and multiple other sources within a distributed brain network can prove beneficial.

Several limitations to our study should be noted. First, we have not studied all the spatiotemporal mental fields (e.g., alternative facets of perception, cognition, emotion, mental resources) and their dynamics within the exercise setting. Second, magnetic resonance imaging was not used to capture the neurophysiological mechanisms behind the interaction of attention-pain and this may have shed more light on the pain dynamics. Third, pre-existing brain state was not measured and finally, participants' personal beliefs or expectations about pain were not evaluated. Finally, prompting protocol used herein may also present a limitation. It is plausible that, due to the reporting task, participants' attention focus was somewhat biased. This protocol was implemented, however, to follow a systematic and regularly imposed rating strategy. Traditionally, the data of pain ratings were obtained in lower recording frequency, for instance varying between 1 and 3 min intervals (Angius et al., 2015), before and after physical activity (Choi et al., 2013), or once per day (Burnett et al., 2010). Some researchers have also recorded pain ratings at high frequencies with use of 30 s (Cook et al., 1998) or 15 s (Slapsinskaite et al., 2015). Intra-individual changes are, however, better captured through short frequency recording of self-reports precisely because participants may not be able to attend and report all changes within lower recording frequency settings. To that end, with regards to the present study, it is important to note that the test administrator was frequently prompting the self-report with no prompting of any particular pain location *per se*.

CONCLUSION

To the best of our knowledge, this study remains a first attempt to illustrate and explain the pain-attention information processing dynamics within an exercise setting. Finally, from a translational standpoint greater knowledge into pain dynamics during exercise can help practitioners design effective strategies to cope with painful sensations during effort. This is important in that within effortful settings, somatic pain is associated with negative affective responses to exercise and eventual lack of exercise-adherence (Ekkekakis et al., 2011). Consequently, strategies to allow improved pain management during activity are likely to facilitate exercise-related enjoyment, and help long term exercise-engagement (Saanijoki et al., 2015).

AUTHOR CONTRIBUTIONS

Conceived and designed the experiments: NB, RH, AS; performed the experiments: AS, NB; analyzed the data: AS, NB, RH, GT, SR; contributed reagents/materials/analysis tools: RH, AS, NB, SR, GT; wrote the paper: AS, SR, NB, RH.

FUNDING

This study was supported by the Institut Nacional d'Educacio Física de Catalunya (INEFC), the Generalitat de Catalunya. AS is the recipient of a predoctoral fellowship from the Institut Nacional d'Educacio Física de Catalunya (INEFC). We would like to thank TECNO SPORT for the technical support. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

REFERENCES

Angius, L., Hopker, J. G., Marcora, S. M., and Mauger, A. R. (2015). The effect of transcranial direct current stimulation of the motor cortex on exercise-induced pain. *Eur. J. Appl. Physiol.* 115, 2311–2319. doi: 10.1007/s00421-015-3212-y

Aragonés, D., Balagué, N., Hristovski, R., Pol, R., and Tenenbaum, G. (2013). Fluctuating dynamics of perceived exertion in constant-power exercise. *Psychol. Sport Exerc.* 14, 796–803. doi: 10.1016/j.psychsport.2013.05.009

Balagué, N., Hristovski, R., Aragonés, D., and Tenenbaum, G. (2012). Nonlinear model of attention focus during accumulated effort. *Psychol. Sport Exerc.* 13, 591–597. doi: 10.1016/j.psychsport.2012.02.013

Balagué, N., Hristovski, R., García, S., Aguirre, C., Vázquez, P., Razon, S., et al. (2015). Dynamics of perceived exertion in constant-power cycling: time-and workload-dependent thresholds. *Res. Q. Exerc. Sport* 86, 371–378. doi: 10.1080/02701367.2015.1078870

Bovier, A., and Den Hollander, F. (2016). *Metastability: A Potential-Theoretic Approach*. Cham: Springer.

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

Bressler, S. L., and Kelso, S. (2016). Coordination dynamics in cognitive neuroscience. *Front. Syst. Neurosci.* 10:397. doi: 10.3389/fnins.2016.00397

Burnett, D., Smith, K., Smeltzer, C., Young, K., and Burns, S. (2010). Perceived muscle soreness in recreational female runners. *Int. J. Exerc. Sci.* 3, 108–116.

Casari, G., Sander, C., and Valencia, A. (1995). A method to predict functional residues in proteins. *Nat. Struct. Biol.* 2:171. doi: 10.1038/nsb0295-171

Chalmers, D. J. (1996). *The Conscious Mind: In Search of a Fundamental Theory*. Oxford: Oxford University Press.

Choi, J. C., Min, S., Kim, Y. K., Choi, J. H., Seo, S. M., and Chang, S. J. (2013). Changes in pain perception and hormones pre- and post-kumdo competition. *Horm. Behav.* 64, 618–623. doi: 10.1016/j.yhbeh.2013.08.013

Cook, D. B., O'Connor, P. J., Oliver, S. E., and Lee, Y. (1998). Sex differences in naturally occurring leg muscle pain and exertion during maximal cycle ergometry. *Int. J. Neurosci.* 95, 183–202. doi: 10.3109/00207459809003340

Deco, G., Jirsa, V. K., and McIntosh, A. R. (2013). Resting brains never rest: computational insights into potential cognitive architectures. *Trends Neurosci.* 36, 268–274. doi: 10.1016/j.tins.2013.03.001

Ekkekakis, P., Parfitt, G., and Petruzzello, S. J. (2011). The pleasure and displeasure people feel when they exercise at different intensities. *Sport Med.* 41, 641–671. doi: 10.2165/11590680-000000000-00000

Fabrigar, L. R., Wegener, D. T., MacCallum, R. C., and Strahan, E. J. (1999). Evaluating the use of exploratory factor analysis in psychological research. *Psychol. Methods* 4:272. doi: 10.1037/1082-989X.4.3.272

Freeman, W. J. (1992). Tutorial on neurobiology: from single neurons to brain chaos. *Int. J. Bifurc. Chaos* 2, 451–482. doi: 10.1142/S0218127492000653

Garcia, S., Balagué, N., Razon, S., Hristovski, R., and Tenenbaum, G. (2015). Dynamic stability of task-related thoughts in trained runners. *Sport Psychol.* 29, 302–309. doi: 10.1123/tsp.2014-0094

Garland, E. (2013). Pain processing the human nervous system: a selective review of nocicetive and biobehavioral pathway. *Prim. Care* 39, 561–571. doi: 10.1016/j.pop.2012.06.013.Pain

Gobet, F., Lane, P. C. R., Croker, S., Cheng, P. C. H., Jones, G., Oliver, I., et al. (2001). Chunking mechanisms in human learning. *Trends Cogn. Sci.* 5, 236–243. doi: 10.1016/S1364-6613(00)01662-4

Gogos, A., Jantz, D., Sentürker, S., Richardson, D., Dizdaroglu, M., and Clarke, N. D. (2000). Assignment of enzyme substrate specificity by principal component analysis of aligned protein sequences: an experimental test using DNA glycosylase homologs. *Proteins* 40, 98–105. doi: 10.1002/(SICI)1097-0134(20000701)40:1<98::AID-PROT110$>$3.0.CO;2-S

Haken, H. (1987). "An approach to self-organization," in *Self-Organizing Systems: The Emergence of Order*, ed. F. Yates (New York, NY: Plenum Press), 417–437.

Izhikevich, E. M. (2010). Hybrid spiking models. *Phil. Trans. R. Soc. A* 368, 5061–5070. doi: 10.1098/rsta.2010.0130

Jirsa, V. K., Friedrich, R., Haken, H., and Kelso, J. A. S. (1994). A theoretical model of phase transitions in the human brain. *Biol. Cybern.* 71, 27–35. doi: 10.1007/BF00198909

Jolliffe, I. (2014). "Principal component analysis," in *Wiley StatsRef: Statistics Reference Online*, eds N. Balakrishnan, T. Colton, B. Everitt, W. Piegorsch, F. Ruggeri, and J. L. Teugels (Hoboken, NJ: John Wiley & Sons, Ltd), doi: 10.1002/9781118445112.stat06472

Kelso, J. A. S. (1997). *Dynamic Patterns: The Self-Organization of Brain and Behavior*. Cambridge: MIT press.

Kucyi, A., and Davis, K. D. (2015). The dynamic pain connectome. *Trends Neurosci.* 38, 86–95. doi: 10.1016/j.tins.2014.11.006

Legrain, V., Van Damme, S., Eccleston, C., Davis, K. D., Seminowicz, D. A., and Crombez, G. (2009). A neurocognitive model of attention to pain: behavioral and neuroimaging evidence. *Pain* 144, 230–232. doi: 10.1016/j.pain.2009.03.020

Lutz, A., Slagter, H. A., Dunne, J. D., and Davidson, R. J. (2008). Attention regulation and monitoring in meditation. *Trends Cogn. Sci.* 12, 163–169. doi: 10.1016/j.tics.2008.01.005

Marcora, S. M. (2010). "Effort: perception of," in *Encyclopedia of Perception*, ed. E. B. Goldstein (Thousaand Oaks, CA: Sage), 380–383.

Margolis, R. B., Tait, R. C., and Krause, S. J. (1986). A rating system for use with patient pain drawings. *Pain* 24, 57–65. doi: 10.1016/0304-3959(86)90026-6

O'Connor, P. J., and Cook, D. B. (2001). Moderate-intensity muscle pain can be produced and sustained during cycle ergometry. *Med. Sci. Sport Exec.* 33, 1046–1051. doi: 10.1097/00005768-200106000-00026

Pageaux, B. (2016). Perception of effort in exercise science: definition, measurement and perspectives. *Eur. J. Sport Sci.* 16, 1–10. doi: 10.1080/17461391.2016.1188992

Peters, M. L., and Crombez, G. (2007). Assessment of attention to pain using handheld computer diaries. *Pain Med.* 8, 110–120. doi: 10.1111/j.1526-4637.2007.00375.x

Pfaff, D. W. (2013). *Neuroscience in the 21st Century: From Basic to Clinical*. New York, NY: Springer, doi: 10.1007/978-1-4614-1997-6

Rabinovich, M. I., Huerta, R., Varona, P., and Afraimovich, V. S. (2008). Transient cognitive dynamics, metastability, and decision making. *PLoS Comput. Biol.* 4:e1000072. doi: 10.1371/journal.pcbi.1000072

Rabinovich, M. I., and Muezzinoglu, M. K. (2010). Nonlinear dynamics of the brain: emotion and cognition. *Physics Uspekhi* 53, 357–372. doi: 10.3367/UFNe.0180.201004b.0371

Rabinovich, M. I., Muezzinoglu, M. K., Strigo, I., and Bystritsky, A. (2010). Dynamical principles of emotion-cognition interaction: mathematical images of mental disorders. *PLoS ONE* 5:e12547. doi: 10.1371/journal.pone.0012547

Rabinovich, M. I., Tristan, I., and Varona, P. (2015). Hierarchical nonlinear dynamics of human attention. *Neurosci. Biobehav. Rev.* 55, 18–35. doi: 10.1016/j.neubiorev.2015.04.001

Rabinovich, M. I., and Varona, P. (2011). Robust transient dynamics and brain functions. *Front. Comput. Neurosci.* 5:24. doi: 10.3389/fncom.2011.00024

Rabinovich, M. I., Varona, P., Tristan, I., and Afraimovich, V. S. (2014). Chunking dynamics: heteroclinics in mind. *Front. Comput. Neurosci.* 8:22. doi: 10.3389/fncom.2014.00022

Saanijoki, T., Nummenmaa, L., Eskelinen, J.-J., Savolainen, A. M., Vahlberg, T., Kalliokoski, K. K., et al. (2015). Affective responses to repeated sessions of high-intensity interval training. *Med. Sci. Sport Exerc.* 47, 2604–2611. doi: 10.1249/MSS.0000000000000721

Schooler, J. W., Smallwood, J., Christoff, K., Handy, T. C., Reichle, E. D., and Sayette, M. A. (2011). Meta-awareness, perceptual decoupling and the wandering mind. *Trends Cogn. Sci.* 15, 319–326. doi: 10.1016/j.tics.2011.05.006

Slapsinskaite, A., García, S., Razon, S., Balagué, N., Hristovski, R., and Tenenbaum, G. (2016). Cycling outdoors facilitates external thoughts and endurance. *Psychol. Sport Exerc.* 27, 78–84. doi: 10.1016/j.psychsport.2016.08.002

Slapsinskaite, A., Razon, S., Balagué Serre, N., Hristovski, R., and Tenenbaum, G. (2015). Local pain dynamics during constant exhaustive exercise. *PLoS ONE* 10:e0137895. doi: 10.1371/journal.pone.0137895

Thompson, E., and Varela, F. J. (2001). Radical embodiment: neural dynamics and consciousness. *Trends Cogn. Sci.* 5, 418–425. doi: 10.1016/S1364-6613(00)01750-2

Williams, A. C., and Craig, K. D. (2016). Updating the definition of pain. *Pain* 157:1. doi: 10.1097/j.pain.0000000000000613

Yeomans, K. A., and Golder, P. A. (1982). The Guttman-Kaiser criterion as a predictor of the number of common factors. *J. R. Stat. Soc. Ser. B* 31, 221–229.

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

CHAPTER FIVE

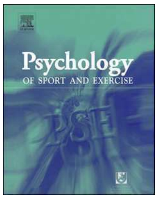
RESEARCH ARTICLE IV

Psychology of Sport and Exercise 27 (2016) 78–84

Contents lists available at ScienceDirect

Psychology of Sport and Exercise

journal homepage: www.elsevier.com/locate/psychsport



Cycling outdoors facilitates external thoughts and endurance

Agne Slapsinskaite [a], Sergi García [a, b, *], Selen Razon [c], Natàlia Balagué [a],
Robert Hristovski [d], Gershon Tenenbaum [e]

[a] Complex Systems in Sport Research Group, INEFC Barcelona University, Avda. De l'Estadi, 12-22, 08038 Barcelona, Spain
[b] EUSES, University of Girona, Carrer de Francesc Macia, 65, 17190 Salt, Spain
[c] West Chester University, 700 S. High St, West Chester, PA 19382, USA
[d] Univ. St. Cyril and Methodius, Zeleznicka BB, 1000 Skopje, The Former Yugoslav Republic of Macedonia
[e] Florida State University, 600 W. College Avenue, Tallahassee, FL 32306, USA

ARTICLE INFO

Article history:
Received 23 April 2016
Received in revised form
1 August 2016
Accepted 1 August 2016
Available online 3 August 2016

Keywords:
Thought dynamics
Static cycling
Volitional exhaustion
Environment
Attention focus

ABSTRACT

Objectives: The aims of this study were twofold: (a) to compare the effects of indoor and outdoor environments on cycling endurance and thought dynamics, (b) to investigate a possible link between cycling endurance and the adherence to task-unrelated thoughts (TUT) in both environments. Design: An experimental, within-subject design with two-trial random assignment was used.

Methods: Participants ($n = 13$) cycled at constant power until volitional exhaustion while imposing TUT. They reported thought changes using self-selected key words that were subsequently classified based on task-relatedness (TUT, and task-related thoughts (TRT)) and direction (internal, external). Mean values of relative time spent in TUT and TRT categories were computed and compared for 5 equal time intervals. The association between cycling endurance and time spent at each thought-related category was analyzed.

Results: Analyses revealed a decrease of TUT and an increase of TRT as a function of time (spent cycling) in both environments. Three qualitative thought phases emerged: an initially stable TUT phase was followed by a metastable phase characterized by shifts between TUT and TRT, and a final stable TRT phase appeared nearing exhaustion. Participants cycled longer outdoors than indoors $M_{\text{outdoors}} = 12.54$ min, $SEM = 2.17$ s, $M_{\text{indoors}} = 11.35$ min, $SEM = 1.52$ s ($Z = -2.27$, $p < 0.05$, $d(95\%\ \text{CI}) = 0.56\ (-0.80, 3.07)$), with a dominance of external thought categories. Cycling endurance seemed to be facilitated by TUT-E outdoors and TRT-I in both types of environments.

Conclusion: Outdoor environment resulted in improved cycling endurance and greater use of external thoughts (i.e., dissociative attentional strategy) relative to indoor environment. The effectiveness of thought categories seemed contingent upon their stability, which in turn depended on effort accumulation.

Individuals select different environments for physical activity (PA; Thompson Coon et al., 2011). Outdoor environments correspond either to natural settings with high levels of vegetation or urban settings with sparse vegetation and human-built structures (Sundstrom, Bell, Busby, & Asmus, 1996). Indoor environments correspond to controlled settings and can include either laboratory or indoor-gym sites (Blanchard, Rodgers, & Gauvin, 2004).

Differential effects of diverse environments on performance and performance-related psychological variables remain relatively unknown. Recent work suggests that exercising in laboratory and natural settings result in distinct psychological processes (i.e., enjoyment levels, affective responses, future intentions to exercise; Calogiuri & Chroni, 2014; Focht, 2009). Attention restoration theory (Kaplan, 1995) has, for instance, suggested that natural environments nourish and replenish attention and revive depleted energy sources. Busy urban environments, on the other hand, challenge attention with constant stimulation and induce cognitive fatigue. Others have also revealed that outdoor environments help decrease stress and fatigue, improve mood (Van den Berg, Koole, & van der

---

* Corresponding author. Complex Systems in Sport Research Group, INEFC Barcelona University, Avda. De l'Estadi, 12-22, 08038 Barcelona, Spain.

E-mail addresses: agne.slapsinskaite@gmail.com (A. Slapsinskaite), sgarciaretortillo@gmail.com (S. García), srazon@wcupa.edu (S. Razon), nataliabalague@gmail.com (N. Balagué), robert_hristovski@yahoo.com (R. Hristovski), gtenenbaum@admin.fsu.edu (G. Tenenbaum).

http://dx.doi.org/10.1016/j.psychsport.2016.08.002
1469-0292/

Wulp, 2003), and enhance subjective vitality (Ryan et al., 2010). This finding is possibly due to the color green found in outdoor environments that may facilitate positive psychophysiological responses (Akers et al., 2012). Similarly, recent findings have confirmed the occurrence of a quicker stress recovery process among individuals exercising in outdoor environments (Aspinall, Mavros, Coyne, & Roe, 2015).

While exercising, individuals make use of attentional strategies to help cope with effort (Brick, Macintyre, & Cambell, 2014). Initially, attentional strategies were categorized into the dichotomy of association and dissociation (Morgan & Pollock, 1977). Association refers to attention directed inward and towards somatic cues and/or effort pace, while dissociation refers to attention directed away from somatic cues and outward stimuli. Although this initial classification provides some explanatory value, others have extended it to account for a larger spectrum of thought-nuances that emerge during effort situations. To that end, Stevinson and Biddle (1998) suggested that active-self regulation and internal sensory monitoring during dissociation or distraction to be considered as either active distraction or involuntary distraction. An alternative approach to the earlier attentional dichotomy of association and dissociation is also Schomer's (1986) thought-related categories: external and internal task-related thoughts (TRT-E, TRT-I), and external and internal task-unrelated thoughts (TUT-E, TUT-I).

Research into task endurance, task performance, and running economy have revealed both pros and cons for dissociative and associative attentional strategies (Birrer & Morgan, 2010; Schücker, Hagemann, Strauss, & Völker, 2009). Specifically, attention is known to be altered voluntarily between the two strategies during low and moderate workloads. However, when the workload and/or time on task increase, attention gradually shifts internally and becomes exclusively narrow and associative (Tenenbaum & Connolly, 2008; Tenenbaum, 2001). Nevertheless, researchers have not yet reached conclusive agreements on the merits of either association or dissociation in endurance settings (Brick et al., 2014).

Nonlinear, dynamical approaches to endurance exercise have also added that sudden involuntary shifts of attentional focus and intended thoughts are a consequence of effort dependent dynamic instabilities (Balagué, Hristovski, Aragonés, & Tenenbaum, 2012; Hristovski, Venskaitytė, Vainoras, Balagué, & Vazquez, 2010). Specifically, through the use of the intrinsic-intentional paradigm, a number of studies have shown that intended thoughts destabilize with increased effort (Balagué et al., 2012, 2015). Thus, although TUTs can be volitionally imposed and apparently sustained at higher intensities (Schücker, Anheier, Hagemann, Strauss, & Völker, 2013), due to the emergence of unintended TRTs, TUTs lose their stability nearing exhaustion. The nonlinear model of attention focus has consistently shown, under imposed TUT conditions, three thought phases emerge during exercises performed until exhaustion: an initially stable TUT phase, a metastable TUT/TRT phase characterized by shifts among intended TUT and non-intended TRT, and a final stable TRT phase nearing volitional exhaustion (Balagué, Aragonés, Hristovski, García, & Tenenbaum, 2014; Balagué et al., 2012, 2015; Garcia, Razon, Hristovski, Balagué, & Tenenbaum, 2015). As for the thoughts direction, some have argued that, relative to field settings, individuals may exhibit less TUT-E in laboratory settings (Brunswik, 1956; Mitchell, 2012). This is important considering that the environmental cues do not only influence thought content but also the exercise-performance. For instance, participants were shown to take less time to complete an outdoor trial relative to a laboratory trial (83.0 min vs. 96.3 min) during high intensity cycling, despite similar environmental conditions, attentional styles, and perceived exertion rates (Mieras, Heesch, & Slivka, 2014). Particularly relevant to the present study, during a running task within outdoor environments, individuals have reported less perceived exertion relative to laboratory settings (LaCaille, Masters, & Heath, 2004). To our knowledge, even though researchers have called for additional work into the realm of human-environment interactions and the effects of environment on effort-related variables (see LaCaille et al., 2004), the effects of environment type on thought dynamics during exercise, and overall task-endurance, has not yet been investigated. Consequently, the aims of the present study were twofold: (a) to compare the effects of indoor and outdoor environments on cycling endurance and thought dynamics, and (b) to examine any potential link between cycling endurance and time spent in different thought categories in these environments. Accordingly, we hypothesized that participants will make greater use of external thoughts and endure longer in the outdoor environment compared to the indoor environment. We also hypothesized that three thought phases (an initially stable TUT phase, a metastable TUT/TRT phase, and a final stable TRT phase) will be discerned during cycling in both environments and that greater use of external thoughts will be associated with longer cycling endurance.

1. Method

1.1. Participants

To determine the sample size, a power analysis was computed using G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007). In similar studies of thought dynamics as a function of task endurance, a large effect size has been observed (Balagué et al., 2015). Thus, using an effect size of $d = 1.0$, $\alpha < 0.05$, power $(1 - \beta) = 0.95$, we estimated an $n = 13$. The data was collected from 13 Caucasian physical education students (10 male; 3 female; $M_{\text{age}} = 21.69$ years, $SEM = 0.78$). Students received no compensation or course credit for participating in this study. On average they were active 5.23 days/week ($SEM = 0.37$) and spent 60 min/week ($SEM = 4.3$) in vigorous activity, and 65.85 min/week ($SEM = 7.10$) in moderate activity. Time spent walking and sitting were 83.08 min/week ($SEM = 12.55$) and 330.77.5 min/week ($SEM = 14.90$) respectively. The study was approved by the local ethical committee and informed consent was obtained from all participants prior to any data collection.

1.2. Study design and procedure

Completion of this study took a total of four sessions. Each session lasted approximately 30 min and were scheduled one week apart. During Session 1, participants performed a peak power output test (see below). During Session 2, the participants completed a familiarization test for the upcoming experimental cycling endurance test, the self-monitoring, and reporting procedures. During Sessions 3 and 4, the participants performed the cycling endurance task in indoor and outdoor settings. The order of the settings for each participant were randomized and counterbalanced. Specifically for the indoor condition, participants cycled on a cycle ergometer in a human performance laboratory. Environmental conditions within the laboratory were constant with the cycle ergometer placed in front of the wall. The placement of the ergometer restricted the available scenery. For the outdoor condition, using a cycle ergometer, participants cycled in an urban setting near a roadway and a state park with sparse vegetation and some mountain scenery. Seven participants completed the indoor trial first, and six participants completed the outdoor trial first. All trials took place in the morning during the springtime. The temperature in the outdoor setting ranged between 18 and 22 °C with ~71% humidity and no precipitation. In the indoor setting, the temperature ranged between 20 and 21.5° C.

Thought monitoring and reporting procedures. Participants' thought contents during the indoor and outdoor conditions were recorded using the self-caught measurement approach and the experimenter-classified method (Balagué et al., 2015; Smallwood & Schooler, 2006). The self-caught method requires participants to report whenever they catch their own mind-wandering. In the experimenter-classified method, it is the experimenter, not the participant, who classifies the type of thoughts. Participants were instructed to self-monitor and self-report their spontaneous and deliberate thought flow using a continuous, verbalization of their thoughts (see Balagué et al., 2015; Giambra, 1995). This protocol requires to report each change of thought content as it occurs instantaneously, using a self-selected single key word. Some of the key words included "weekend," "tree," "revolutions," and "pain." One researcher collected the list of key words upon completion of the cycling endurance test. The same researcher then interviewed the participants on the thought content related to each key word. Next, the key words were classified according to their task-relatedness (TUT and TRT) and direction (internal, external). Examples of these included, "thinking about my weekend," or "thinking about the trip," for TUT-I; "looking at the tree," or "looking at the wall," for TUT-E; "focusing on the cycling pace monitor," or "concentrating on external control over velocity," for TRT-E; and "I feel calf pain," or "I monitor my breathing," for TRT-I.

Peak power output test (PPO). The rating of perceived exertion RPE 6–20 scale and its original rating instructions were handed out and verbally explained prior to the PPO test. The PPO test consisted of an initial load of 20 W (for females) and 25 W (for males) followed by increases of 20 W/min (for females) and 25 W/min (for males) until participants could not keep the required cadence (70 rpm) for 5 consecutive seconds in the sitting position (Balagué et al., 2015). During the last 10 s of every imposed workload increment, participants were asked to self-monitor and verbally report their RPE on the RPE 6–20 Borg scale with the corresponding anchors placed in front of them at eye level. The workload value corresponding to RPE = 15 (hard) was recorded for each participant. When the clamped RPE value (15) was not reported, the workload of RPE value 14 was recorded instead.

Familiarization. Participants practiced a simulated cycling endurance test (see "cycling endurance test" below) until they reported at least five different key words to ensure they properly understood the thought monitoring and reporting procedures.

Cycling endurance test. The cycling endurance test was performed using a Sport Excalibur 92590 cycle ergometer with saddle and handlebar specifications adjusted to fit the preference of each participant. The cycle and the specific saddle/handlebar specifications were kept identical during both indoor and outdoor conditions. The test included two consecutive parts: an incremental warming-up and a constant-power cycling. The warm-up started with a 2 min rest following an initial load of 20 W (for females) and 25 W (for males). The load was increased by 20 W/min (for females) and 25 W/min (for males) until reaching the RPE = 15 as initially computed in the PPO test. The reached work-load corresponding to the individual's RPE = 15 indicated the start of the constant-power cycling test which was terminated when participants could no longer maintain the required pace (70 rpm) for 5 consecutive seconds. Once the tests began, participants were no longer exposed to any verbal communication or other interaction. During the second part of the cycling endurance test (i.e., constant-power cycling), participants were instructed to consciously self-impose any type of freely chosen TUT from the outset and to maintain it intentionally throughout the test. The participants reported the keyword corresponding to the primarily chosen self-imposed TUT prior to the test. Upon test completion, an 11-point Likert-type scale with anchors ranging from 0 (*not at all*) to 10 (*greatly*) was administered to gauge participants' commitment to the cycling endurance test (i.e., "*Have you pedaled as long as you can, achieving your exhaustion point?*"), and the thought reporting and monitoring procedure (i.e., "*Have you reported all the changes in your thoughts, as soon as they have occurred?*").

1.3. Data analysis

The TUT and TRT time series of each participant were divided into five equal temporal intervals. Relative time spent in each task-related category (TUT and TRT) were computed for each of the five non-overlapping time intervals (time spent in TUT or TRT within the time interval divided by the total time of the interval). Thus, the duration of each temporal interval varied among participants. To test the null hypothesis of a constant median over the five time intervals, a Friedman ANOVA was performed separately for both TUT and TRT categories.

Thought phases were defined as follows: stable TUT-phase (TUTs only), metastable TUT/TRT phase (switches between TUT and TRT), and stable TRT phase (TRTs only). A Wilcoxon matched pairs test was used to contrast between the indoor and outdoor conditions for cycling endurance and the absolute and relative time spent on thought-related categories in the different thought phases (i.e., the time spent in each thought-related category divided by the time spent in the phase). Effect sizes (Cohen's *d* coefficients; 95% confidence interval) were computed to demonstrate mean differences where effects approached $p < 0.05$ level. Spearman's correlation coefficient was used to estimate the association between cycling endurance and time spent at each thought-related categories.

2. Results

2.1. Manipulation check

All participants reported a high level of commitment to the cycling endurance test and to the procedures of the experiment. Specifically, responses to the commitment check questionnaire revealed that participants adhered equally to the thought contents reporting and monitoring procedures in the indoor ($M_{RPE} = 9.01$, $SEM = 0.16$; $M_{cognitive} = 8.89$, $SEM = 0.1$) and outdoor environment (MRPE = 9, SEM = 0.2; Mcognitive = 9, SEM = 0.17). Additionally, in Session 3, participants reported a total of 44.92 thoughts ($SE = 7.28$) while in Session 4 they reported a total of 49.54 thoughts ($SE = 10.48$, $Z = -0.35$, $p = 0.726$, $d(95\%\ \mathrm{CI}) = 0.14\ (-11.87, 12.16)$). No differences were observed for the amount of thoughts per trial.

2.2. Cycling endurance

Cycling endurance was significantly longer outdoors than indoors: $M_{outdoors} = 12.54$ min, $SEM = 2.17$ s, $M_{indoors} = 11.35$ min, $SEM = 1.52$ s ($Z = -2.27$, $p < 0.05$, $d(95\%\ \mathrm{CI}) = 0.56\ (-0.80, 3.07)$).

2.3. Thought-related categories as a function of time

The results of a Friedman ANOVA revealed a significant effect of time on the relative time spent at TUT and TRT in both the indoor ($\chi^2(13, 4) = 28.39$, $p < 0.05$ for TUT, and $\chi^2(13, 4) = 20.96$, $p < 0.05$ for TRT) and outdoor environments ($\chi^2(13, 4) = 34.06$, $p < 0.05$ for TUT, and $\chi^2(13, 4) = 32.61$, $p < 0.05$ for TRT). As shown in Fig. 1, the relative time spent in TUT decreased gradually from interval 1 to interval 5. In contrast, the relative time spent in TRT increased gradually from interval 1 to interval 5. Cohen's *d* coefficients for TUT and TRT categories between the time windows in indoor and

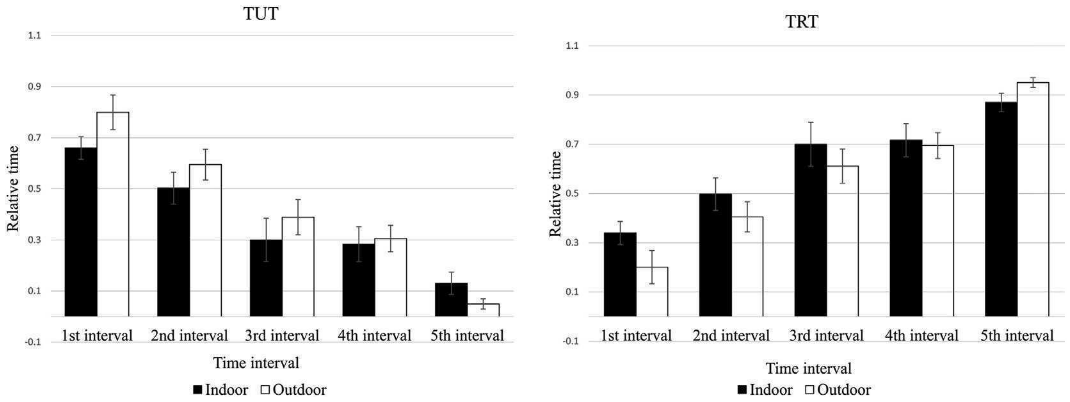


Fig. 1. TUT (External and Internal Task-Unrelated Thoughts), TRT (External and Internal Task-Related Thoughts) time spent in thought categories over time. Data are presented as mean ± *SD*.

outdoor environments are shown in Table 1.

2.4. Thought phases

TUT/TRT time series resulted in three qualitative thought phases in both the indoor and outdoor environments: an initial stable TUT-phase (only TUTs) was followed by an intermediate metastable TUT/TRT phase (switches between both categories), and a final stable TRT phase (only TRTs) in both the indoor and outdoor conditions (see Fig. 2). The absolute time (measured in seconds) spent at the TUT phase increased in the outdoor condition: $M = 46.62$ s, $SEM = 16.78$ s vs. $M = 100.23$ s, $SEM = 21.64$ s ($Z = -1.92$, $p = 0.05$, d(95% CI) = 0.79 (0.38, 1.17) (see Fig. 3) but no differences were observed in relative time spent in any other phases (see Fig. 4).

Specifically, time spent in TUT-E category was longer in the outdoor condition during the TUT phase ($Z = -2.67$; $p < 0.05$, d(95% CI) = 1.62 (1.56, 1.62)) and TUT/TRT phase ($Z = -2.28$; $p < 0.05$, d(95% CI) = 0.91 (0.53, 1.02)). TRT-E thought category also lasted longer in the outdoor condition within the TRT phase ($Z = -2.02$, $p < 0.05$, d(95% CI) = 0.39 (0.36, 0.47)). Fig. 4 depicts these differences.

2.5. Correlation between cycling endurance and time spent in thoughts categories

In the outdoor condition, cycling endurance was significantly correlated with relative time spent in TUT-E ($r = 0.44$, $p < 0.05$), and TRT-I ($r = 0.68$, $p < 0.05$) during the TUT/TRT phase. In the indoor condition, cycling endurance was significantly correlated with time spent in TRT-I ($r = 0.73$, $p < 0.05$) during the TUT/TRT phase.

3. Discussion

Our findings indicated that cycling endurance increased in the outdoor condition compared to the indoor condition. The accumulated effort effected the thought-related categories producing the emergence of three thought phases (stable TUT, metastable TUT/TRT, stable TRT) in both environments, external thought-related categories (TUT-E and TRT-E) prevailed in the outdoor condition, and cycling endurance associated with time spent in TUT-E in the outdoor condition and TRT-I in both the indoor and outdoor conditions.

Consistent with the present findings, some have reported that relative to indoor, laboratory settings, outdoor settings may result in reduced perception of exertion and prolonged endurance outcomes during a running task (LaCaille et al., 2004). However, not all studies have confirmed that outdoor settings lead to reduced perception of exertion (e.g., Mieras et al., 2014). Some of the discrepancy in these findings can be due to the differences in methodology. For instance, LaCaille et al. (2004) used a closed loop exercise protocol (i.e., running a distance of 5 km) instead of the open loop protocol presently used. In fact, there is a lack of studies comparing endurance in open loop exercises performed indoors and outdoors. To that end, the actual vs. speculative benefits of exercising indoors and outdoors should be clarified. It is also important to know that perception of the changes in the environment produces immediate effects in the subsequent action (perception-action coupling; Smits, Pepping, & Hettinga, 2014). Consequently, investigating the effects of the indoor vs. outdoor environments on endurance during static pedaling could prove particularly beneficial.

Further consistent with the present findings, previous evidence also indicates a shift from external to internal thoughts and from dissociative to associative patterns of attention as a function of increasing effort (Schomer, 1986; Tenenbaum, 2001). Specifically, the present findings confirm the nonlinear dynamic predictions of sudden shifts of thought content as a function of effort expenditure. In fact, in recent reports (Balagué et al., 2015), individuals that exercise to volitional exhaustion, while imposing TUT, have been shown to experience the same three qualitative thought phases (stable TUT, TUT/TRT switches and stable TRT) within both indoor and outdoor environments. Thus, the present result further

Table 1
Cohen's d values for means' differences in TUT/TRT dynamics between different temporal windows, in both indoor and outdoor conditions.

Indoor			Outdoor		
TW	TUT (95% CI)	TRT (95% CI)	TW	TUT (95% CI)	TRT (95% CI)
1rst-3rd	1.56 (1.47, 1.72)	1.46 (1.28, 1.55)	1rst-3rd	1.74 (1.6, 1.87)	1.72 (1.56, 1.86)
1rst-5th	3.44 (3.35, 3.53)	3.62 (3.55, 3.71)	1rst-5th	4.34 (4.21, 4.38)	4.34 (4.30, 4.47)
3rd-5th	0.73 (0.56, 0.77)	0.72 (0.64, 0.89)	3rd-5th	1.94 (1.80, 1.97)	1.91 (1.77, 1.95)

Note. TW = Temporal windows TUT = Task-Unrelated Thoughts; TRT = Task-Related Thoughts.

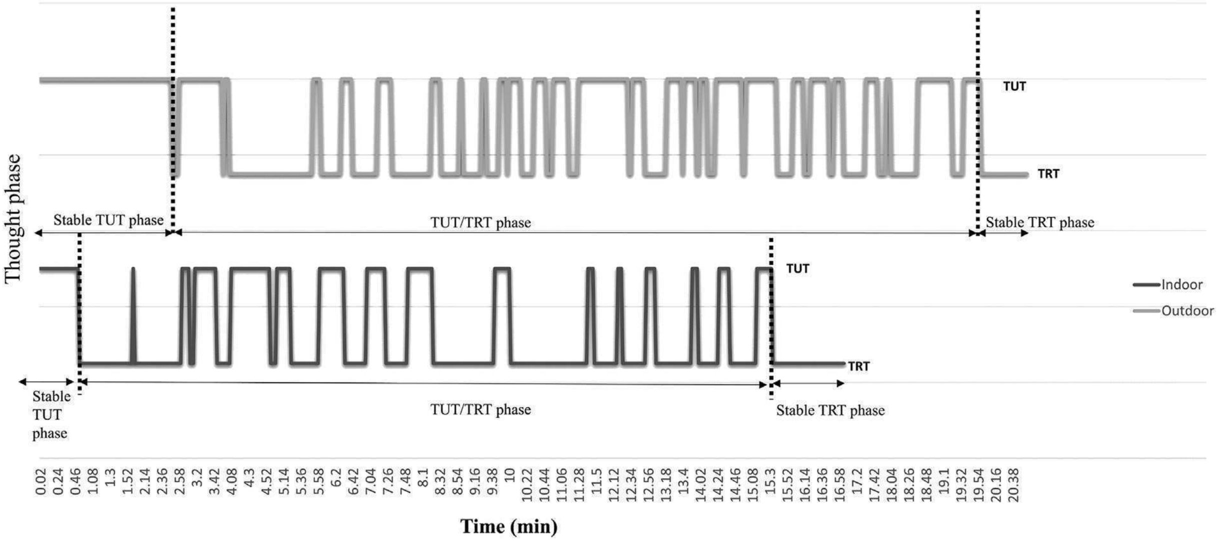


Fig. 2. Sample of typical individual thought phases and time spent in each phase within the indoor and outdoor environments. TUT = Task-Unrelated Thoughts; TRT = Task-Related Thoughts.

supports the nonlinear model of attention focus, tested across diverse personal (e.g., sex, fitness level) and task (e.g., type of exercise, reporting protocol) constraints. Nevertheless, it should be pointed out that the present results related to the nonlinear model of attention focus are not the product of a sole group effect but have been detected on an individual level in all participants. Although each participant herein reported different thought contents and either changed them at different moments or kept them for different time lengths, all participants displayed the same reproducible thought phases. These results are therefore in line with the assertion that thoughts are emergent products and cannot be considered as the single result of volitional interventions (Balagué et al., 2012; Hristovski et al., 2010). Consequently, these results confirm the notion that the salience of environmental constraints likely influences the perception and tolerance of exertion (Tenenbaum, 2001).

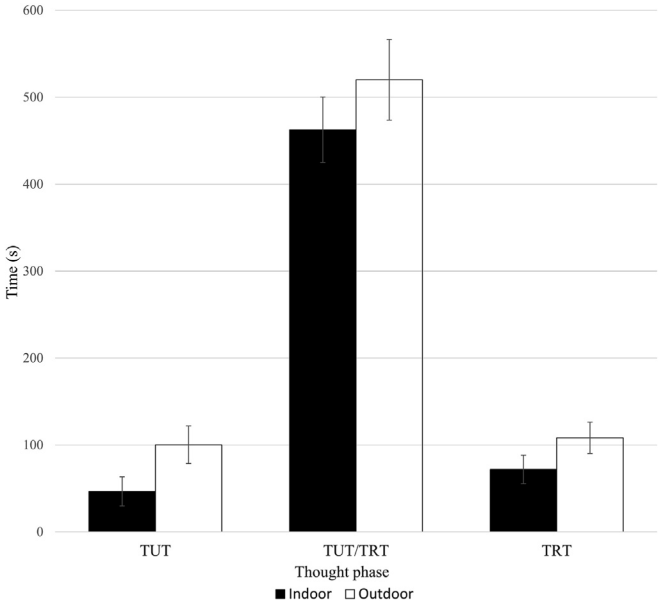


Fig. 3. Absolute time of thought phases in indoor and outdoor conditions. TUT = Task-Unrelated Thoughts; TRT = Task-Related Thoughts.

Similarly to present findings, recent research into the effects of environment on thought contents has also suggested that attention is rather external and thoughts are non-task-related in outdoor exercise in comparison to indoor and laboratory settings (Focht, 2009). It should be noted that the present participants in the outdoor condition seemed to prolong their TUT stable phase by increasing the time spent in external type of thoughts (i.e., TUT-E). To that end, the TUT-E category may have, in turn, exerted an ergogenic effect to increase cycling endurance for these participants. This performance benefit observed in the outdoor condition may be attributable to the differences between the attention focus that may have resulted from the environment and thought phases. Although these results cannot imply causation, there is previous evidence to suggest that external thoughts and dissociative attention facilitate distraction and help decrease fatigue symptoms during task performance (Blanchard et al., 2004; Brick et al., 2014).

From a methodological standpoint, these results concur with early findings indicating that environmental cues in lab studies are amongst the determinants of one's thought contents (Brunswik, 1956). Given that the present participants maintained TUTs and a primarily TUT-E thought category for a prolonged period within the outdoor setting, our findings lend direct support for the notion that individuals in lab studies may adhere less to TUT and report fewer TUT-E contents as compared to field studies (Mitchell, 2012). These findings also align with the attention restoration theory (Kaplan, 1995), which postulates the role of natural environments for nourishing and replenishing attention, as well as other accounts that stress the influence of environment in the way people think, feel, and behave (Atchley, Strayer, & Atchley, 2012).

Of important note from the present study, time spent in specific thought-related categories, as a measure of their stability, seemed to be associated with cycling endurance. Specifically, the TUT-E that prevailed in the outdoors and TRT-I that prevailed in the indoors seemed to associate closely with the cycling endurance. This observation strengthens the argument that there may be no specific thought-related category (TUT, TRT) and/or direction (internal, external) that supersedes another one, and the effectiveness of these is rather contingent upon their dynamic stability. As such, stable thought patterns (such as TUT in the stable TUT phase) can be more easily intentionally sustained than the unstable ones (such

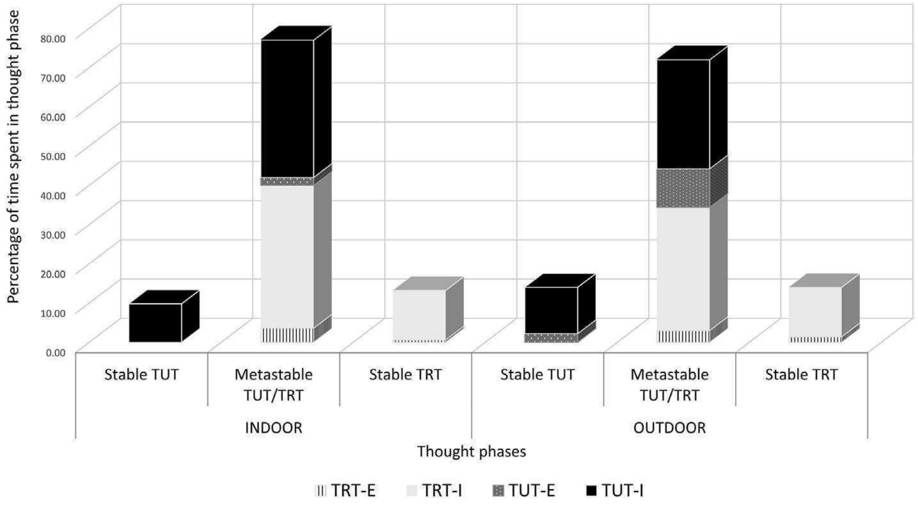


Fig. 4. Thought-related categories during thought phases in indoor and outdoor conditions. TUT-E = External Task-Unrelated Thoughts; TUT-I= Internal Task-Unrelated Thoughts; TRT-E = External Task-Related Thoughts, TRT-I = Internal Task-Related Thoughts.

as TUT in the metastable TUT/TRT phase or the stable TRT phase). In fact, drawing attention towards thoughts that are predominantly unstable may limit the potentially ergogenic effect of an otherwise appropriate attention focus (Garcia et al., 2015).

This said, not all thought categories showed a significant association to cycling endurance. Thus, seeking for a sequence of thought categories instead of a sole category would be a viable option in the quest for performance enhancement in effortful settings. In fact, this would help to clarify important controversies present in the literature. Specifically, while some research findings indicated that TUTs exert greater benefits for performance in 6 min circular pedaling (Schücker et al., 2016) and running (Morgan, Horstman, Cymerman, & Stokes, 1983), others indicated that TRTs exert greater benefits for performance in short distance swimming (Freudenheim, Wulf, Madureira, Pasetto, & Corrêa, 2010), static cycling (Razon, Mandler, Arsal, Tokac, & Tenenbaum, 2014), and long distance running (Saintsing, Richman, & Bergey, 1988). Based on the current results, the thought phases indicating dynamic stability of each thought-related category would determine whether a specific type of thought is associated with cycling endurance. However, future research based on direct manipulation of the thought-related categories ought to establish causation between thought-related categories and task endurance.

Despite statistical significance, these results should be generalized with caution. Specifically, a static bicycle was used in both of our conditions, thus the ecological validity of our results could be somewhat hindered. Also, the present participants were not asked for their preference or personal expectations from the environment nor for their preferred attentional focus. This particular constraint could have led to different dynamic stability of thought categories and cycling endurance (Wilkie & Clouston, 2015). Consequently, upcoming work with participants deliberately choosing their type of thought (TUT or TRT) may reveal more suitable for testing between endurance and thought patterns within differential environments. Additionally, it is important to note that self-caught measures used herein primarily rely on the individuals' reporting their own thought as they occur hence may carry some risks for response biases and/or social desirability (Kormos & Gifford, 2014). Finally, the present participants cycled in an outdoor urban setting with sparse vegetation and limited nature scenery, but not necessarily in a "natural environment," and this may have further jeopardized the ecological validity of some of our conclusions. Lastly, during self-caught procedures, there may be a risk of disruption to natural thought development (Ericsson & Simon, 1993) and to the extent the participants should report thoughts as freely as possible this may be a concern.

4. Conclusions

In conclusion, our findings support the view that different indoor and outdoor environments may exert different effects on thought contents and subsequently on task endurance. The outdoor condition within the present study resulted in greater use of external thoughts and prolonged cycling endurance relative to indoor condition. Future research ought to clarify whether the type of thoughts or their dynamic stability effect endurance. Considering the nonlinear nature of attention focus and thought patterns inherent to effort expenditure, these results pave the way for additional research into the effects of environment and environmental cues on effort. From a practical standpoint, based on the evidence presented herein, there is an empirical basis for the use of specific settings in effort expenditure. Given that participants seem to last longer and distract themselves better in outdoor settings, when prescribing the most optimal exercise for individuals, tasks such as outdoor cycling or outdoor running could yield distinct cognitive and endurance-related advantages over the indoor alternatives. While it is likely that some individuals would express unique preferences for one type of environment over the other, careful alignment of exercise environment to one's exercise goals (i.e., endurance, distraction etc.) could prove beneficial for both the practitioner and the exerciser. We therefore conclude by emphasizing that the present results can help practitioners design interventions to embed specific environments, or environmental cues, to reinforce select cognition-performance couplings in order to ultimately allow optimal performance and adherence to effort, which are key elements to individuals' exercise experience.

Acknowledgements

This study was supported by the Institut Nacional d'Educació Física de Catalunya (INEFC), the Generalitat de Catalunya. Agnė Slapšinskaitė is the recipient of a predoctoral fellowship from the Institut Nacional d'Educació Física de Catalunya (INEFC). We would like to thank TECNO SPORT for the technical support. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

References

Akers, A., Barton, J., Cossey, R., Gainsford, P., Griffin, M., & Micklewright, D. (2012). Visual color perception in green exercise: Positive effects on mood and perceived exertion. *Environmental Science & Technology, 46*, 8661–8666. http://dx.doi.org/10.1021/es301685g.

Aspinall, P., Mavros, P., Coyne, R., & Roe, J. (2015). The urban brain: Analysing outdoor physical activity with mobile EEG. *British Journal of Sports Medicine, 49*, 272–276. http://dx.doi.org/10.1136/bjsports-2012-091877.

Atchley, R. A., Strayer, D. L., & Atchley, P. (2012). Creativity in the Wild: Improving creative reasoning through immersion in natural settings. *PLoS ONE, 7*, 1–3. http://dx.doi.org/10.1371/journal.pone.0051474.

Balagué, N., Aragonés, D., Hristovski, R., García, S., & Tenenbaum, G. (2014). El foco de atención emerge espontáneamente durante el ejercicio progresivo y máximo. *Revista de Psicologia Del Deporte, 23*, 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. http://dx.doi.org/10.1016/j.psychsport.2012.02.013.

Balagué, N., Hristovski, R., Garcia, S., Aragonés, D., Razon, S., & Tenenbaum, G. (2015). Intentional thought dynamics during exercise performed until volitional exhaustion. *Journal of Sports Sciences, 33*, 48–57. http://dx.doi.org/10.1080/02640414.2014.921833.

Birrer, D., & Morgan, G. (2010). Psychological skills training as a way to enhance an athlete's performance in high-intensity sports. *Scandinavian Journal of Medicine & Science in Sports, 20*, 78–87. http://dx.doi.org/10.1111/j.1600-0838.2010.01188.x.

Blanchard, C. M., Rodgers, W. M., & Gauvin, L. (2004). The influence of exercise duration and cognitions during running on feeling states in an indoor running track environment. *Psychology of Sport and Exercise, 5*, 119–133. http://dx.doi.org/10.1016/S1469-0292(03)00006-2.

Brick, N., Macintyre, T., & Cambell, M. (2014). Attentional focus in endurance activity: New paradigms and future directions. *International Review of Sport and Exercise Psychology, 7*, ,106–134. http://dx.doi.org/10.1016/S1469-0292(03)00006-2.

Brunswik, E. (1956). *Perception and the representative design of psychological experiments* (2nd ed.). Berkeley, CA: University of California Press.

Calogiuri, G., & Chroni, S. (2014). The impact of the natural environment on the promotion of active living: An integrative systematic review. *BMC Public Health, 14*, 873. http://dx.doi.org/10.1186/1471-2458-14-873.

Ericsson, K. A., & Simon, H. A. (1993). *Protocol analysis (revised edition). Overview of methodology of protocol analysis*. Cambridge, MA: MIT Press.

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. http://dx.doi.org/10.3758/BF03193146.

Focht, B. C. (2009). Brief walks in outdoor and laboratory environments: Effects on affective responses, enjoyment, and intentions to walk for exercise. *Research Quarterly for Exercise and Sport, 80*, 611–620. http://dx.doi.org/10.5641/027013609X13088500159840.

Freudenheim, A. M., Wulf, G., Madureira, F., Pasetto, S. C., & Corrĕa, U. C. (2010). An external focus of attention results in greater swimming speed. *International Journal of Sports Science & Coaching, 5*, 533–542. http://dx.doi.org/10.1260/1747-9541.5.4.533.

Garcia, S., Razon, S., Hristovski, R., Balagué, N., & Tenenbaum, G. (2015). Dynamic stability of task-related thoughts in trained tunners. *The Sport Psychologist, 29*, 302–309. http://dx.doi.org/10.1123/tsp.2014-0094.

Giambra, L. M. (1995). A laboratory method for investigating influences on switching attention to task-unrelated imagery and thought. *Consciousness and Cognition, 4*, 1–21.

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

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology, 15*, 169–182.

Kormos, C., & Gifford, R. (2014). The validity of self-report measures of pro-environmental behavior: A meta-analytic review. *Journal of Environmental Psychology, 40*, 359–371. http://dx.doi.org/10.1016/j.jenvp.2014.09.003.

LaCaille, R. A., Masters, K. S., & Heath, E. M. (2004). Effects of cognitive strategy and exercise setting on running performance, perceived exertion, affect, and satisfaction. *Psychology of Sport and Exercise, 5*(4), 461–476. http://dx.doi.org/10.1016/S1469-0292(03)00039-6.

Mieras, M. E., Heesch, M. W. S., & Slivka, D. R. (2014). Physiological and psychological responses to outdoor vs. laboratory cycling. *The Journal of Strength & Conditioning Research, 28*, 2324–2329. http://dx.doi.org/10.1519/JSC.0000000000000384.

Mitchell, G. (2012). Revisiting truth or triviality the external validity of research in the psychological laboratory. *Perspectives on Psychological Science, 7*, 109–117. http://dx.doi.org/10.1177/1745691611432343.

Morgan, W. P., Horstman, D. H., Cymerman, A., & Stokes, J. (1983). Facilitation of physical performance by means of a cognitive strategy. *Cognitive Therapy and Research, 7*, 251–264.

Morgan, W. P., & Pollock, M. L. (1977). Psychologic characterization of the elite distance runner. *Annals of the New York Academy of Sciences, 301*, 382–403.

Razon, S., Mandler, K., Arsal, G., Tokac, U., & Tenenbaum, G. (2014). Effects of imagery on effort perception and cycling endurance. *Journal of Imagery Research in Sport and Physical Activity, 9*, 23–38. http://dx.doi.org/10.1515/jirspa-2013-0011.

Ryan, R. M., Weinstein, N., Bernstein, J., Brown, K. W., Mistretta, L., & Gagné, M. (2010). Vitalizing effects of being outdoors and in nature. *Journal of Environmental Psychology, 30*, 159–168. http://dx.doi.org/10.1016/j.jenvp.2009.10.009.

Saintsing, D., Richman, C., & Bergey, D. (1988). Effects of three cognitive strategies on long-distance running. *Bulletin of the Psychonomic Society, 26*, 34–36. http://dx.doi.org/10.3758/BF03334853.

Schomer, H. (1986). Mental strategies and the perception of effort of marathon runners. *International Journal of Sport Psychology, 14*, 41–59.

Schücker, L., Anheier, W., Hagemann, N., Strauss, B., & Völker, K. (2013). On the optimal focus of attention for efficient running at high intensities. *Sport, Exercise, and Performance Psychology, 2*, 207–219. http://dx.doi.org/10.1037/a0031959.

Schücker, L., Fleddermann, M., de Lussanet, M., Elischer, J., Böhmer, C., & Zentgraf, K. (2016). Focusing attention on circular pedaling reduces movement economy in cycling. *Psychology of Sport and Excercise, 27*, 9–17. http://dx.doi.org/10.1016/j.psychsport.2016.07.002.

Schücker, L., Hagemann, N., Strauss, B., & Völker, K. (2009). The effect of attentional focus on running economy. *Journal of Sports Sciences, 27*, 1241–1248. http://dx.doi.org/10.1080/02640410903150467.

Smallwood, J., & Schooler, J. W. (2006). The restless mind. *Psychological Bulletin, 132*, 946–958. http://dx.doi.org/10.1037/0033-2909.132.6.946.

Smits, B. L. M., Pepping, G.-J., & Hettinga, F. J. (2014). Pacing and decision making in sport and exercise: The roles of perception and action in the regulation of exercise intensity. *Sports Medicine, 44*, 763–775. http://dx.doi.org/10.1007/s40279-014-0163-0.

Stevinson, C. D., & Biddle, S. J. (1998). Cognitive orientations in marathon running and “hitting the wall”. *British Journal of Sports Medicine, 32*, 229–234.

Sundstrom, E., Bell, P. A., Busby, P. L., & Asmus, C. (1996). Environmental psychology 1989-1994. *Annual Review of Psychology, 47*, 485–512. http://dx.doi.org/10.1146/annurev.psych.47.1.485.

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. http://dx.doi.org/10.1016/j.psychsport.2007.09.002.

Thompson Coon, J., Boddy, K., Stein, K., Whear, R., Barton, J., & Depledge, M. H. (2011). Does participating in physical activity in outdoor natural environments have a greater effect on physical and mental wellbeing than physical activity outdoors? A systemic review. *Environmental Science and Technology, 45*, 1761–1772. http://dx.doi.org/10.1021/es102947t.

Van den Berg, A. E., Koole, S. L., & van der Wulp, N. Y. (2003). Environmental preference and restoration: (How) are they related? *Journal of Environmental Psychology, 23*, 135–146. http://dx.doi.org/10.1016/S0272-4944(02)00111-1.

Wilkie, S., & Clouston, L. (2015). Environment preference and environment type congruence: Effects on perceived restoration potential and restoration outcomes. *Urban Forestry & Urban Greening, 14*, 368–376. http://dx.doi.org/10.1016/j.ufug.2015.03.002.

CHAPTER SIX

DISCUSSION

In an effort to further add to the existing research in pain (Astokorki & Mauger, 2016; Cook et al., 1998; Mauger, 2013; Mauger & Hopker, 2012; O'Connor & Cook, 1999) and attention (Balagué et al., 2012; Basevitch et al., 2011; Garcia et al., 2015; Vancleef & Peters, 2006), and contribute to develop the Nonlinear psychobiological model of exercise induced fatigue, this thesis focus on the study of pain dynamics and attention in alternative settings. The aims can be summarized twofold: (a) to delineate the body locations dynamics of exertive pain during exercise performed until exhaustion (b) to investigate the dynamics of attention focus in different environments and its effects on endurance. Attention connects the two main aims in that pain attracts attention and attention constraint the type of thoughts. It is the attention focus that gives raise to the subjective feeling of pain and its location in the body. Both collective variables (i.e., pain locations and thoughts) emerge from the interaction among body, mind and environment and its behavior is rooted in common dynamical processes governed by the same general dynamical laws, which are direct consequences of a self-organized process.

Summary of the findings. In light of the findings, the current thesis: (1) defined the relationship between constant exercise and location dynamics of pain in group pulled data, (2) extended the results on individual pain dynamics by exploring the spread patterns of the pain locations, (3) advanced the understanding of generated sequential switching nature of attention-pain dynamics and, finally, (4) provided clarification on the environmental effects on attention focus and cycling endurance. Of further importance, the individual data analysis of pain locations dynamics herein revealed idiosyncratic pain patterns during incremental exhaustive exercise. In other words, the present findings suggested that the subjects were adding new locations (i.e., "and" logic), shifting between existing locations (i.e., "or" logic) or using a combination of both. This type of categorization provided an initial taxonomy for pain distribution patterns: (1) adders, (2) jumpers and, (3) adder-jumpers. In fact, based on this classification, the number of painful locations may not increase with time spent on task (i.e., jumpers), and this is important to consider. It is, therefore, highly plausible that the pain distributed within the body during running and cycling is indirectly linked to accumulated effort. This means that different distribution patterns of pain might result from the interconnection of diverse internal influences of ever-changing variables during exhaustive exercise. This different distribution of pain throughout the body with increased effort output could be attributed to the progressive global *instability* phenomena that occurred over the neuromuscular axis that characterizes the exercise-induced fatigue. Importantly, this *instability,* involving attention and motivational control loops was thought to ultimately lead to task disengagement (Hristovski & Balagué, 2010). Notwithstanding, additional inquiries need to discern if the spread patterns of perceived exertive pain are subject to qualitative changes.

Theoretical, methodological and practical contributions. Previous studies have revealed an effect of time on task (i.e., effort accumulation) and the presence of critical phenomena examining the dynamics of attention focus and effort perception during constant cycling and running until volitional exhaustion (Aragonés et al., 2013; Balagué, Hristovski, Garcia, et al., 2015; Balagué, Aragonés, et al., 2014; Balagué et al., 2012; Garcia et al., 2015). Results herein added to these findings that there is an association between exercise endurance and the number of switches (i.e., prolonged metastable state) among painful locations during exercise. The increased reports of changes (i.e., switches) in perceived painful locations were associated with extended time on task. As such, the jumper pattern for instance seemed to have a positive influence on endurance. For the adder pattern on the other hand, subjects repeatedly reported the same locations with the exception of a few changes thereby suggesting higher rigidity and stability of painful zones. These results are particularly relevant for the realm of performance science where task endurance is a central topic of interest. Potential applications of these findings to clinical and medical settings and more concretely to the development of individual pain coping and management strategies require further investigation.

It is important to consider the notion that subjective observation of pain remains one of its most reliable indicators. Within this thesis (research articles I-III) adopting a purpose to delineate the pain location dynamics of exertive pain we used the 50-item pain body map together with the dynamic approach. Pain as a final product of the noxious stimulus differs from typical perceptual processes as it is localized within the body. On the other hand, the perception of pain requires a short-term *integration* between a number of continuously interplaying components such as the environment, periphery and the brain itself. Moreover, perception of pain and attention to pain *per se* are multidimensional and tend to interrelate through hierarchical dynamical processes (Rabinovich et al., 2015). Therefore, research articles presented within this thesis demonstrated for the first time, how dynamics of mental hierarchies may be formed by component perceptions (i.e., pain) that dwell over different time scales. This is a finding that demonstrates that the phenomenological subjective experiences, so called *qualia* (Chalmers, 1996) are grounded in identical dynamical principles to the neural tissue, i.e., the brain.

In agreement with our second set of expectations, present findings revealed that different environments exert specific effects on attention focus and cycling endurance. This very influence of the environment on attention may feed the argument that the subjective feeling of pain can also be affected by the type of environment. Our results indicated that cycling endurance increased in the outdoor condition compared to the indoor condition. We postulated that, attention allocation on external TUT may have, in turn, exerted this ergogenic effect to aid cycling endurance. Given that the subjects maintained TUTs and a primarily external TUT category for a prolonged period within the outdoor condition, one can argue that subjects in lab studies may adhere less to TUT and report fewer external TUT contents as opposed to field studies (Mitchell, 2012). This notion further aligns with the statement that continuous interplay between environment, periphery and the brain plays a crucial role on the fatigue-induced task disengagement.

Briefly put, the take-home message is the following: It is essential to admit the importance of the metastability for body-mind-environment components interaction and integration. Instability and metastability in the context of fatigue and exercise driven changes have clear *evolutionary stabilized role*. They represent generic dynamical mechanisms of biological systems for spontaneous formation of decisions and alternative solutions for coping with organismic changes that otherwise may result in serious injuries or decapacitation (Vázquez, Hristovski, Balagué, 2016). The spontaneous emergence of pain and discomfort perceptions during exercise signals the novel physiological atmosphere within which the organism performs. The final spontaneous task disengagement clearly functions as an archaic preventive decision mechanism. Their sequential emergence (i.e., first discomfort then task disengagement) may then reflect the degree of the tradeoff between the set goal and discomfort tolerance. For example, although the intended task goal may be focusing the attention on task unrelated thoughts, it is clear that the increased discomfort destabilizes the intended attention mode and spontaneously forms other attention solutions (e.g., TUT-E, TRT-E etc.). The metastability here offers the capacity for spontaneous switching between and testing the effectiveness of attention solutions that may help in prolonging the set goal (i.e., time on task). However, close to the exercise termination the system finally stabilizes in a state of minimal cognitive effort and reverts to the protectively most salient TRT-I category. In similar vein the attention to pain locations switch in a spontaneous manner although the most probable behavior is the growth of the number of painful areas. Metastability of attention-pain dynamics may enable similar effect to the set goal of prolonging the time on task. The role of this type of switching however warrants further investigation. Finally, the spontaneous task disengagement is the ultimate protective decision mechanism (Hristovski & Balagué 2010) that, in fact, eliminates the cause of the discomfort i.e., the exercise task itself.

In regards to the implications and applications associated with the present results: first and foremost, this thesis considered that it is the integration of brain, periphery and environment that characterized psychobiological features of exercise-induced fatigue and the task-disengagement phenomenon. Although different local patterns were observed in cycling and running, pain appeared to spread throughout the body as the effort output and time on task increased. Secondly, this thesis used general dynamical principles to study the attentional changes in different environments. From a translational standpoint greater knowledge into pain dynamics during exercise could help practitioners design effective strategies to cope with painful sensations during effort. This is important in that exercise professionals and health care providers would regularly and appropriately measure exercise-related pain in both of its components such as induction and reduction within their exercise prescriptions and recommendations

(Dannecker & Koltyn, 2014). Finally, from a practical standpoint, there is an empirical basis for the use of specific settings in effort expenditure. Given that the subjects herein seem to last longer and distract themselves better in outdoor settings, when prescribing the most optimal exercise for subjects, tasks such as outdoor cycling or outdoor running could yield distinct endurance-related advantages over the indoor alternatives. These effects should be further investigated in relation to pain locations dynamics.

Limitations and challenges for the future. Two main limitations of this thesis should be noted. First, the data collection of this thesis heavy relied on prompting methodology. It is plausible that, due to the reporting task, subjects' attention focus was somewhat interrupted and biased. However, this type of protocol was implemented to collect data systematically and regularly. Previously, the data of pain ratings were obtained in lower recording frequency, for instance at high frequencies with use of 30 s (Cook et al., 1998), varying between 1 and 3 min intervals (Angius et al., 2015), or low frequencies before and after physical activity (Choi et al., 2013), or once per day (Burnett, Smith, Smeltzer, Young, & Burns, 2010). Intra-individual changes are, however, better captured through short frequency recording of self-reports. To that end, it is important to note that the test administrator in these research experiments was instructed to frequently prompt self-report with no prompting of any particular pain location. Second, this thesis also made use of the self-caught measures. This methodology primarily relies on the subjects' reporting their own thought as they occur, thus, may carry some risks for response biases and/or social desirability (Kormos& Gifford, 2014). Finally, during self-caught procedures, there may be a risk of disruption to natural thought development (Ericsson & Simon, 1993) and these deserves to be considered in upcoming trials and research into pain dynamics.

Researchers are encouraged to use pain-attention temporal nestedness and the proposed taxonomy based on attention-driven mechanisms as a fruitful avenue to pursue for future investigation. Moreover, future research should also focus on the dynamic approach to reinforce the study on dynamic body-mind-environment couplings. Consequently this may lead to better understand of exercise-related phenomena, also may guide practitioners to design adequate interventions to increase exercise endurance and tolerance within different settings. Finally, future research could address alternative clinical/medical type of pain and could study it on the bases of the Nonlinear psychobiological model of exercise-induced fatigue.

CHAPTER SEVEN

CONCLUSIONS

Within the framework of the nonlinear psychobiological model of exercise-induced fatigue the present results are pioneer in that they a) offer an initial account of pain location dynamics during constant exhaustive exercise, b) recognize the individuality of pain patterns dynamics, c) detect a nested temporal organization of subjective experiences (qualia) through the study of pain-attention dynamics, and finally d) highlight the effect of the environment on attention and endurance.

Specifically, these results suggested that: a) the number of body locations with perceived pain increased through the effort, b) three consistent individual pain distribution patterns were present during constant cycling and running: adders, adders/jumpers, and jumpers, c) pain-attention dynamics during incremental exercise displayed a metastable and nested organization, identical to the one shown by the neural tissue in the brain, d) outdoor environment, compared to indoor environment, increased the use of external thoughts and helped improve task endurance.

From a theoretical standpoint, this thesis emphasizes the nonlinear integration of brain, periphery and environment during exercise. Subsequently, implications from this thesis point towards the recommendation to study pain and attention from a dynamical and nonlinear integration point of view. From a practical standpoint, the present findings can help practitioners to design effective interventions to further aid exertive pain and its tolerance, performance and regulation of exercise effort within different settings and/or in response to different environmental cues. It is therefore our hope that the upcoming work extends on these findings to further reinforce the study of dynamic body-mind-environment couplings to understand exercise-related phenomena, and ultimately allow optimal performance and adherence to effort, which are central to subjects' exercise experience at the least and their healthy life styles at large. Moreover, this approach may be used for studying other types of clinical pain presentations. The study of medical pain in its temporal nestedness and proposed taxonomy of attentionally driven mechanisms (adders, adder/jumpers and jumpers) as well as the effects of attentional strategy in modulatory purposes may prove a much promising and rewarding realm of investigation.

CONCLUSIONS

En el marc d'un model psicobiològic no lineal de fatiga induïda per l'exercici els presents resultats son pioners en quant a que: a) ofereixen una descripció inicial de la localització del dolor durant un exercici constant i intens, b) reconeixen la individualitat de patrons dinàmics de dolor, c) detecten una organització temporal niada d'experiències subjectives (qualia) a través de l'estudi de la dinàmica dolor-atenció, i finalment d) ressalten l'efecte de l'entorn en el focus d'atenció i la resistència.

Concretament, aquests resultats suggereixen que: a) el nombre de localitzacions corporals on hi ha percepció de dolor augmenten durant l'esforç, b) durant un exercici de pedalejar i córrer, es revelen tres patrons individuals de dolor consistents: "adders", "adders-jumpers" i "jumpers" , c) la dinàmica dolor-atenció durant un exercici progressiu mostra una organització metaestable i niada, idèntica a la que presenta el teixit neuronal del cervell, d) l'ambient exterior, comparat amb l'interior, augmenta l'ús de pensaments externs i augmenta la resistència.

Des d'un punt de vista teòric, aquesta tesi emfatitza la integració no lineal del cervell, la perifèria i l'entorn durant l'exercici. Posteriorment, les implicacions d'aquesta tesi apunten a recomanar l'estudi del dolor i l'atenció des d'un punt de vista integratiu dinàmic i no lineal. Des d'una perspectiva pràctica, els resultats obtinguts poden ajudar als practicants a dissenyar intervencions efectives per augmentar la tolerància al dolor durant l'esforç, a millorar el rendiment i a regular l'esforç en entorns diferents i/o en resposta a senyals ambientals diferents. Per tant, s'espera que els pròxims treballs ampliïn aquestes troballes i reforcin l'estudi de l'acoblament dinàmic cos-ment-entorn per entendre millor els fenòmens relacionats amb l'exercici i, en última instància, per possibilitar un rendiment òptim i adherència a l'esforç, aspectes centrals per aconseguir un estil de vida saludable. A més, aquest enfocament pot ser utilitzat per estudiar altres tipus de dolor. L'estudi del dolor en clínica, la seva estructura temporal i l'aplicació de la taxonomia dels mecanismes d'atenció proposada (adders, adder-jumpers and jumpers), així com els efectes moduladors de l'estratègia d'atenció, poden resultar un tema d'investigació molt prometedor i gratificant en el futur.

REFERENCES

Almeida, T. F., Roizenblatt, S., & Tufik, S. (2004). Afferent pain pathways: a neuroanatomical review. *Brain Research*, *1000*(1), 40–56.

Angius, L., Hopker, J. G., Marcora, S. M., & Mauger, A. R. (2015). The effect of transcranial direct current stimulation of the motor cortex on exercise-induced pain. *European Journal of Applied Physiology*, *115*(11), 2311–2319. http://doi.org/10.1007/s00421-015-3212-y

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*(6), 796–803. http://doi.org/10.1016/j.psychsport.2013.05.009

Astokorki, A. H. Y., & Mauger, A. R. (2016). Tolerance of exercise-induced pain at a fixed rating of perceived exertion predicts time trial cycling performance. *Scandinavian Journal of Medicine & Science in Sports*, *27*(3), 309–317. http://doi.org/10.1111/sms.12659

Atkins, D., Uskul, A. K., & Cooper, N. R. (2016). Culture shapes empathic responses to physical and social pain., *16*(5), 587–601. http://doi.org/10.1037/emo0000162

Balagué, N., Aragonés, D., Hristovski, R., García, S., & Tenenbaum, G. (2014). El foco de atención emerge espontáneamente durante el ejercicio progresivo y máximo. *Revista de Psicología Del Deporte*, *23*(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*(5), 591–597. http://doi.org/10.1016/j.psychsport.2012.02.013

Balagué, N., Hristovski, R., García, S., Aguirre, C., Vázquez, P., Razon, S., & Tenenbaum, G. (2015). Dynamics of perceived exertion in constant-power cycling: time-and workload-dependent thresholds. *Research Quarterly for Exercise and Sport*, *86*(4), 371–378. http://doi.org/10.1080/02701367.2015.1078870

Balagué, N., Hristovski, R., Garcia, S., Aragonés, D., Razon, S., & Tenenbaum, G. (2015). Intentional thought dynamics during exercise performed until volitional exhaustion. *Journal of Sports Sciences*, *33*(1), 48–57. http://doi.org/10.1080/02640414.2014.921833

Balagué, N., Hristovski, R., Vázquez, P., & Slapsinskaite, A. (2014). Psychobiology of endurance and exhaustion a nonlinear integrative approach. *Research in Physical Education, Sport and Health*, *3*(1), 3–11.

Basevitch, I., Thompson, B., Braun, R., Razon, S., Arsal, G., Tokac, U., … Tenenbaum, G. (2011). Olfactory effects on attention allocation and perception of exertion. *Sport Psychologist*, *25*(2), 144–158. http://doi.org/http://dx.doi.org/10.1123/tsp.25.2.144

Bovier, A., & Den Hollander, F. (2016). *Metastability: a potential-theoretic approach* (Vol. 351). Springer.

Branstetter-Rost, A., Cushing, C., & Douleh, T. (2009). Personal values and pain tolerance: Does a values intervention add to acceptance? *The Journal of Pain*, *10*(8), 887–892. http://doi.org/10.1016/j.jpain.2009.01.001

Bressler, S. L., & Kelso, J. A. S. (2001). Cortical coordination dynamics and cognition. *Trends in Cognitive Sciences*, *5*(1), 26–36.

Bressler, S. L., & Kelso, S. (2016). Coordination dynamics in cognitive neuroscience. *Frontiers in Systems*

Neuroscience, *10*, 1–7. http://doi.org/10.3389/fnins.2016.00397

Brooks, J. C. W., Nurmikko, T. J., Bimson, W. E., Singh, K. D., & Roberts, N. (2002). fMRI of thermal pain: effects of stimulus laterality and attention. *Neuroimage*, *15*(2), 293–301.

Brown, J. C., Miller, C. J., Posthumus, M., Schwellnus, M. P., & Collins, M. (2011). The COL5A1 gene, ultra-marathon running performance, and range of motion. *Int J Sports Physiol Perform*, *6*(4), 485–496.

Burnett, D., Smith, K., Smeltzer, C., Young, K., & Burns, S. (2010). Perceived muscle soreness in recreational female runners. *International Journal of Exercise Science*, *3*(3), 108–116.

Butler, D. S., & Moseley, G. L. (2013). *Explain Pain 2nd Edn.* Noigroup Publications.

Caldwell, L. S., & Smith, R. P. (1966). Pain and endurance of isometric muscle contractions. *Journal of Engineering Psychology*, *5*(1), 25–32.

Casey, K. L., & Bushnell, M. C. (2000). *Pain imaging* (Vol. 18). International Assn for the Study of Pain.

Cazzola, M., Atzeni, F., Salaffi, F., Stisi, S., Cassisi, G., & Sarzi-Puttini, P. (2009). Which kind of exercise is best in fibromyalgia therapeutic programmes? A practical review. *Clinical and Experimental Rheumatology*, *28*(6), 117–124.

Chen, R., Liang, F. X., Moriya, J., Yamakawa, J., Sumino, H., Kanda, T., & Takahashi, T. (2008). Chronic fatigue syndrome and the central nervous system. *Journal of International Medical Research*, *36*(5), 867–874. http://doi.org/10.1177/147323000803600501

Chesterton, L. S., Barlas, P., Foster, N. E., Baxter, G. D., & Wright, C. C. (2003). Gender differences in pressure pain threshold in healthy humans. *Pain*, *101*(3), 259–266.

Choi, J. C., Min, S., Kim, Y. K., Choi, J. H., Seo, S. M., & Chang, S. J. (2013). Changes in pain perception and hormones pre- and post-kumdo competition. *Hormones and Behavior*, *64*(4), 618–623. http://doi.org/10.1016/j.yhbeh.2013.08.013

Coghill, R. C., McHaffie, J. G., & Yen, Y.-F. (2003). Neural correlates of interindividual differences in the subjective experience of pain. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(14), 8538–8542. http://doi.org/10.1073/pnas.1430684100

Cook, D. B., O'Connor, P. J., Eubanks, S. A., Smith, J. C., & Lee, M. (1997). Naturally occurring muscle pain during exercise: assessment and experimental evidence. *Medicine & Science in Sports & Exercise*, *29*(8), 999–1012. Retrieved from http://journals.lww.com/acsm-msse/Fulltext/1997/08000/Naturally_occurring_muscle_pain_during_exercise_.4.aspx

Cook, D. B., O'Connor, P. J., Oliver, S. E., & Lee, Y. (1998). Sex differences in naturally occurring leg muscle pain and exertion during maximal cycle ergometry. *The International Journal of Neuroscience*, *95*(3–4), 183–202. http://doi.org/10.3109/00207459809003340

Dannecker, E. A., & Koltyn, K. F. (2014). Pain during and within hours after exercise in healthy adults. *Sports Medicine*, *44*(7), 921–942. http://doi.org/10.1007/s40279-014-0172-z

Deco, G., Jirsa, V. K., & McIntosh, A. R. (2013). Resting brains never rest: computational insights into potential cognitive architectures. *Trends in Neurosciences*, *36*(5), 268–274. http://doi.org/10.1016/j.tins.2013.03.001

Dunckley, P., Aziz, Q., Wise, R. G., Brooks, J., Tracey, I., & Chang, L. (2007). Attentional modulation of visceral and somatic pain. *Neurogastroenterology and Motility*, *19*(7), 569–577.

http://doi.org/10.1111/j.1365-2982.2007.00908.x

Eccleston, C., & Crombez, G. (1999). Pain demands attention: a cognitive-affective model of the interruptive function of pain. *Psychol Bull*, *125*(3), 356–366. http://doi.org/10.1037/0033-2909.125.3.356

Ellingson, L. D., Koltyn, K. F., Kim, J., & Cook, D. B. (2014). Does exercise induce hypoalgesia through conditioned pain modulation? *Psychophysiology*, *51*(3), 267–276. http://doi.org/10.1111/psyp.12168

Ellingson, L. D., Shields, M. R., Stegner, A. J., & Cook, D. B. (2012). Physical activity, sustained sedentary behavior, and pain modulation in women with fibromyalgia. *The Journal of Pain*, *13*(2), 195–206. http://doi.org/10.1016/j.jpain.2011.11.001.

Eyring, H. (1935). The activated complex in chemical reactions. *The Journal of Chemical Physics*, *3*(2), 107–115.

Fillingim, R. B., Maixner, W., Kincaid, S., & Silva, S. (1998). Sex differences in temporal summation but not sensory-discriminative processing of thermal pain. *Pain*, *75*(1), 121–127.

Garcia-Larrea, L., & Peyron, R. (2013). Pain matrices and neuropathic pain matrices: A review. *Pain*, *154*(1), 29–43. http://doi.org/10.1016/j.pain.2013.09.001

Garcia, S., Balagué, N., Razon, S., Hristovski, R., & Tenenbaum, G. (2015). Dynamic stability of task-related thoughts in trained runners. *Sport Psychologist*, *29*(4), 302–309.

Garland, E. (2013). Pain processing the human nervous system: a selective review of nocicetive and biobehavioral pathway. *Prim Care.*, *39*(3), 561–571. http://doi.org/10.1016/j.pop.2012.06.013.Pain

Haken, H. (1983). *Advanced synergetics*. Springer Berlin.

Hristovski, R., & Balagué, N. (2010). Fatigue-induced spontaneous termination point - Nonequilibrium phase transitions and critical behavior in quasi-isometric exertion. *Human Movement Science*, *29*(4), 483–493. http://doi.org/10.1016/j.humov.2010.05.004

Hristovski, R., Balagué, N., & Schöllhorn, W. I. (2014). Basic notions in the science of complex systems and nonlinear dynamics. In *Complex Systems in Sport* (pp. 3–18).

Jameson, C., & Ring, C. (2000). Contributions of local and central sensations to the perception of exertion during cycling: effects of work rate and cadence. *Journal of Sports Sciences*, *18*(4), 291–298.

Janal, M. N., Glusman, M., Kuhl, J. P., & Clark, W. C. (1994). On the absence of correlation between responses to noxious heat, cold, electrical and ischemie stimulation. *Pain*, *58*(3), 403–411.

Jirsa, V. K., Friedrich, R., Haken, H., & Kelso, J. A. S. (1994). A theoretical model of phase transitions in the human brain. *Biological Cybernetics*, *71*(1), 27–35.

Katz, L. N., Lindner, E., & Landt, H. (1935). On the nature of the substance(s) producing pain in contracting skeletal muscle: Its bearing on the problems of angina pectoris and intermittent claudication. *Journal of Clinical Investigation*, *14*(6), 807–821. http://doi.org/10.1172/JCI100729

Kelso, J. A. S. (1997). *Dynamic patterns: The self-organization of brain and behavior*. MIT press.

Key, B. (2016). Why fish do not feel pain. *Animal Sentience*, *3*, 1–33. Retrieved from http://users.ecs.soton.ac.uk/harnad/Temp/KEY/Key_A_Target.04.11.15.pdf

Khalsa, P. S. (2004). Biomechanics of musculoskeletal pain: Dynamics of the neuromatrix. *Journal of Electromyography and Kinesiology*, *14*(1), 109–120. http://doi.org/10.1016/j.jelekin.2003.09.020

Koban, L., & Wager, T. D. (2016). Beyond conformity: Social influences on pain reports and physiology. *Emotion*, *16*(1), 24–32. http://doi.org/10.1037/emo0000087

Kopell, N. J., Gritton, H. J., Whittington, M. A., & Kramer, M. A. (2014). Beyond the connectome: the dynome. *Neuron*, *83*(6), 1319–1328. http://doi.org/http://dx.doi.org/10.1016/j.neuron.2014.08.016

Krahé, C., Springer, A., Weinman, J. A., & Fotopoulou, A. (2013). The social modulation of pain: others as predictive signals of salience - a systematic review. *Frontiers in Human Neuroscience*, *7*, 386. http://doi.org/10.3389/fnhum.2013.00386

Kucyi, A., & Davis, K. D. (2015). The dynamic pain connectome. *Trends in Neurosciences*, *38*(2), 86–95. http://doi.org/10.1016/j.tins.2014.11.006

Larsson, A., Palstam, A., Löfgren, M., Ernberg, M., Bjersing, J., Bileviciute-Ljungar, I., … Mannerkorpi, K. (2015). Resistance exercise improves muscle strength, health status and pain intensity in fibromyalgia-a randomized controlled trial. *Arthritis Research & Therapy*, *17*(1), 161. http://doi.org/10.1186/s13075-015-0679-1

Lazarus, R. S., & Folkman, S. (1984). *Stress, appraisal, and coping*. Springer publishing company.

Legrain, V., Van Damme, S., Eccleston, C., Davis, K. D., Seminowicz, D. A., & Crombez, G. (2009). A neurocognitive model of attention to pain: behavioral and neuroimaging evidence. *Pain*, *144*(3), 230–232. http://doi.org/10.1016/j.pain.2009.03.020

Leknes, S. (2011). The pain modulatory cocktail. *Scandinavian Journal of Pain*, *2*(3), 105–107. http://doi.org/10.1016/j.sjpain.2011.05.007

Linblom, U., Mersky, H., & Mumford, J. M. (1986). Pain terms: a current list with definitions and usage. *Pain*, *3*, 215–221.

Loeser, J. D., & Treede, R. D. (2008). The Kyoto protocol of IASP Basic Pain Terminology. *Pain*, *137*(3), 473–477. http://doi.org/10.1016/j.pain.2008.04.025

Marcora, S. M., Bosio, A., & de Morree, H. M. (2008). Locomotor muscle fatigue increases cardiorespiratory responses and reduces performance during intense cycling exercise independently from metabolic stress. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *294*(3), R874–R883.

Marcora, S. M., & Staiano, W. (2010). The limit to exercise tolerance in humans: Mind over muscle? *European Journal of Applied Physiology*, *109*(4), 763–770. http://doi.org/10.1007/s00421-010-1418-6

Mauger, A. R. (2013). Fatigue is a pain-the use of novel neurophysiological techniques to understand the fatigue-pain relationship. *Frontiers in Physiology*, *104*(4), 1–4. http://doi.org/10.3389/fphys.2013.00104

Mauger, A. R., & Hopker. (2012). The pain of exercise – insights in to the role of pain on exercise regulation and performance. *Journal of Sports Medicine & Doping Studies*, *2*(4), 1–2. http://doi.org/10.4172/2161-0673.1000e115

McCaffery, M. (1968). *N-110B Clinical Nursing: Nursing Practice Theories Related to Cognition, Bodily Pain, and Man-environment Interactions*. Regents of the University of California.

Meagher, M. W., Arnau, R. C., & Rhudy, J. L. (2001). Pain and emotion: effects of affective picture modulation. *Psychosomatic Medicine*, *63*(1), 79–90. http://doi.org/10.1097/00006842-200101000-00010

Melzack, R. (2005). Evolution of the neuromatrix theory of pain. The Prithvi Raj lecture: presented at the third world congress of world institute of pain, Barcelona 2004. *Pain Practice*, *5*(2), 85–94.

Melzack, R., & Wall, P. D. (1967). Pain mechanisms: a new theory. *Survey of Anesthesiology*, *11*(2), 89–90.

Moayedi, M., & Davis, K. D. (2012). Theories of pain: from specificity to gate control. *Journal of Neurophysiology*, *109*(1), 5–12. http://doi.org/10.1152/jn.00457.2012

Morton, D. P., & Callister, R. (2014). Exercise-related transient abdominal pain (ETAP). *Sports Medicine*, *45*(1), 23–35. http://doi.org/10.1007/s40279-014-0245-z

Morton, D. P., Richards, D., & Callister, R. (2005). Epidemiology of exercise-related transient abdominal pain at the Sydney City to Surf community run. *Journal of Science and Medicine in Sport*, *8*(2), 152–162. http://doi.org/10.1016/S1440-2440(05)80006-4

Moseley, G. L., & Butler, D. S. (2015). Fifteen years of explaining pain: The past, present, and future. *Journal of Pain*, *16*(9), 807–813. http://doi.org/10.1016/j.jpain.2015.05.005

Motl, R. W., Gliottoni, R. C., & Scott, J. A. (2007). Self-efficacy correlates with leg muscle pain during maximal and submaximal cycling exercise. *Journal of Pain*, *8*(7), 583–587. http://doi.org/10.1016/j.jpain.2007.03.002

Naugle, K. M., Naugle, K. E., Fillingim, R. B., & Riley, J. L. (2013). Isometric exercise as a test of pain modulation: effects of experimental pain test, psychological variables, and sex, *15*, 692–701. http://doi.org/10.1111/pme.12312

Nicolis, G., & Prigogine, I. (1977). Self-organization in non-equilibrium systems (Interscience, New York).

Noakes, T. D., St Clair Gibson, A., & Lambert, E. V. (2005). From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. *Br J Sports Med*, *39*(2), 120–124. http://doi.org/10.1136/bjsm.2003.010330

O'Connor, P. J., & Cook, D. B. (1999). 5 exercise and pain: the neurobiology, measurement, and laboratory study of pain in relation to exercise in humans. *Exercise and Sport Sciences Reviews*, *27*(1), 119–166.

O'Connor, P. J., & Cook, D. B. (2001). Moderate-intensity muscle pain can be produced and sustained during cycle ergometry. *Medicine & Science in Sports & Execise*, *33*(6), 1046–51. Retrieved from http://pdfs.journals.lww.com/acsm-msse/2001/06000/00026.pdf

Peters, M. L., & Crombez, G. (2007). Assessment of attention to pain using handheld computer diaries. *Pain Medicine*, *8*(s3), 110–120. http://doi.org/10.1111/j.1526-4637.2007.00375.x

Petrovic, P., Petersson, K. M., Ghatan, P. H., Stone-Elander, S., & Ingvar, M. (2000). Pain-related cerebral activation is altered by a distracting cognitive task. *Pain*, *85*(1), 19–30.

Pfaff, D. W. (2013). *Neuroscience in the 21st century: From basic to clinical. Neuroscience in the 21st Century: From Basic to Clinical.* http://doi.org/10.1007/978-1-4614-1997-6

Ploghaus, A., Becerra, L., Borras, C., & Borsook, D. (2003). Neural circuitry underlying pain modulation: expectation, hypnosis, placebo. *Trends in Cognitive Sciences*, *7*(5), 197–200. http://doi.org/http://dx.doi.org/10.1016/S1364-6613(03)00061-5

Prescott, S. A., Ma, Q., & De Koninck, Y. (2014). Normal and abnormal coding of somatosensory stimuli causing pain. *Nat Neurosci*, *17*(2), 183–191. Retrieved from http://dx.doi.org/10.1038/nn.3629

Price, D. D. (1999). Psychological mechanisms of pain and analgesia. *Hippocampus*, *19*, 893–901.

Rabinovich, M. I., Tristan, I., & Varona, P. (2015). Hierarchical nonlinear dynamics of human attention.

Neuroscience and Biobehavioral Reviews, *55*, 18–35. http://doi.org/10.1016/j.neubiorev.2015.04.001

Rabinovich, M. I., Varona, P., Tristan, I., & Afraimovich, V. S. (2014). Chunking dynamics: heteroclinics in mind. *Frontiers in Computational Neuroscience*, *8–10*, 22. http://doi.org/10.3389/fncom.2014.00022

Raja, S. N., Hoot, M. R., & Dougherty, P. M. (2011). *chapter 1 - Anatomy and physiology of somatosensory and pain processing. Essentials of Pain Medicine (Third Edition)* (Third Edit). Elsevier Inc. http://doi.org/http://dx.doi.org/10.1016/B978-1-4377-2242-0.00010-9

Razon, S., Arsal, G., Nascimento, T., Simonavice, E., Gershgoren, L., Loney, B., … Tenenbaum, G. (2010). Perceptions of exertive pain, attention allocation, and task adherence in patients with fibromyalgia using imagery. *Journal of Multidisciplinary Research*, *2*(2), 5–24.

Ruble, S. B., Hoffman, M. D., Shepanski, M. A., Valic, Z., Buckwalter, J. B., & Clifford, P. S. (2005). Thermal pain perception after aerobic exercise. *Archives of Physical Medicine and Rehabilitation*, *86*(5), 1019–1023. http://doi.org/http://dx.doi.org/10.1016/j.apmr.2004.09.024

Salomons, T. V, Johnstone, T., Backonja, M.-M., & Davidson, R. J. (2004). Perceived controllability modulates the neural response to pain. *The Journal of Neuroscience*, *24*(32), 7199–7203. http://doi.org/10.1523/JNEUROSCI.1315-04.2004

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., … Sugihara, G. (2009). Early-warning signals for critical transitions. *Nature*, *461*(7260), 53–59. http://doi.org/10.1038/nature08227

Schludermann, E., & Zubek, J. P. (1962). Effect of age on pain sensitivity. *Perceptual and Motor Skills.*

Seminowicz, D. A., & Davis, K. D. (2007). A re-examination of pain–cognition interactions: Implications for neuroimaging. *Pain*, *130*(1–2), 8–13. http://doi.org/10.1016/j.pain.2007.03.036

Sullivan, M. J. L. (2008). Toward a biopsychomotor conceptualization of pain: implications for research and intervention. *The Clinical Journal of Pain*, *24*(4), 281–290. http://doi.org/10.1097/AJP.0b013e318164bb15

Tenenbaum, G., Fogarty, G., Stewart, E., Calcagnini, N., Kirker, B., Thorne, G., & Christensen, S. (1999). Perceived discomfort in running: scale development and theoretical considerations. *Journal of Sports Sciences*, *17*(3), 183–196. http://doi.org/10.1080/026404199366082

Tracey, I. (2010). Getting the pain you expect: mechanisms of placebo, nocebo and reappraisal effects in humans. *Nat Med*, *16*(11), 1277–1283. http://doi.org/10.1038/nm.2229

Tracey, I., & Mantyh, P. W. (2007). The cerebral signature for pain perception and its modulation. *Neuron*, *55*(3), 377–391. http://doi.org/10.1016/j.neuron.2007.07.012

Van Dijk, J. F. M., Vervoort, S. C. J. M., Van Wijck, A. J. M., Kalkman, C. J., & Schuurmans, M. J. (2016). Postoperative patients' perspectives on rating pain: a qualitative study. *International Journal of Nursing Studies*, *53*, 260–269. http://doi.org/10.1016/j.ijnurstu.2015.08.007

Van Hulle, L., Van Damme, S., Spence, C., Crombez, G., & Gallace, A. (2013). Spatial attention modulates tactile change detection. *Experimental Brain Research*, *224*(2), 295–302. http://doi.org/10.1007/s00221-012-3311-5

Vancleef, L. M. G., & Peters, M. L. (2006). The interruptive effect of pain on attention. *Journal of Pain*, *7*(1), 21–22. http://doi.org/10.1016/j.jpain.2005.11.003

Vázquez, P., Hristovski, R., & Balagué, N. (2016). The Path to Exhaustion: Time-Variability Properties of Coordinative Variables during Continuous Exercise. *Frontiers in Physiology*, *7*.

Viane, I., Crombez, G., Eccleston, C., Devulder, J., & De Corte, W. (2004). Acceptance of the unpleasant reality of chronic pain: effects upon attention to pain and engagement with daily activities. *Pain*, *112*(3), 282–288. http://doi.org/10.1016/j.pain.2004.09.008

Wiech, K., Ploner, M., & Tracey, I. (2008). Neurocognitive aspects of pain perception. *Trends in Cognitive Sciences*, *12*(8), 306–313. http://doi.org/10.1016/j.tics.2008.05.005

Williams, A. C., & Craig, K. D. (2016). Updating the definition of pain. *Pain*. http://doi.org/10.1097/j.pain.0000000000000613

Yantis, S. (2008). The neural basis of selective attention: cortical sources and targets of attentional modulation. *Current Directions in Psychological Science*, *17*(2), 86–90. http://doi.org/10.1111/j.1467-8721.2008.00554.x

Yezierski, R. P. (2012). The effects of age on pain sensitivity: preclinical studies. *Pain Medicine*, *13*(2), 27–36. http://doi.org/10.1111/j.1526-4637.2011.01311.x