An Ecological Dynamics Perspective on Flow in Sport

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A thesis submitted in partial fulfilment of the requirements of Sheffield Hallam University for the degree of Doctor of Philosophy

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Dedication:

Dedicated to my wife Georgia and my whole family for their unwavering love and support, without which this thesis would not have been possible.

Candidate Declaration

I hereby declare that:

1. I have not been enrolled for another award of the University, or other academic or professional organisation, whilst undertaking my research degree.

2. None of the material contained in the thesis has been used in any other submission for an academic award.

3. I certify that this thesis is my own work. The use of all published or other sources of material consulted have been properly and fully acknowledged. I confirm that I have sought and obtained copyright permission for any third-party materials included in this thesis.

I confirm that no AI tools were used in the preparation or completion of this assessment. This submission aligns with AITS 1 of the Artificial Intelligence Transparency Scale (AITS).

4. The work undertaken towards the thesis has been conducted in accordance with the SHU Principles of Integrity in Research and the SHU Research Ethics Policy, and ethics approval has been granted for all research studies in the thesis, as shown in the table below.

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Abstract

This thesis utilises an ecological dynamics perspective to investigate the concept of flow experiences in the domain of sport. The study of flow in sport is motivated by the objective of understanding the nature of sport and the experiences which may motivate individuals to engage in it. To support these aims, the theoretical and empirical contributions of this thesis focus on the fundamental action and perception processes underlying competitive coordination to facilitate new directions for flow research. **Chapter One** provides a background for the thesis by identifying a common language for analysing the ontological nature of sports and the experiences they are capable of providing. **Chapter Two** uses the framework developed in Chapter One to query the metatheoretical foundations of the concept of flow and identify difficulties prevalent framings may create for flow research. Beginning from the alternative foundations of the ecological metatheory, **Chapter Three** develops a theoretical account of flow in sport and generates testable hypotheses about the dynamics of performance behaviour in flow activities. **Chapter Four** begins the empirical portion of the thesis by testing the hypothesis that performance behaviour in a dyadic 1v1 task would involve nonlinear cross-scale interactivity. The results of multifractal analysis and surrogate analysis identified cross-scale interactions in all trials, supporting the hypothesis of interaction-dominant dynamics. Chapter four introduces the cascade modelling strategy used throughout the thesis while also bringing a measure of anticipatory synchronisation developed in the study of chaotic systems to the behavioural sciences. **Chapter Five** utilises cascade dynamics to model a self-report measure of flow as a dependent variable, finding that the multifractal properties of both attackers and defenders were significant predictors of flow. **Chapter Six** extends the cascade modelling strategy to the level of intra- and inter-team coordination through analysis of player movements in a football match. Vector autoregressive modelling of time-variation in local Hurst exponents identified directional influences in the spread multifractal fluctuations within and across teams. **Chapter Seven** reviews the thesis and summarises its contributions to research. The thesis advances the study of flow in sport through metatheoretical analysis, theoretical development, the introduction of new methods to the field, and empirical findings.

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only hope that we will also share in many good things to come in the wonderful life we've built together.

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PhD Research Outputs

Peer-Reviewed Journal Articles and Book Chapters

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Farrokh, D. What Can Action and Perception in Sport Tell Us About Adaptive Systems? Illinois State University, Department of Psychology Colloquium Series. Normal, IL, September 2024.

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Chapter 1:

Background and Introduction: What is Sport?

1.1 Introduction

Despite its global impact, the question "what is sport?" remains difficult to answer clearly. It is unclear whether there is a definition which captures all instances of sport while excluding all other activities; neither the intensions nor extensions (i.e. inclusion criteria and complete set of valid instances, respectively) of sport have been agreed upon (McBride, 1975) and the feasibility of this task remains contested (McFee, 2004; Pisk, 2014). Evidently, this impasse in the philosophy of sport does not create immediate difficulty for athletes, coaches, and other sports practitioners as they carry on their day-to-day involvement in sports. Nevertheless, sports do continue to emerge and evolve by some set of processes regardless of our explicit understanding of them and taking an active role in shaping the longer-term future of sport may ultimately require a stronger grasp of these processes. Because this thesis addresses the concept of flow experience within the domain of sport, this introductory chapter outlines an ontology of sport at a general scientific level to provide a shared foundation for subsequent theoretical and methodological developments.

Beyond the initial difficulty defining sport, ontological accounts of sport face a second challenge: if sport can be understood from a multiplicity of domain-specific lenses, why should any one of these perspectives be privileged or considered more fundamental than another? For instance, the biomechanist may offer a movement-based account of sport, while the sport psychologist will likely begin with the psychological aspects of sport. It is not clear that either perspective can, or should, be reduced to the other. In the resulting need to relate different perspectives on sport, a tension between generality and specificity of explanations emerges. On one hand, a sporting event such as a tennis match is only one portion of a continuous flow of energy and matter and might be described in the general terms of universal natural laws. The skilful actions of the weightlifter, high jumper, or shot putter are impressive given the backdrop of gravitational

forces these athletes struggle against. Flying balls can be understood thanks to the conservation of momentum and the equations of projectile motion, rolling balls by the symmetry of the sphere, and bouncing balls by the elasticity and internal pressure of the ball (Noether, 1971). Significant changes to any of these laws of nature would render most sports unplayable or in need of sweeping revision. Natural law is clearly indispensable to any comprehensive account of sport which is, after all, a type of *physical* activity.

At some point, however, the generality of universal natural law becomes a hindrance to understanding sports. The equations of motion (Ardema, 2005; Hill, 1951) that might equally describe a meteor hurtling through space or a tennis ball speeding across a court have little to say about the significance of a match point in a championship game. Useful concepts such as tennis balls and match points are not part of the physicist's sparse "desert ontology" (Wimsatt, 1994). Psychologists and social scientists have often preferred to assume that cultural phenomena require more specific "special sciences" (Fodor, 1974, 1997) which begin their analyses in a landscape pre-populated with tennis balls, match points, and other useful concepts. Taking tennis balls, societies, and human minds and emotions for granted (i.e., positing them as *a priori* features of an ontology) enables a narrowed focus which highlights meaningful aspects of specific sporting events situated in specific times and places. That is, in addition to its proximity to natural law, sport is also undeniably a human socio-cultural phenomenon that both shapes and is shaped by its *specific* contingent contexts.

1.2 Laws and Rules

The tension between generality and specificity can be expressed more precisely as a question about the relationship between laws and rules (Pattee & Rączaszek-Leonardi, 2012; Waters, 2021). The symmetries of natural laws ensure that they apply equally at all times and places – they are universal (Weyl, 2015). Natural laws are

inexorable; they proceed without any external mechanism, and they cannot be evaded by any means (Pattee & Rączaszek-Leonardi, 2012). By contrast, rules apply to a limited range of times and places, can be broken or modified, and rely on external mechanisms for their creation and application (Waters, 2021). Much of the difficulty in developing an ontology of sport resides in adequately addressing the relation between laws and rules – universal generality and local specificity (see Shaw et al., 2019). To illustrate this relationship more concretely, consider a football player tracking the flight of a football after the goalkeeper's drop kick. The natural laws governing the ball's arcing trajectory cannot be circumvented by trickery or power of will. The ball cannot be suspended midair, and the player cannot levitate to intercept it. By contrast, the player awaiting the ball's descent may break the rules of football by handling the ball. Furthermore, the rule prohibiting handling of the ball in football is not directly determined by natural law**.** Understanding the relationship between these two factors, the roles they play in shaping sports, and the influence they exert on the behavior and experience of athletes is a central concern of this thesis.

Because natural laws are general, the philosophy of sport has largely been the study of the rules and norms which govern and thereby differentiate specific sports. The identification of a sport with its rules is referred to as *formalism* in the philosophy of sport (Suits & Hurka, 1978). Formalists propose that all sports involve goals, means, rules, and require certain attitudes of the players. A popular formalist definition of games is "a voluntary attempt to overcome unnecessary obstacles" with the added criteria that the game involves physical skill required to distinguish the subset of games which are sports (Suits & Hurka, 1978, p. 43). Critics of formalism argue that it struggles to account for rule-breaking actions as well as the influence of norms which are not encoded into the formal set of rules (D'Agostino, 1981). To address these issues, conventionalism offers a broader picture of sport which includes the official rules as well as other unwritten norms

which capture the 'spirit of the game' (D'Agostino, 1981). Finally, broad internalism or interpretivism claims that both rules and norms in sport require interpretation considering deeper principles such as respect for the game, or the pursuit of excellence (Simon, 2000). Notably, while conventionalism and interpretivism go beyond the codified rules of the sport, all three of the major philosophies of sport remain focused on rules as defined in the present context (i.e., contra natural law).

1.2.1 Rules as Constraints

The difficulty reconciling laws and rules extends beyond sport. The claim that human cognition is unique by virtue of "being governed by *rules* acting on symbolic representations" as opposed to "merely instantiating causal physical or biological *laws*" (Pylyshyn, 1980, p. 111, emphasis added) has inspired cognitive psychologists for generations. The tension between laws and rules can be traced further to the two complementary modes of description required for the scientific measurement and record of events: natural laws are written as rate-dependent, time-reversible equations governing the dynamic flows of energy and matter while the initial conditions, measurement system, and events at far slower timescales are described with an irreversible and timeless or rate-independent language called *constraints* (Pattee & Rączaszek-Leonardi, 2012; Polanyi, 1968). Constraints arise due to dynamics at different timescales or levels of organization (Umerez & Mossio, 2013). For example, when scientists observe a reaction in a test tube, they are interested in the reaction rather than the test tube itself, which is produced and decays at a different timescale of events (Polanyi, 1968). Attempting to include the initial conditions or measurement apparatus into the lawful description results in a logical regress and signifies the inevitability of both laws and constraints in any recorded description of events (Von Neumann, 1955).

Most broadly, these two forms of description appear to be a logical necessity for the evolution of heritability in self-replicating systems (Von Neumann & Burks, 1966).

One part of the system must operate slowly enough to function as a memory which guides or *constrains* a faster construction process. The classic example is the assembly of a cell, where the genetic sequence constrains the dynamic process of protein folding (Pattee, 2012a). The difference between the two timescales must be great enough that the slower process appears fixed from the timescale of the faster process. Note that this heterogeneity or contrast in rates of flow will underpin the empirical methods utilised in this thesis. Constraints result in a reduction in the degrees of freedom available to a system (Hooker, 2013; Umerez & Mossio, 2013). Polanyi (1968) describes constraints as boundary conditions which *harness* natural laws. Returning to sport, the necessity of both laws and constraints can be illustrated practically. Consider again the football player tracking the flight of a drop-kicked football, natural law enables us to understand the trajectory of the ball and the optical information laws (e.g., cancelling optical acceleration) the player may exploit to intercept it (Chapman, 1968; Zaal & Bootsma, 2011). However, these laws do not and cannot explain why football players must not control the ball with their hands. Clearly, the prohibition on handling the ball is more like a rule or constraint than a law of nature; it can be violated or changed, it applies in football games but not basketball games, and it must be upheld by some external arbitrator.

The importance of relative timescales in the differentiation of these two modes of description can be explained as follows. The player tracks the flight of the ball at a timescale of several seconds. At this fast timescale, the handball rule constraining the player's behaviour *must* function as a fixed entity. However, a deeper analysis of the evolution of football and even its more recent rule changes would reveal that this constraint has changed over time. For instance, the rules on handling the ball have been changed to consider factors such as the position of the arm, the use of the arm for support, and deflections off nearby players (The International Football Association Board, 2025). Importantly, however, this process of rule change operates at the timescale of years,

decades, and centuries – far slower than a player intercepting a ball. Scale thus becomes a central factor in the relationship between laws and constraints (Kelty-Stephen, 2024) and this thesis, by extension. Because constraints are local or scale-bound and natural laws are not, the relationship between laws and constraints has much to do with the selection of unit (see Farrokh, 2025; Kelty-Stephen et al., 2025). Because sporting events occurring at the relatively fast timescale of seconds, minutes, and hours are the most commonly analysed, the slow change of rules of sports are less often considered.

Crucially, it is these slow-changing rules or constraints which enable sports to act as self-replicating systems (Waters, 2012) which persist across time in identifiable form. While no two football matches are identical, an observer walking by a group of individuals competing to manipulate a ball with the feet and not the hands might reasonably conclude they are playing football. Broadening the timescale of observation would reveal the tell-tale branching which characterises the diversification of self-replicating systems. “Association football” is but one member of the football family which is nested within a broader class of invasion games. Branching off from association football are established sports such as futebol de salão or “futsal” as well as the green shoots of emerging sports such as teqball and sepak tekraw which combine elements of association football with table tennis and volleyball, respectively. The task constraints (Balagué et al., 2019; Newell, 1986) which shape behaviour in sports can be manipulated, altered, and combined in an endless number of ways.

Given this central role of rules and other constraints in the shaping of sporting behaviour, it is reasonable to ask what else might be left to analyse in an ontology of sport. Here, the constraint concept reveals considerable nuance beneath its deceptively simple surface. In fact, the primary metatheories of psychological or cognitive sciences can all be interpreted as different perspectives on the relationship between constraints and natural laws (Farrokh, 2025; Kelty-Stephen, 2024). These different understandings of

constraints motivate different ontologies of sport and have entailments which can be tested empirically. While different aspects of sport (e.g., skill acquisition, coaching practice, performance analysis) have been considered from these metatheoretical viewpoints (Davids et al., 1994), they are scarcely mentioned in philosophical discussions of the fundamental nature of sport. For instance, Suits and Hurka's (1978) specification that sports must involve *physical* skill can be interpreted in multiple ways, based on one's metatheoretical understanding of the relationship between laws and constraints.

1.3 Metatheoretical foundations

Underpinning the present work is the idea that constraints do not possess meaning independently but acquire it progressively, based their history of interaction with lawful, dynamic flows of energy and matter (Pattee, 2012b; Pattee & Rączaszek-Leonardi, 2012; Rączaszek-Leonardi, 2012). This proposition bears close resemblance to the naturalistic philosophy of pragmatism which seeks to situate the meaning of constraints like language, rules, and norms, within the context of their impact on everyday behaviour (Austin, 1975; Dewey, 1929; Gibson, 2014; James, 1890; Peirce, 1955). The pragmatic emphasis on the continual flow of dynamic processes can be contrasted with a long tradition stretching at least back to Plato in which constraints are considered independently of any dynamical context and, thus, become timeless symbolic abstractions putatively accessed through mental representation. More recently, the attempt to separate constraints from laws has been expressed in the computational theory of mind which seeks to identify cognition with purely formal processes (Fodor, 1980; Pylyshyn, 1980). The strand of pragmatic theorising which most clearly motivates the present work is the ecological approach, developed by James Gibson during the study of visual perception (Gibson, 1966, 2014). The contemporary synthesis of the ecological approach to psychology and nonlinear dynamical systems (Kelso, 1995) theory which has been termed "ecological dynamics" (Araújo et al., 2006; Davids et al., 1994) provides the

guiding rationale for this thesis. While this framework has already supported robust theoretical and empirical analysis of skilful behaviour in sports and other contexts (Araújo et al., 2025), the following sections apply its logic to the foundations of sport.

The claim that constraints become meaningful only when they shape dynamic flows affords immediate application to the ontology of sport. Just as traffic signs can direct existing flows of traffic but not generate them, the rules of a sport require participating athletes. More concretely, *a rule enforcing participation in a sport is nonsensical and circular because only those who have already agreed to participate in the sport abide by its rules.* As such, the identification of a sport exclusively with its rules ignores the complementary role of dynamics by taking the existence of willing participants for granted. Furthermore, if the rules of a specific sport were to be erased or destroyed, the lawful dynamics governing movement would continue under other constraint regimes. But if the dynamic flow of participation ceases, the rules of the sport become meaningless. This asymmetry may go unnoticed in the analysis of mature global sports with large, stable followings, but it precludes any analysis of the processes by which sports first emerge, develop, and flourish. Because all sports must emerge at some point in history and go through a subsequent growth process, a comprehensive ontology of sport cannot be limited to the analysis of mature or established sports. At least some portion of inquiry must study the processes by which sports emerge and sustain themselves. Although established sports can be shaped by the interests of economic stakeholders, generate large spectator audiences, and even become significant cultural forces, these factors only apply to the subset of sports that attain a certain type of popularity. A thorough analysis of the entire lifecycle of a sport can be supported by applying scholarship on the relationship between constraints and dynamics in other domains to sports.

1.4 The selection of replicable constraints

Previous scholarship on constraint selection in the development of language (Rączaszek-Leonardi, 2012) reveals three properties of constraints which can be usefully applied to the ontology of sport.

1.4.1 Physical Embodiment

While the laws of nature are incorporeal, even the most complicated rules must have some physical instantiation (Pattee, 1973). Physical embodiment allows constraints to make non-mysterious causal contact with the dynamics they constrain (Rączaszek-Leonardi, 2012). The rules of a sport may be written, spoken, or observed but they must exist in a physical form to act as constraints which reduce degrees of freedom and thus shape behaviour.

1.4.2 Replicability

For a sport to persist across time, its constraints must be replicable. Replication may occur through processes such as demonstration and observation, verbalisation, pictorial representation, and symbolic codification. Individuals may devise activities *ad hoc* (as children often do) with no intention of replicating the activity in the future, but without replication the activities do not become sports. Notably, replication applies not only to the rules of the sport but also other constraints such as the equipment, playing area or surface, and any other necessary apparatus. For instance, some Winter sports may be limited to replication within regions with sufficient snow or ice. Replicability is, thus, an important requirement for constraints selected in the evolution of a sport.

1.4.3 Selection

Most importantly to the present work, the reproduction and evolution of every sport involve a process of constraint selection. It is claimed that analysis of this constraint selection process has the potential to provide insight into the ontological core of both

sports, generally, and individual sports, specifically. The selection of replicable constraints is evidenced by the fact that, while the constraints of any sport can be modified to various degrees, some constraint ecologies are regularly selected (e.g., common sports) and others are not (e.g., “dead” or “extinct” sports). Additionally, the constraints of any given sport can be shown to evolve over time. In what follows, the primary subject of this thesis will be introduced in the context of influences on constraint selection in the development of a sport.

1.5 Experience and motivation in the selection of replicable constraints

As mentioned previously, rule- or norm-based theories of sport have sometimes recognised the fact that sports require a certain attitude of the players (Suits & Hurka, 1978). Conceptualising these rules as constraints which depend on dynamics for their meaning raises additional questions about this important aspect of sporting behaviour. Consider the beginning of a sporting match. Typically, the referee will give some indication that the game is underway. For example, an ice hockey referee may drop the puck in the game’s opening face-off. However, nothing in the rules of ice hockey commands the players to attempt to win the puck. Both players and teams act legally when they allow the ball the puck drop to the ice and proceed to skate aimlessly around the rink. Of course, this total lack of goal-oriented competitive action is rarely seen in sport. Legal but apathetic actions such as sitting down or standing still on the playing area might rightly be interpreted as some form of protest or indication of a larger issue with the competitive context—an exception that proves the rule of competitive engagement. For example, the rules governing the opening tip-off in basketball refer to the two players competing for the tossed ball as “jumpers” without explicitly requiring the players to jump (National Basketball Association, 2025). Jumping is simply expected to emerge from the competitive interaction. Just as the rules of a sport are unable to command individuals to

participate in the sport, they are also unable to prescribe the basic form of effort or competitive engagement that is typically exhibited in sports at all levels of competition.

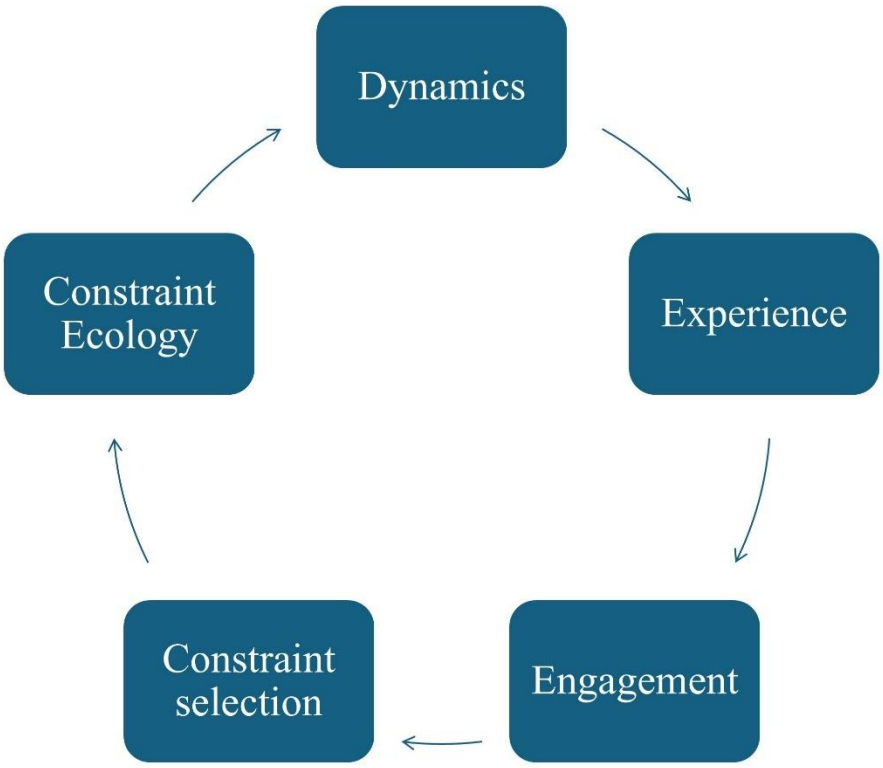
It may be tempting to attribute this competitive tension to the broader norms, conventions, or underlying principles of the sport, but this merely avoids the question by conflating an outcome (competitive engagement) attained by *some* sports with the process by which it is achieved. Considering the early part of a sport's lifecycle is, again, helpful. Proposing a novel sport would require an appropriate number of initial participants to provide a degree of initial willingness to try out the sport but their longer-term attitude towards participation will likely depend on their appraisal of the experience, among other factors. It is possible that the newly proposed sport may gain popular appeal and wide participation, but more likely the players will eventually abandon the game and fail to ever develop the type of tautly poised competitive tension we expect at the face-off of an ice-hockey game, tip-off of a basketball game, or starting gun of a race. So, while competitive engagement is an expectation within the norms of any established sport, this expectation must rely on some more fundamental process since only certain constraint ecologies achieve association with widespread competitive engagement. By way of analogy, water wheels might connote rotation, but rotation is not a property which can be predicated to water wheels alone. Rather, it is the fact that water wheels are typically positioned within a continuous flow of water that enables them to rotate. Likewise, competitive engagement is not a property of rules or norms alone.

For a set of constraints to become a recognised sport, it must be pruned and refined in a manner which allows dynamic flows of participation to continue coursing through it with optimal intensity (see Figure 1.1). In other words, if constraints acquire meaning through their application to dynamics, *ontological analyses of sport must ask what is selected for during constraint selection*. As sports mature, they acquire additional layers of influence on this selection process. For instance, the governing body of a popular

spectator sport may lengthen pauses in play to increase revenue from television advertisements. These outer layers must be peeled back, though not ignored, if the core process by which the sport ever became a televised affair is to be uncovered. Long before entertainment value or revenue can become factors in constraint selection, the sport must attract a stable flow of participants. Emerging sports have few external pressures on their constraint selection, but they also have few external rewards to offer. Potential motivating factors or rewards also accumulate as a sport matures. The potential of status or wealth might motivate participation in a mature sport, but they are unlikely rewards during the sport's early years.

Figure 1.1.

Depiction of the constraint selection process in the formation of a sport.



Without traditional rewards to motivate participation, experience becomes a primary influence on the constraint selection process early in the formation of a sport.

Grasping the ontological core of a sport, therefore, requires understanding the experiences its players and rule-makers have pursued. Put simply, emerging sports must strive to be "autotelic" or self-rewarding activities (Csikszentmihalyi, 1975) if they are to reliably attract eager participants and grow to maturity. This formulation does not specify exactly which experiences might motivate individuals to participate in a sport, only that those experiences which do entice individuals to participate must be selected if the sport is to develop and retain competitive engagement. For example, after the 1992 European Championships, the rules of football were adapted to prohibit the goalkeeper from picking up an intentional pass from their own teammate (The International Football Association Board, 2025). Explaining why this slightly different set of constraints was selected requires reference to the *experience* of playing the game. Without the back-pass rule, teams in the lead were able to repeatedly pass the ball back to the goalkeeper who could pick the ball up. In common language, the legality of this sequence of events threatened to "kill the game" by making it dull and predictable for players and spectators alike. Similarly, basketball introduced a shot clock to keep teams from stalling indefinitely. In both cases, the constraints of each sport were selectively adapted to avoid a certain type of stale experience which threatens to reduce participation over time if not rectified.

1.6 Thesis outline

The questions which arise from analysis of this constraint selection process are those which this thesis attempts to address. Namely, how do different laws-constraints relationships proposed by different metatheories support or hinder understanding of experience in sporting contexts? How does the experience of a performer relate to their ability to coordinate with a performance environment? Because the experience of dexterity or fluid, adaptive coordination with a performance environment overlaps significantly with previous scholarship on the concept of *flow* - an enjoyable form of absorption in a task at hand (Csikszentmihalyi, 1975, 1990) - the present work is framed

as an ecological dynamics perspective on flow in sport. Analysis of prevalent metatheoretical framing of the concept of flow and review of the current state of flow research suggested the need to consider different understandings of the fundamental action and perception processes underlying skilful performance behaviour. Following from this analysis, the primary objective of the empirical portion of this thesis is to test hypotheses motivated by the (meta)theoretical reconceptualisation in the context of a dyadic competitive coordination task and utilise empirical findings to develop new empirical markers of flow. Notably, a significant portion of the empirical research presented in this thesis aims at foundational questions in the study of competitive coordination in order to lay the groundwork for future empirical research on flow in sport.

Therefore, the aims of the thesis can be summarised in the following objectives:

Objective 1: Develop an ontology of sport through analysis of the constraint selection process (Chapter One).

Objective 2: Explain how different laws-constraints relationships proposed by different metatheories support or hinder understanding of experience in sporting contexts (Chapter Two).

Objective 3: Reconceptualise flow within the ecological metatheory (Chapter Three).

Objective 4: Test the key ecological hypothesis of interaction-dominant dynamics in a competitive coordination task (Chapter Four).

Objective 5: Utilise multiscale dynamics to model and explain flow experiences in a competitive coordination task (Chapter Five).

Objective 6: Utilise network modelling techniques to examine the spread of multiscale dynamics in group coordination (Chapter Six).

A more detailed summary of each chapters and the research questions utilised to address these objectives (See Figure 1.2) is provided in the following.

Following this introductory chapter, the second chapter explores the emergence of the concept of flow during the study of intrinsically engaging or motivating activities (see Figure 1.2). Because the concept of flow is recognised to be in a state of crisis (Swann et al., 2018), a thorough analysis of the metatheoretical foundations which have underpinned its formulation and subsequent study are deemed to be necessary. As such, the second chapter identifies metatheoretical stances which remain prevalent across multiple domains of flow research while outlining the limitations these foundations might create for explanations of flow. This chapter suggests that the protracted difficulty in the scientific explanation of flow suggests two alternative possibilities: flow is either a fundamentally flawed concept or an "anomalous finding" that does not fit well within the metatheories it has, thus far, been framed within.

Figure 1.2.

Representation of the plan for the thesis with the title and research questions of each chapter.

Thesis Plan

Chapter 1

Background and introduction: What is Sport?

- **Research Question (RQ) 1.1** What ontological framing of sport best supports analysis of experience in sport?
- **RQ 1.2** What characterises the experiences selected for in the formation of sports?

Chapter 2

Why Isn't Flow Flowing? Metatheoretical Issues in Explanations of Flow

- **RQ 2.1** How did the concept of flow emerge during the study of intrinsically engaging activities?
- **RQ 2.2** Why has the scientific study of flow experiences faced such difficulty?
- **RQ 2.3** Is the concept of flow well framed by prevalent psychological metatheories?

Chapter 3

Towards an Ecological Dynamics Theory of Flow in Sport

- **RQ 3.1** How does the ecological metatheory reconceptualise flow?
- **RQ 3.2** How do constraints and dynamics relate in the shaping of flow experiences in sport?
- **RQ 3.3** What empirical hypotheses are motivated by an ecological dynamics theory of flow in sport and which methods are best suited to testing them?

Chapter 4

Multifractality in Antagonistic Couplings: Cross-Scale Interactions in 1v1 Futsal Dyads

- **RQ 4.1** Are competitive interactions characterised by component-dominant or interaction-dominant dynamics?
- **RQ 4.2** What constraints would evidence of interaction-dominant dynamics place on psychological explanations of competitive coordination?
- **RQ 4.3** What eco-physical variables might be used to study flow in 1v1 dyads?
- **RQ 4.4** What is the logical structure of competitive coordination?

Chapter 5

The Multiscale Dynamics of Flow in Competition

- **RQ 5.1** Can multiscale dynamics methods (e.g., cascade modelling) support an explanation of flow in competition?
- **RQ 5.2** How might cascade models inform the selection of constraints to enhance flow in sports?

Chapter 6

Group Tensegrity and Group Flow: Network Modelling of Local Hurst Exponents

- **RQ 6.1** Can the multiscale dynamics methods applied in dyads be extended to groups?
- **RQ 6.2** Do multifractal fluctuations spread interpersonally during cooperative and competitive coordination

Chapter 7

Epilogue

- Review of the thesis
- Summary of contributions

The third chapter asks which aspects of flow require reconceptualisation within the alternative framing of the ecological metatheory. The ecological dynamics framework is used to reconsider fundamental aspects of flow such as experience, skill, information, intention, attention, temporality, and adaptivity and develop an ecological dynamics theory of flow in sport. This theory of flow in sport builds on the ideas presented in this introductory chapter to investigate the relationship between the dynamical laws governing flows of energy and matter and the rule-like constraints that are selected to shape these dynamics in the formation of sports and other potential flow activities. An important hypothesis that arises from this theory is the prediction that interaction-dominant dynamics will be prevalent in sports performance. The quantitative methods this approach suggests for the study of flow are briefly introduced and contrasted with previously utilised methods.

Chapter four introduces the empirical methods (i.e., cascade modelling techniques such as multifractal analysis and surrogate analysis) in the context of one-v.-one futsal task. The implications of component-dominant and interaction-dominant dynamics for psychological explanations of sporting performance and the ability of the proposed methods to distinguish between them are reviewed. In this study, attacker score is modelled as a dependent variable to assess the contribution of cross-scale interactions to competitive coordination and identify eco-physical variables which might be used to understand the emergence of flow experiences in this task. A measure of anticipating synchronisation originally proposed in the field of chaotic systems (Senthilkumar & Lakshmanan, 2007) is also introduced to the behavioural sciences. The findings of this study are discussed within the broad context of the processes which might support the adaptivity of evolved organisms in competitive interactions and include a set-theoretic analysis of the logical structure of competitive coordination.

Chapter five utilises the insights gained from the analyses of chapter four to develop an explanation of flow experiences in the same one-v.-one task. A self-reported measure of flow is modelled as a dependent variable to demonstrate the potential of previously identified eco-physical variables and cascade dynamics to predict flow experiences. New insights into the manner in which the nonlinear release and constraints of degrees of freedom (Kelty-Stephen & Farrokh, 2025) impact flow experience in skilled performance are provided through analysis of cascade dynamics. Because cascade models simultaneously encode both dynamic flows and the constraints that shape them, the relationship between observable dynamics, manipulable constraints, and flow experiences is clarified.

Chapter six looks ahead to explore what possibilities for further research are created by the theoretical and empirical work of the thesis. Because the task analysed in chapters four and five is dyadic in nature, the potential of extending multiscale dynamics methods to the study of flow in larger groups of competing or cooperating athletes is a central concern. The multiscale methods are discussed in the context of the emerging group tensegrity hypothesis (Caldeira et al., 2021) and new directions are proposed. Network modelling of time-variation of local Hurst exponents across the body has revealed important markers of health and adaptivity in clinical movement science (Mangalam, Carver et al., 2020a) and a demonstration of how this method can be extended to competing and cooperating groups or teams. This analysis further investigates the processes which are proposed to support action and perception in flow and supports future research on the study of flow in team sports. Finally, chapter seven reviews the entirety of the thesis and summarises its contributions to research.

Chapter 2:

Why Isn't Flow Flowing? Metatheoretical Issues in Explanations of Flow

This chapter is adapted from: Farrokh, D., Stone, J. A., Davids, K., Strafford, B. W., & Rumbold, J. L. (2024). Why isn't flow flowing? Metatheoretical issues in explanations of flow. *Theory & Psychology*, *34*(2), 257-276. doi.org/10.1177/09593543241237492

2.1 Introduction

The concept of flow was first proposed by Csikszentmihalyi, (1975) after initial research into activities that were experienced as intrinsically rewarding (autotelic). Flow is defined as an "enjoyable experience of full absorption in an activity in which the demands are perceived as optimally compatible with one's skills" (Peifer & Engeser, 2021a, p. 424). Flow has been an important concept in the positive psychology movement (Csikszentmihalyi, 2000) and is widely recognised as a desirable state due to its association with positive emotional and psychological outcomes (e.g., well-being, personal growth, clear focus, heightened control) across the lifespan (Freire et al., 2021). Traditionally, flow has been considered a multidimensional construct comprising three antecedents and six characteristics (Csikszentmihalyi, 1990). A balance between skills and challenges, clear goals, and unambiguous feedback are considered important pre-conditions of flow whilst distortion of time, merging of action and awareness, concentration on the task at hand, loss of self-consciousness, autotelic experience, and sense of control are characteristics of the experience itself (Csikszentmihalyi, 1990).

In the decades following Csikszentmihalyi's (1975) initial work, flow grew into a globally recognised concept (Csikszentmihalyi, 2021). More recently, however, progress in understanding flow has stalled due to perceived limitations of current prevailing theorising (for a review, see Alameda et al., 2021; Goddard et al., 2021). As these issues are well-documented and generally acknowledged in flow research spanning different fields of psychology (Peifer et al., 2022; Swann et al., 2018), this chapter does not seek to provide a comprehensive review of the history of, or current issues in, the field at the *theoretical* level. Rather, the arguments are focused on the contention that traditional *metatheoretical* commitments and assumptions may exert a limiting effect on flow researchers' attempts to explain flow in many different domains. This chapter illustrates how ontological and epistemological positions that may restrict understanding of flow

remain pervasively assumed, even as researchers studying flow have sought to address potential shortcomings in the field. First, the motives and context surrounding Csikszentmihalyi's original work are examined and then metatheoretical issues in the explanation of flow are considered. To facilitate development of the field, an alternative metatheoretical framework for flow research is proposed, highlighting ways in which new concepts of measurement and explanation underpinned by this framework may enrich understanding of flow.

2.2 Desiderata for an Explanation of Flow: Ontological and Epistemological Considerations

Swann et al. (2018) argued that, due to its descriptive nature, Csikszentmihalyi's original work on flow is best characterised as a model rather than a theory. Swann et al. (2018) emphasised that explanation is the core of a good theory and reiterated the need to understand the causal mechanisms of flow and generate testable predictions. Similarly, outstanding questions about the antecedents of flow (Peifer et al., 2022) highlight the role of causality in explaining flow. While understanding the causes of flow is an important objective, there are several key issues that require attention before causality can be meaningfully discussed.

The protracted difficulty explaining how and why flow experiences emerge suggests that not only theoretical, but also *metatheoretical* re-consideration may be essential to progress in understanding. Scientific research programmes operate within nested conceptual frameworks in which *metatheory* defines the ontological and epistemological contexts within which theories are constructed (Juarrero, 2023; Molenaar et al., 2014). When considered as an integrated whole, these nested structures comprise a paradigm (Kuhn, 1997). Importantly, different metatheories may utilise different conceptualisations of causality and, consequently, endorse different forms of explanation (Stepp et al., 2011). The metatheory that a theory of flow has been developed within

determines the responses to ontological and epistemological questions about what experiences such as flow *are*, and how they can be *understood*. For example, the assertion that flow is a subjective state reflects metatheoretical commitments (of the prevailing conceptualisation in cognitive psychology) which influence empirical methods (e.g., emphasising verbal reports of subjective experience, identifying putative neural correlates of subjective experience) used to study flow.

There may be two key issues that implicate metatheoretical challenges in current explanations of flow. First, a major concern is that traditional psychological theorising, emphasising the role of mediating internal states in understanding behaviour and experiences, has developed an *organismic asymmetry* in its explanatory rationale, a bias which has neglected the importance of understanding the person-environment coupling (Dunwoody, 2006). A relevant causal explanation of human behaviour or experience requires an understanding of the relationship between insights at many different scales of analysis including sociological, developmental, behavioural, and neural (Turvey, 2018). Any conceptualisation of the relationship between these scales reflects ontological and epistemological stances and determines the *causal entailment* (strict logical implication) structures utilised in explanations of a phenomenon. Theories developed at one scale may provide an explanatory conceptualisation that may be difficult to interpret at another scale of analysis without re-consideration of the metatheoretical framework for understanding the relationships between events observed at different scales (Kelso, 1995).

Second, the relationship between flow experiences and physical events, such as the actions of the performer, needs to be better understood. The relationship between psychological and (neuro)physiological theories of flow is of particular importance since integration has so far been viewed as problematic (Alameda et al., 2022). Any proposed relationship between these psychological and neurophysiological forms of analysis unavoidably implicates metatheoretical positions about the nature of mind and body, and

relations between. Summarily, for causes of flow to be explained, the ontological status of the experience, the temporal and spatial scales of events relevant to it, and the relationship between these scales must be better understood. An examination of metatheoretical frameworks that have explicitly or implicitly guided theories of flow, and an analysis of their suitability is, therefore, critical for the progression of research. In the following section the historical context of flow is over-viewed, and some constraints that may have been imposed on its metatheoretical framing are examined.

2.3 The Origins of Flow

While flow has become a relatively well-known concept, the events surrounding and leading to its development are less commonly discussed. Examining this additional context may help to situate Csikszentmihalyi's original ideas and inform discussion of the present and future of flow. Csikszentmihalyi's early life was profoundly influenced by war, the loss of his brother, and the relocation of his family (Csikszentmihalyi & Lebuda, 2017). These hardships provided the motivation for Csikszentmihalyi's life work in psychology:

> I don't think anyone was happy with this way, with all the killing. People had to start again with nothing. It was such a wasteful and horrible way of living; on the other hand, humans could do all the other wonderful things. So that was the basis for my attitude towards knowledge, towards learning, it was to learn somehow to make life better. (Csikszentmihalyi & Lebuda, 2017, p. 813)

As such, Csikszentmihalyi's (1975) early work engaged with sociology and philosophy to analyse the meaningful activities that underpinned functioning societies. Csikszentmihalyi was attracted to the intersection of three areas of psychology: intrinsic motivation, play, and peak experience, but these areas had always been considered independently (Csikszentmihalyi, 1975). The concept of flow emerged from interviews

that explored participants' experiences (e.g., surgeons, artists, athletes) in activities that required significant investment of energy and skills but provided few traditional or extrinsic rewards as outcomes (Csikszentmihalyi, 1975).

A central theme of this early work was dissatisfaction with prevalent meta-narratives that claimed that motivations for human behavior could be exhaustively explained by extrinsic factors such as power, money, pleasure, or approval. Rather, the title of Csikszentmihalyi's (1975) first book, *Beyond Boredom and Anxiety*, is suggested by some to be a subtle response to prominent behaviourist B.F. Skinner's (1971) book, *Beyond Freedom and Dignity* (Engeser et al., 2021). Csikszentmihalyi (1975) observed that people were not only willing to forego extrinsic rewards to participate in certain activities, but experienced these activities as deeply, intrinsically rewarding. The metatheoretical landscape of psychology at the time of flow's inception, therefore, exerted a significant influence on the way flow was framed. The need to respond to external and deterministic paradigms in psychology may have contributed to the internal and subjective ontological framing of flow experiences.

2.4 Explanations of Flow

Commencing academic training in the heyday of behaviourism in psychology, Csikszentmihalyi was dissatisfied that "inner experience ha[d] been exiled to a scientific no-man's-land" (1975 p. x). Instead, Csikszentmihalyi chose a method that would prioritise the first-person experience of participants. As such, he turned to a phenomenology underpinned by principles of information (processing) theory to inform his explanation of flow (Csikszentmihalyi, 1990). Consciousness was construed as residing in an internal representation of the world, which is constrained by humans' limited capacity to process information. Csikszentmihalyi (1990) asserted that "a mental event can be best understood if we look at it directly as it was experienced", while

conceding that “it is understood that whatever happens in the mind is the result of electrochemical changes in the central nervous system” (p. 26).

Csikszentmihalyi (1990) expressed concern about overly mechanistic explanations of flow and preferred first-person reports. Although different research traditions have different understandings of retrospective and descriptive forms of data collection, a causal explanation of flow would likely benefit from additional methods that collect data *during* flow activities (Peifer & Tan, 2021). Given Csikszentmihalyi’s (1990) original assertion that flow occurs in the optimal internal processing of information, the prevailing assumption has been that the mental processes or ‘cognitive mechanisms’ underlying flow experiences must be identified and correlated with neural or physiological processes occurring inside the performer (e.g., Dietrich, 2004).

While many different psychological and neural theories of flow have been proposed, the assumed conceptualisation of mental and neuropsychological processes defines the metatheory adopted. For example, early attempts focused on the subjective experience of “effortless attention” in flow, proposed implicit processing and automaticity of skills as underpinning cognitive mechanisms, and linked to neural processes such as transient hypofrontality (Dietrich, 2004). Although both the effortlessness of attention and transient hypofrontality have been called into question (Harris et al., 2017), these criticisms have tended to emerge within the same cognitive metatheoretical framework and the assumed relationships between mind, body, and experience, and the form of explanation pursued have rarely been challenged. Just as concerningly, despite the proposition of numerous neural theories of flow (Gold & Ciorciari, 2021; Huskey et al., 2018), a recent review summarised that “evidence is sparse and inconclusive, with major methodological shortcomings that prevent us from drawing solid conclusions” (Alameda et al., 2022, p. 358). Alameda et al. (2022) questioned “whether we are indeed ready to identify and quantify reliable neural correlates of the flow state” (p. 360).

Considering these criticisms, it is worth examining the nature of the cognitive processes that neural theories of flow have purported to ground in physiological processes (Sullivan, 2016). While different theories have been proposed (e.g., Peifer & Tan, 2021; Swann et al., 2015), a number of component processes are typically arranged in a chain-like sequence. For example, the integrated model proposes that flow in sport occurs "through a positive event, which leads to positive feedback and increased confidence, which in turn results in a challenge appraisal and the setting of open goals—the pursuit of which leads to the experience of flow" (Swann et al., 2021, p. 54). Neural theorists of flow (e.g., Dietrich, 2004; Harris et al., 2017) then attempt to identify the neural processes responsible for cognitive processes such as the cognitive appraisal of a task, or the setting of goals. The following section demonstrates the influence of the cognitive metatheory on this explanatory strategy.

2.5 Origins of Cognitive Psychology

While it is often assumed that scientific psychology emerged relatively recently, some have traced the foundations of modern cognitive psychology much farther back in history. For example, Edward Reed (1982) located the roots of mainstream cognitive psychology in the Cartesian hypothesis of corporeal ideas – that all awareness is awareness of brain states (dating back to the first half of the 17th century). This hypothesis is corollary to the idea that sense data is impoverished and must be enriched via some mediating process *within* the nervous system before perceptual experience is arrived at. The key outcome of this hypothesis is that perception of the world becomes a three-term relationship in which organisms only experience some internal process that mediates between perception and actions in the world (Turvey, 2018).

In the twentieth century, after World War II, the development of information theory (Shannon, 1948) allowed the relationship between signals in input and output channels to be precisely understood, providing a key breakthrough in the development of

computers. The Cartesian hypothesis that mind and matter intersected in the brain (Reed, 1982) was combined with information theory to underpin computational models of mental processes mediating between putative input (sensory systems) and output (action systems) channels as the cognitive metatheoretical framework approached its current form. The ontological commitment to defining cognition as symbolic operations performed on mental representations defines the *metatheoretical framework* of the cognitive paradigm in psychology.

The cognitive metatheory is exemplified by Newell's (1980) physical symbol system hypothesis in which symbol manipulation performed by algorithms of computers is used as a theory-constitutive metaphor for cognition. The physical symbol system hypothesis is built on the assumption that cognitive systems are *nearly decomposable*, or that the timescale at which a putative mental process operates can be considered independently (Simon, 1977). The importance of separation between timescales must be emphasised since it is central to common forms of explanation that assume cognitive abilities arise from stable components that make distinct, independent contributions to a behavioural outcome (Van Orden & Holden, 2002; Wallot & Kelty-Stephen, 2018). For example, the assumption of near decomposability is reflected in the common models of processing stages in response times (e.g., Sternberg, 1969) because the interval between stimulus and response is considered to function independently of the longer timescales it is embedded within (Van Orden et al., 2003). Notably, both theorists of sport and flow have generally preferred this cognitive metatheoretical strategy of analysing scale-dependent rules to the exclusion of dynamical laws which flow across many scales.

The preference for linear causal chains (efficient cause) as an explanatory form within the cognitive metatheoretical framework has important implications. Only *predicative entailments,* which refer to causes flowing upward from parts to wholes, are considered. *Impredicative entailments* that involve closed loops between parts and wholes

are discouraged because they confound chain-like explanations (Chemero & Turvey, 2007). Hence, observations at the scale of the performer must be explained with reference to smaller scales of analysis, such as neurophysiology. Practically, these commitments have motivated 'box and arrow' models of cognitive processes purportedly corresponding to system components, modelled as networks in the brain. With these assumptions in place, causal mechanisms are typically sought in subcomponents of the individual performer's body and within an isolated temporal window. The activity of the nervous system *during* a flow activity is, therefore, assumed to underpin cognitive processes that result in the experience of flow. Notably, this form of explanation reflects the epistemological and ontological stances of the cognitive metatheory and accepts only certain types of (i.e., linear, efficient) causality. As will be discussed in section 2.8, there may be good reason to believe additional forms of causality are operative in flow. It is worth stressing, therefore, that calls for causal mechanisms (e.g., Swann et al., 2018) of flow are underspecified and implicate metatheoretical commitments that must be examined.

Csikszentmihalyi (1990) made his commitment to the cognitive metatheory explicit in his endorsement of information-theoretic analyses of mental processes. More broadly, the claim that flow experiences are necessarily subjective, internal, and representational in nature would need to be overturned for any explanation of flow to depart from the cognitive metatheory. Given the challenges in explaining flow within cognitive psychology, concepts such as the nine-dimension model and the four-quadrant model have come into question (Swann et al., 2017). The conservation of the cognitive metatheory is evident, however, in the continued assumption that one must look *inside* the individual to observe the causes of flow. In conclusion, the deep roots of the cognitive metatheory have shaped both the conceptualisation and study of flow across many different subdomains of psychology (for notable exceptions see Montull et al., 2020;

Vervaeke et al., 2018). The following section delves more deeply into points at which the relationship between flow and the cognitive metatheory becomes strained, implying the need for more research within alternative conceptual frameworks.

2.6 Limitations and Anomalous Findings

While Csikszentmihalyi's (1990) formal explanation located the source of flow experiences inside the individual, there are several key points of tension with the cognitive metatheory. For example, it has been claimed (e.g., Nakamura & Csikszentmihalyi, 2014) that dynamic interactions should be emphasised rather than decontextualised traits of the individual. It is also understood that flow does not exist independently in either individuals or activities but arises when *concrete feedback* provides intrinsic motivation and supports a continuous stream of action (Csikszentmihalyi, 1975). This ideation of feedback is expanded upon in claims that an essential feature of flow activities is the sustained merging of action and awareness that occurs when action 'resonates' with the performance environment (Csikszentmihalyi & Bennett, 1971). Additionally, although Csikszentmihalyi's version of phenomenology referred to an internal mirror of the world, other flow researchers have pursued phenomenological interpretations of flow which centre the performer-context relationship. For example, Jackman et al., (2022) highlighted the importance of performers' interactions with performance environments for understanding spatial, temporal, and social aspects of flow experiences. Jackman et al. (2023) also drew attention to phenomenological accounts of the mind-body-world relationship in flow.

These recognitions of performer-environment interactions in flow raise important questions about the process by which action and perception are related to the environment via *concrete feedback* (i.e., information for action) and suggest that constraints and dynamics of flow be investigated simultaneously. Because flow describes experience in *skilled* performance, precise spatiotemporal relations with the performance environment

are necessitated. For example, athletes must often move with temporal and spatial precision if they are to intercept a flying ball. It is possible that the prevalent cognitive framing of flow through internal states has limited further exploration of these questions, which might benefit from forms of explanation provided by the ecological metatheory (see section 2.10). Rather than exploring what form of coupling between the performer and the environment would support adaptive movements in flow, Csikszentmihalyi's metatheoretical commitments lead back to a series of *internal* processes thought to regulate consciousness (Nakamura & Csikszentmihalyi, 2014), with the relationship between the performer and performance environment remaining unexplored in many prominent theories of flow.

The recognition that behaviours must relate unambiguously to a performance environment presents a major obstacle to *all* explanations of flow situated within the cognitive metatheory. Theories that conceptualise flow experience as an internal representation of the world, such as Csikszentmihalyi's claim that consciousness is a mirror that imposes "a reality of its own" (1990, p. 26), preclude understanding of unambiguous relations with an external performance environment (Turvey, 2018). Notably, even if the physical correlates of a subjective experience were identified, no information about an individual's relation to a performance environment would be provided since a subjective experience is not reliably related to actual states of affairs (Michaels & Carello, 1981). This is highly problematic because in many flow activities (e.g., rock climbing, gymnastics, surfing) not only the performance, but also the safety of the performer, requires an unambiguous relationship with the environment.

A striking example is provided in Kotler et al.'s (2022) account of the neurobiology of the onset of flow which utilises a fictional scenario involving a motorcycle rider who must swerve to avoid a collision on the highway. While a sequence of events at the neural scale is described in great detail, when it comes to the relationship

between these neural processes and the environmental context (i.e., rapidly approaching obstacles), the authors state that "the relationship between these two categories of context is not completely understood" (p. 10), although it is recognised that this context must play a role in some manner. This ambiguity is quite surprising since a rider travelling at such high speeds must maintain a very precise spatiotemporal relationship with the environment if grave danger is to be avoided. Since the *consequences* for the performer exist at this level of performer-environment relations, it is reasonable to propose that the *meaning* of the activity for the performer may exist at this scale. The next section will discuss the ontological status of experience in flow states.

2.7 The Content of Flow Experiences

If flow refers to some subset of experiences, it must also be asked what these experiences refer to. In other words, what are experiences called 'flow' experiences *of*? More broadly, the question concerns the ontological status of experience. In the cognitive metatheory, the influence of Descartes' hypothesis of corporeal ideas leads to the conclusion that experience refers to internal (e.g., neural) states of the performer (see Csikszentmihalyi's endorsement of this relationship in section 2.4). However, consider again the motorcycle rider who has been cut off by another vehicle while traveling at a high speed. It would seem highly implausible that the content of the rider's experience cannot refer to the scale at which the consequences for the rider exist. These consequences cannot be found exclusively in the internal or neural states of the rider, or the objective (context-free) properties of the impeding vehicle. Determining the consequences, and therefore the meaning, of the event requires reference to both the physical performance environment, and also the unique action capabilities of the rider. This relationship cannot be defined internally, as it has causal entailments which extend beyond the mind of the performer into the specific relations between their body and the physical environment.

2.7.1 An Alternative Metatheory

For a performer's actions to be adaptive, as they are in flow states, they must reliably identify higher-order properties of the *performer-environment system*. The content of such experiences is, therefore, neither objective nor subjective, but "double-barrelled" since it cuts across this divide (James, 1912/1976). Utilising and expanding on this relational ontology, Gibson (2014) termed these offerings of the environment, with respect to the action capabilities of the performer, *affordances*. Affordances can be thought of as the semantics of ecology (Turvey & Carello, 2012) and present a logical candidate for the content of experience in flow.

For actions to 'resonate' with the environment (Csikszentmihalyi & Bennett, 1971), performers must perceive how features of the environment present opportunities for action, given their own capabilities (Warren, 1984). For example, a skilled rock climber may perceive a feature of the rock face that affords grasping. This feature is simultaneously both an "objective" property of the rock and a "subjective" property because it is defined in relation to the capabilities of the performer and may not afford grasping for another, less-skilled, climber (Gibson, 2014). Given the abilities of the climber, however, the 'graspability' of the rock is not a subjective evaluation. The relationship between the climber's abilities and the feature of the rock exists outside the mind of the performer as a property of a distinct performer-environment system, and the success of the climber's performance depends on their ability to perceive and utilise available affordances like these (Davids et al., 1994). Critically, the ecological metatheory holds that organisms and environments have been co-determined and begins from an ontological position of organism-environment mutuality (Gibson, 2014).

As exemplified, the concept of affordances may be uniquely suited to explaining the deeply intertwined relationship between actions, perceptions, meaning, and challenges in flow experiences. Much of the confusion in current explanations of this

relationship can be shown to result from limitations of the subject-object ontology. For example, Engeser et al. (2021) claimed that it is not the objective balance between challenges and skills that determines aspects of flow such as sense of control, but rather the subjective evaluation of this match. While it is likely that measurement of the challenge or in objective (context-free) units is insufficient, the subjectification of the relationship may be equally problematic. If the experience refers to a process of subjective evaluation, an epistemological gap between these internal processes and the environment that is acted on is created. This loss of contact with the performance environment could present a major obstacle to scientific progress since actions in flow are observed to relate to the performance environment with a tremendous degree of precision, and it is this relationship that determines the meaningful outcome of the event.

In conclusion, if perception is (i.e., a three-term relationship) as proposed in the cognitive metatheory, internal states of the performer become the content of experience in flow, and the adaptive relationship to the performance environment must be presupposed rather than explained. While the ecological concept of affordances would be considered as a candidate to overcome this issue, it is incompatible with the cognitive metatheory and subject-object dualism. Critically, the ecological metatheory denies that experience must be equated with subjectivity (Seifert et al., 2022) and holds that affordances may be perceived directly in an impredicative, two-term relationship between the specific performer and the performance environment (Turvey, 2018). These conclusions are supported by a strong tradition of empirical research in ecological psychology (e.g., Lee & Reddish, 1981; Warren, 1984). The practical advantage of these commitments is that the nature of the relationship with the performance environment can be explained without the limitations of solely subjective or objective accounts. Exploring alternatives to the cognitive metatheory may also have implications for the conceptualisation of causality in flow.

2.8 Causality outside of the cognitive metatheory

The difficulty of explaining flow within the cognitive metatheory might also be understood as a limitation of forms of explanation that have resulted from prevailing conceptualisations of causality (Chemero & Turvey, 2007; Juarrero, 2023). Traditionally, causal entailments have been thought to proceed exclusively from component to function (Turvey, 2007), meaning abilities of the whole should be understood through the contribution of the parts. An outcome or function observed at one level (e.g., an individual performer) must be explained with reference to a smaller scale such as a subcomponent or part of the performer's body. These restrictions on causality imply context-free forms of explanation but do not allow for reference to larger scales such as the performer-environment system, strictly speaking.

This entailment structure in cognitive psychology is exemplified by claims that components such as attentional networks in the brain cause functions such as selective attention observed in flow (Harris et al., 2017). The assumption that flow results from the contributions of some number of hard-assembled components within the performer has motivated explanation in the form of linear chains of efficient cause. However, a growing body of research suggests that the goal-directed behaviour of adaptive organisms may not be approachable in terms of efficient or chain-like cause and may require the introduction of *impredicative entailments* (Chemero & Turvey, 2007; Rosen, 1991; Van Orden & Holden, 2002). Impredicative entailments originate in the analysis of set theory and paradoxes arising from sets that contain themselves as members, thereby creating a circular relationship between parts and wholes (Aczel, 1988). For example, an individual's status as the tallest member of a group is defined with reference to the whole group (i.e., context) that the individual is a part of. Impredicative entailments are, therefore, useful for considering causal relationships that involve interactions between multiple scales or levels such as brain, body, and environment.

2.8.1 Impredicativity

Impredicative definitions are central to the issue of subjective and objective explanations of flow. Nakamura and Csikszentmihalyi (2002) claim that "there is no objectively defined body of information and set of challenges within the stream of the person's experience" (p. 91). Traditionally, objectivity has been associated with predicative definitions that require reference to some independent, context-free unit of measurement. For example, a bike ramp measured in meters is defined predicatively because the unit of measurement is independent of the system being measured. This predicative definition is context-free and does not reflect differences in the unique abilities of different performers. A bike ramp measuring two meters may provide too great a challenge for some performers to experience flow and too little for others. In recognizing the insufficiency of predicative definitions, flow theories have unnecessarily equated non-predicative definitions with subjectivity.

By contrast, the "jump-ability" affordance of the ramp is impredicative because it is defined with respect to the greater performer-environment system the ramp is a part of. The ramp may afford jumping (and flow experiences) when it participates in some performer-environment systems but not others. The action capabilities of the performer are the important unit of measurement (Warren, 1984). More generally, impredicative entailments are needed to formalise affordances (Chemero & Turvey, 2007), but they should not be confused with subjective evaluations. Impredicatively-defined properties refer to *real relations* and track both mind-independent properties of the performance environment as well as the abilities and dispositions of the specific performer. The relationship between the specific performer and the flow activity can, therefore, be accounted for without framing flow as a subjective experience of internal processes.

While *predicative* definitions may be sufficient to model operations within formal symbol systems or computer programs, events occurring within complex performer-

environment systems (e.g., flow activities) likely require richer *impredicative* definitions that refer to circular interactions between scales (Rosen, 1991; Turvey, 2018). Impredicative definitions are *context-dependent* and reverse the direction of explanation towards larger scales an observation occurs within. Notably, performers in flow must perceive impredicative properties (i.e., affordances) to act adaptively. For example, a skier who perceives a large obstacle looming in their visual field may experience a sense of anxiety which grows as the affordances to navigate around the obstacle dissolve. Affordances and impredicative entailments may be useful in understanding challenges posed by flow activities. A new form of measurement with direct relevance to key issues in flow research may, therefore, be made available by the ecological metatheory.

In this expanded understanding, the function of a system component may be understood to depend on impredicative loops involving higher levels of organisation (larger spatial and temporal scales of embedding context) (Turvey, 2007). Rather than having pre-defined functions, components may spontaneously take on a function by virtue of their relationship to the embedding context. For example, a smooth piece of cardboard may spontaneously take on the function of a sled when surrounded by children and snow-covered hills. Systems that are soft-assembled and context dependent have been called interaction-dominant (Ihlen & Vereijken, 2010; Van Orden et al., 2003) Because the function of a given component changes fluidly with context, the behavior of interaction-dominant systems cannot be reduced to the independent contribution of modular components (e.g., attentional networks in the brain) and explanation via linear causal chains is contraindicated. If flow experiences are dominated by interactions, the difficulty encountered by common forms of explanation might be explained. The conceptualisation of nested systems afforded by the ecological metatheory may also clarify the role of neuroscientific research on flow (Dotov, 2014; Van Orden et al., 2012).

Notably, impredicative, interaction-dominant systems exhibit nonlinear interactions between scales, directly contradicting the cognitive hypothesis of near-decomposability and independence of timescales (Kelty-Stephen & Wallot, 2017). Events at one scale may be *inter*dependent with events at other scales, such that no single characteristic scale for system description may exist (Marom, 2010). Scale-free phenomena pose problems to some, but not all, definitions of mechanistic explanation (see Bechtel, 2015), so there is a need for precision when discussing suitable forms of causal explanations of flow. While the cognitive metatheory has largely ignored the prospect that psychological phenomena might be scale-free and interaction-dominant, the difficulty explaining flow warrants further consideration of this possibility.

2.9 Scale and Flow

In section 2.2, two key questions were identified pertaining to scale that must be addressed by explanations of flow, including: (i) which scales of events are implicated in flow experiences, and (ii), what causal relations hold between these scales. Section 2.5 outlined the influence of the cognitive metatheory on the way these questions have been responded to by extant theories of flow, outlining the implications of cross-scale interactions for causality and explanation. In what follows, the explanatory scale(s) of analysis for flow are analysed more explicitly.

All empirical research on flow must select some scale of analysis. This scope has narrowed from career-scale reflections to event-based methods (Jackman et al., 2022). Concerningly, however, "nothing is yet known about the dynamics of flow intensity that occur during flow" (Peifer & Engeser, 2021b, p. 427). Practically, this means that once some window of time is selected, flow measures must determine whether this activity as a whole should be classified as a flow experience. As such, questions have been raised over the number of components needed in the flow experience to warrant classification, whether flow is best understood as a discrete or continuous phenomenon (Peifer &

Engeser, 2021a), and whether the use of cut-off points to demarcate flow experiences is appropriate (Jackman et al., 2017). However, the fundamental issue of how many scales a single flow experience may spill across must still be addressed.

The intermittent and erratic nature of many natural phenomena such as turbulence remained a mystery for centuries due to the "difficulty of determining the actual duration of time over which the total observable turbulent energy is spread" (Mandelbrot, 1999, p. 119). The assumption that a turbulent flow could be neatly separated and classified gave way to the recognition that "zooming in" on turbulent flows revealed large areas of laminar flow that contained pockets of turbulence within them (Mandelbrot, 1999). This insight motivated the development of fractal and multifractal methods that deal with the scaling laws which characterise numerous phenomena ranging from seismic events to response times to weather patterns (Bak, 1996; Kelty-Stephen et al., 2013; Mandelbrot, 1999; Van Orden et al., 2005). Flow research could consider the possibility that "zooming in" on an activity that has been designated as a flow experience might reveal stretches of non-flow experiences with brief periods of flow nested within them. Stated differently, it is unclear that chain-like, sequences *within* a single scale should be prioritised over nonlinear cascading relationships *between* scales (Wallot & Kelty-Stephen, 2018).

Let us consider a several-hour period of surfing that has been categorised as a flow experience. It is intuitively apparent that this flow experience contains periods of relative inactivity (e.g., waiting for a wave), and periods of higher intensity (riding a wave) nested within it. Further, within the experience of riding the wave, finer-scale fluctuations of the intensity of flow likely exist at critical points of the surfer's interaction with the wave. Moreover, this several-hour window may be nested within a larger-scale event such as a week-long surfing trip. However, these *cascading* relationships between scales are excluded in explanation via linear chains of cause and effect (Wallot & Kelty-Stephen, 2018). In the event flow entails nonlinear interactions between scales of events,

explanations that take the form of a sequence of internal components related by efficient causality may fail. In interaction-dominant systems, the function of components may be contingently determined by these interactions and, therefore, lack the requisite stability to support common chain-like models (Sullivan, 2016). In such cases, cascade modelling may become an important part of causal explanation (Dixon et al., 2012; Kelty-Stephen et al., 2013).

The hallmark of phenomena that arise due to cascading relationships across scales is *intermittency* (Mandelbrot, 1999). Flow has been characterised as unpredictable, mysterious, and mercurial (Swann et al., 2012), so it might also be described as intermittent. Although further research and additional methods would be needed to confirm the presence of cross-scale interactivity, Ceja and Navarro's (2009) finding that instances of flow are distributed neither randomly, nor regularly, but chaotically provides some initial support for this possibility. Additionally, scale-free patterns may support adaptivity in biological systems and have been associated with health and wellbeing (Van Orden et al., 2011). In fact, the strength of cross-scale interactivity has already been linked with skilled performance (Nonaka & Bril, 2014) and task engagement (Bennett et al., 2022). While a universally positive interpretation of scale-free patterns in behavior is simplistic and their meaning likely depends on context and task constraints (Kelty-Stephen et al., 2023), their established presence in many adaptive processes warrants further consideration of their relationship to flow experiences.

While questions of scale are of immediate concern for a causal explanation of flow, they also relate to broader questions about flow as a concept. Csikszentmihalyi (1975) expressed frustration that the concept of flow was often trivialised. As illustrated in section 2.2, Csikszentmihalyi's vision for the concept was motivated by questions of a much grander scale; meaning and flourishing in human life. Notably, it is in the impredicative and multi-scaled loops of semantic closure that "law-determined physical

aspects of matter become functional (i.e., have survival value, goals, significance, meaning, self-awareness, etc.)" (Pattee & Rączaszek-Leonardi, 2012, p. 212). A metatheoretical framework that emphasises formal symbolic operations on internal representations may struggle to retain this sense of meaning. Indeed, Wertsch (1991) cautioned that this strategy implies that "cultural and social issues can be incorporated as additional variables once the basic forms of mental functioning in the individual have been isolated and understood" (p. 85).

To understand how flow activities obtain their meaningful nature, scales that reach beyond the internal states of the performer must be consulted. Minimally, the scale of analysis must reliably link the performer to the performance environment, but the nested nature of environments and events suggests an analysis that extends across many, if not all, scales. It is possible that reconceptualizing flow experiences within the framework of adaptation across nested scales of context -- as suggested by the ecological metatheory -- may enable the concept to remain meaningfully linked to questions about individual and societal flourishing and as Csikszentmihalyi intended.

2.10 Future Directions

The difficulty of explaining flow has often led to doubts over the concept itself (e.g., Hassmén et al., 2016) but these failures can also be interpreted in a different way. Since nearly all theoretical explanations of flow can be shown to assume the cognitive metatheoretical framework, it is possible that flow represents an anomalous finding for the cognitive metatheory. As illustrated in the preceding, the subjective framing of experience and the assumption of a single, characteristic timescale at which cognitive mechanisms create a causal chain may be poorly suited to explaining flow. The difficulties encountered by this specific set of explanatory tools should not be taken to mean that flow cannot be satisfactorily explained, however. New theories that can generate testable

predictions about flow experiences should be developed within alternative metatheoretical frameworks.

The ecological metatheory developed by James Gibson (2014) and the tools provided by dynamical systems theory (Kelso, 1995) and multifractal geometry (Mandelbrot, 1999) may be particularly well-positioned to support novel explanations of flow. This confluence has been termed ecological dynamics (Araújo et al., 2006; Davids et al., 1994) and brings an established record of theoretical innovation and fruitful empirical research in domains such as skill acquisition and human performance. For example, eco-physical variables have been proposed as useful for addressing the proposed organismic asymmetry in traditional cognitive explanations of phenomena (e.g., Seifert et al., 2022), such as flow experiences, considering the role of ecological cognition in a performer's adaptation to a performance. Eco-physical variables define the relations between each individual and the environment (Seifert et al., 2022) and have been used to continuously track fluctuations of collective system variables related to meaningful possibilities for action (Correia et al., 2013) as well as self-regulation in performance (Carvalho & Araújo, 2022). Given that flow entails skilful, adaptive behaviours, the ability of eco-physical variables to deal with fluid, multi-scaled system (re)organisations that contain impredicative entailments is highly advantageous. Put simply, flow is a phenomenon that involves exquisite sensitivity to a performance environment, but current forms of explanation point inward toward subcomponents rather than outward toward contextual relations. Tools such as eco-physical variables may enable the personally meaningful nature of flow experiences to be analysed with increased precision.

2.11 Conclusion

The challenges in explaining flow experiences suggests that the suitability of metatheoretical frameworks within which explanatory theories have been developed should be examined. Since the assumption that cognition consists of the internal

processing of information was endorsed by Csikszentmihalyi and holds a hegemonic position within psychology, it is not surprising that it has been assumed by theories of flow, despite the organismic asymmetry. This chapter has highlighted the ontological and epistemological assumptions of the cognitive metatheory, particularly as they relate to the nature of experience, perception, and causality. It is possible that these assumptions may preclude a satisfactory explanation of flow but, minimally, they are sufficient to motivate the development of theories of flow within alternative metatheoretical frameworks. Finally, it is proposed that the alternative stances the ecological metatheory adopts on these issues provide a strong foundation for theoretical and empirical research on flow.

Chapter 3:

Towards an Ecological Dynamics Theory of Flow in Sport

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3.1 Introduction

As discussed in the second chapter, flow states describe enjoyable experiences of complete absorption in a task which is perceived as optimally challenging (Peifer & Engeser, 2021a). While flow can arise in many different domains (e.g., music, art, dance, exercise, work) sport has featured as a prominent context for flow experiences from the outset of its initial conceptualisation (Csikszentmihalyi, 1975), remaining an important part of flow research (Jackson & Csikszentmihalyi, 1999; Stoll & Ufer, 2021). The concept of flow has also gained recognition within fields such as sport psychology, performance psychology, and positive psychology (Csikszentmihalyi, 2000). Despite popularised appreciation for the concept, scientific progress in flow research has been hampered by theoretical and methodological issues (Swann et al., 2018). The previous chapter argued that nearly all theories of flow have been constructed within the cognitive metatheoretical framework and suggested that new theories should be developed from alternative metatheoretical foundations.

This chapter seeks to explicate the foundations of the ecological dynamics framework (Araújo et al., 2006), outline key implications for flow, and build towards an explanatory theory of flow in sport. Building on the metatheoretical analysis presented in the previous chapter, it is argued that an ecological dynamics theory of flow can resolve key impediments to the understanding of flow and frame the phenomenon in a more

empirically tractable manner. Given the questions surrounding many traditional flow research frameworks such as the nine-dimension model (Swann et al., 2017), existing frameworks are not used to define the explanandum. Rather, the ecological (transactionalist (Heft, 2012)) metatheory (Gibson, 1966, 2014) is used to return to some questions which originally inspired the concept of flow. In this metatheoretical re-framing, fundamental concepts such as attention, intention, adaptivity and skill, temporality, information, and experience are considered as they relate to flow. Finally, testable predictions this theory might motivate, and steps for future research are discussed.

3.2 Why Should We Study Flow in Sport?

Concepts in psychology tend to flicker in and out of popular awareness, often rapidly gaining prominence only to be discarded and forgotten just as quickly. The prolonged difficulty in explaining flow, as well as its potential to provoke shallow, commercialised interpretations, provide grounds for questions regarding the fundamental validity of the concept (e.g., Hassmén et al., 2016). However, it is argued that flow is worthy of continued consideration (i.e. theoretical and empirical research) for several important reasons, outlined next.

First, flow seeks to explain highly meaningful experiences, linked to many positive life outcomes (Freire et al., 2021; Tavares & Freire, 2016). If the concept of flow is entirely dismissed, then either a similar concept must be proposed to fill this space, or the relevance of meaning itself must be denied. Therefore, ignoring or rejecting the entire area seems an odd choice unless one is committed to an extreme form of nihilism, since flow experiences are meaningful by definition. Csikszentmihalyi (1975) began his academic career by conducting a thorough study of adjacent concepts such as play, peak experiences, and intrinsic motivation, concluding that they did not sufficiently explain the phenomenon he named flow. So, it is unlikely that flow can be satisfactorily subsumed

into other existing concepts. In the terms of the constraint selection model introduced in Chapter One (see Figure 1.1.), something approximating flow experience must motivate constraint selection at early stages of a sport's emergence. This necessity suggests reconceptualising rather than abandoning the flow concept. Second, it is claimed that causes of the difficulty in explaining flow are not specific to flow. Rather, it is proposed that flow is stretched between several dualisms that have caused difficulty across many domains of psychology. These paradoxes or dilemmas include:

Table 3.1.

Common dualisms implicated in flow research

Voluntary	Involuntary/Automatic
Conscious	Unconscious
Internal	External
Present/Online	Absent/Offline
Top-down	Bottom-up

For example, flow researchers analysing the degree of automaticity or voluntary control of action in flow (e.g., Vuorre & Metcalfe, 2016) are dealing with a specific instance of a more general question about the role of intentionality in action (Juarrero, 1999, 2023). Similarly, ambiguity surrounding the loss of self-consciousness and the transformation of time in flow (Swann et al., 2018) is unsurprising, given that self-consciousness and time are complex topics that have been the subject of much philosophical study. While the proximity of flow to so many metatheoretical questions and paradoxes is certainly noteworthy, it is by no means a reason to discard the concept.

Finally, flow may be well positioned to address core questions about our motivations and experiences engaging in sport, which has developed into an economically

and socially significant global phenomenon with an increasing degree of professionalisation (even at recreational levels). The positive experiences (e.g., flow) capable of emerging in sport could dovetail with current societal needs (e.g., enhance physical activity, build community, sense of agency, meaning and value in emotional and psychological experiences). In contrast, a limited understanding of the relationship between flow experiences and sport may allow other ways of defining value and meaning, such as profitability, commercial interests or spectator entertainment value, to exert a higher degree of influence on the future of sports. There may be a fundamentally and mutually significant relationship between flow and sport, such that better understanding of one may afford fundamental insight into the other.

3.3 The Origins of Flow

While many details of the original conception of flow (Csikszentmihalyi, 1975; 1990) have been questioned recently (Swann et al., 2018), several facts about the phenomenon are uncontroversial. The concept was developed by Mihalyi Csikszentmihalyi (1975) during interviews which sought to explore experiences in autotelic (self-motivating) activities. Flow necessarily refers to some subset of experience. It is also generally accepted that these experiences relate to the motivations or intentions of the participant, and result in some optimal form of absorption in the task at hand (Peifer & Engeser, 2021a). According to Csikszentmihalyi (1975), flow is situated at the intersection of play, peak experience and intrinsic motivation. These core themes must be addressed by any theory of flow, regardless of the metatheoretical framework within which it is constructed.

Csikszentmihalyi (1975) emphasised the importance of first-person reports in understanding flow, which has traditionally been conceptualised as a *subjective* (private) experience (Csikszentmihalyi, 1990; Peifer & Engeser, 2021a). Additionally, Csikszentmihalyi was sceptical of mechanistic explanations and questioned how much

neuroscience had to offer to flow research (Beard, 2015). Despite this hesitancy, Csikszentmihalyi (1990) maintained that "whatever happens in the mind is the result of electrochemical changes in the central nervous system" (p.26). Because descriptive accounts have a limited ability to provide a causal explanation of the phenomenon (Swann et al., 2018), contemporary theorists of flow have sought to complete the picture by investigating physiological processes during flow experiences (e.g., Harris et al., 2017). Practically, this has resulted in an expression of dualism with the bifurcation of flow research into subjective-psychological, and objective-physical branches, with difficult challenges faced in each case.

3.4 Naturalism Redux?

Because the term flow is a "native category" which comes from interviewees' own descriptions of experiences in autotelic activities (see Csikszentmihalyi, 1975, p. 36), the nature of the relationship between psychological flow and the flows of energy or matter studied by physical scientists warrants consideration. Csikszentmihalyi (1971) expressed a clear view on this relationship in a paper entitled From Thermodynamics to Values: A Transition Yet to be Accomplished. In this critical commentary, Csikszentmihalyi responds to the idea that breakthroughs in thermodynamics and dissipative systems might provide insights into the (self-)organisation of human behaviour and experience (Katchalsky, 1971) and asserts that human concerns such as symbols, meaning, and values are beyond the reach of the natural sciences. Discussing the relevance of organisation emerging in dissipative systems, Csikszentmihalyi (1971) confidently asserted that the energy flows analysed in the natural sciences hold only "the barest twinkling of an analogy" (p. 164) to human psychology and opined that:

> To understand how values affect the behavior of men, we must recognize the unique forces and systemic characteristics that determine the motions of men. And that requires the study of the laws of consciousness and volition, two uniquely

> human processes which social scientists have shied away from for the exact reason that should have attracted them: consciousness and will are furthest removed from those processes that physical scientists study (p. 166-167).

The sentiment expressed by Csikszentmihalyi (1971) is a common theme in the history of psychology. In fact, Dewey, (1929) had already summarised the issue several decades prior:

> Hence immediate qualities, being extruded from the object of science, were left thereby hanging loose from the "real" object. Since their existence could not be denied, they were gathered together into a psychic realm of being, set over against the object of physics. (p. 264)

Dewey, however, reached a different conclusion to Csikszentmihalyi:

> Given this premise, all the problems regarding the relation of mind and matter, the psychic and the bodily, necessarily follow. Change the metaphysical premise; restore, that is to say, immediate qualities to their rightful position as qualities of inclusive situations, and the problems in question cease to be epistemological problems. They become specifiable scientific problems: questions, that is to say, of how such and such an event having such and such qualities actually occurs. (p. 264-265)

The theory presented here seeks to: (i) transcend the limitations of objective materialism and subjective idealism by restoring the “immediate quality” of flow to the inclusive situation (i.e. the multi-scaled performer-environment system), and (ii) explore how events experienced as flow may occur and may be facilitated.

The present analysis of these “inclusive situations” highlights the utility of research methods which have traditionally been used in the study of physical energy flows (e.g., the multiscale dynamics approaches discussed in section 3.9) to analyse the lawful

support for the real possibilities that give shape to experiences such as flow. However, it is not suggested that psychological flow be *directly* equated with the energy flows studied by physical scientists or deny that flow is experienced by a specific individual performer. The naturalistic attitude proposed here only questions the subjective conceptualisations of flow experience insofar as subjectivity has been understood as irreconcilably opposed to objectivity. Instead, it is proposed that "[t]he supposedly separate realms of the subjective and the objective are actually only poles of attention" (Gibson, 2014, p. 108) and discuss new possibilities for scientific inquiry into attentional processes as they fluctuate between these poles (see sections 3.9 and 3.10). Finally, it is underscored that complementarity of dynamic flows of energy and local constraints (Pattee & Rączaszek-Leonardi, 2012) can accommodate Csikszentmihalyi's (1971) concerns without requiring a rejection of naturalism.

3.5 Ecological Dynamics

The following introduces the ecological dynamics framework (Araújo, et al., 2006) which underpins the subsequent theory of flow in sport. Ecological dynamics is a contemporary framework that synthesises insights from ecological psychology (Gibson, 1966, 2014; Reed, 1988), dynamical systems theory (Kelso, 1995), complexity science (Mandelbrot, 1999; Rosen, 1991), and evolutionary biology (Gottlieb & Lickliter, 2007; Oyama, 2000) to study phenomena self-organising across multi-scaled performer-environment systems. The ecological approach diverges from mainstream cognitive science in fundamental ways which are often overlooked. The hegemonic nature of the cognitive metatheory has often resulted in (mis)interpretations which unknowingly conserve its core assumptions (Costall & Morris, 2015). Key differences between the metatheories and their implications for flow research are highlighted to avoid this outcome.

The ecological approach can usefully be construed as an attempt to re-frame psychology in a manner which turns intractable, ill-posed problems into well-posed ones

(Warren, 2021). The use of "intelligence loans", or ad hoc ontological addenda (e.g., mental entities) to patch over these problems is, therefore, discouraged by the ecological approach (Turvey, 2018). This position can be summarised by Gibson's (2014) insistence that "[k]nowledge of the world cannot be explained by supposing that knowledge of the world already exists" (p. 241). The ecological approach takes the ubiquity of *adaptive* behaviour (such as that observed in flow activities) as the primary explanandum for psychology. The actions of organisms across all kingdoms of life can be observed to relate to the physically extended environment with a high degree of success in tasks ranging from mundane to spectacular (Araújo et al., 2023). It should be emphasised that precise relations between the performer and the performance environment are assumed by *any* theory of flow. It is anticipated that an account of the action and perceptual systems that support these precise relationships with the performance environment will be helpful in explaining flow.

Gibson (2014) recognised that philosophical assumptions common within the psychology of perception excluded the explanation of adaptive behaviour *a fortiori*. Perception conceptualised as the internal enrichment of impoverished stimulation (e.g., inference or prediction) *presupposes* knowledge about the world to explain cognition. In place of these representationally mediated, three-term relationships between perceiver and environment, Gibson proposed a direct, two-term theory of perception (Gibson, 2014). Ecological approaches do not start with a disembodied mind trying to establish epistemic contact with an external world since organisms and environments have been ontologically co-determined through co-adaptative processes across many scales (Reed, 1996). From this perspective, organism-environment and perception-action comprise nested, interdependent systems that can only be understood in the context of their history of interactions (Gibson, 1966).

Ecological psychology holds that, affordances – defined as "what the environment

offers the animal, what it *provides* or *furnishes*, either for good or ill" (Gibson, 2014, p. 119) can be directly perceived, and the nested structure of affordances supports direct perception even in linguistic and social interactions (Kelty-Stephen, 2024; Rączaszek-Leonardi, 2012; Stoffregen & Wagman, 2024). Affordances transcend dichotomies such as subjective-objective or physical-mental, and can only be understood as part of a broader rejection of Cartesian dualism - exemplified by Gibson's exasperated remark "Why must we seek explanation in either Body or Mind? It is a false dichotomy" (Gibson, 2014, p. xii). While this alternative metatheory dissolves many intractable problems in psychology (such as the dichotomies noted in table 3.1), it also necessitates the reconceptualisation of several fundamental concepts and implies a broader understanding of causality (Juarrero, 1999, 2023). It is claimed that the alternative accounts of core concepts such as causality, intention, attention, perception, temporality, and experience are ideally positioned to resolve the dilemmas facing flow researchers.

It should be noted that the following themes are not intended as a model of a linear temporal sequence and are only arranged with consideration for the convenience of the reader. Additionally, aspects of flow detailed here often display significant overlap or interdependence. This is to be expected within the ecological metatheory (Gibson, 2014), as the modularity of distinct cognitive faculties is called into question. The theory developed here utilises concepts from the natural sciences to understand the way in which performers and their experiences spill out and cascade across the many scales of the performance environment. The intermittent, circular, and scale-free nature of such processes do not lend themselves to "box and arrow" models describing chains of component contributions familiar to traditional psychology (Wallot & Kelty-Stephen, 2018).

3.6 An Ecological Conceptualisation of Experience for Flow Research

Because flow is recognised to be some type of experience, the present theory

begins by discussing the conception of experience used within the theory. While flow has often been defined as a *subjective* experience (Peifer & Engeser, 2021a), this is a metatheoretical preference which needs to be critically examined. Alternatively, William James (1976) illustrated that experience is not primarily subjective or objective but participates in multiple frames of reference at once. An ecological dynamics perspective builds on these Jamesian insights and holds that experiences such as flow refer to *both* the physical performance environment and the action capabilities and history of the performer (Seifert et al., 2022). Experience is, therefore, meaningful without being exclusively subjective or internal.

The *personally* meaningful nature of challenges in flow activities has often been used to support exclusively subjective conceptualisations of the experience (e.g., Csikszentmihalyi, 1990). Note, however, that this stance assumes a subject-object ontology in which the environment comprises value-free objects. The ecological approach rejects this ontological bifurcation and reconsiders the relationship between experience, value and meaning:

> The perceiving of an affordance is not a process of perceiving a value-free physical object to which meaning is somehow added in a way that no one has been able to agree upon; it is a process of perceiving a value-rich ecological object. Any substance, any surface, any layout has some affordance for benefit or injury to someone. (Gibson, 2014, pp. 131-132)

For example, certain snow-covered slopes may elicit feelings of excitement in an individual who enjoys skiing. The *meaning* of the slope is only found in a relationship which includes both its physical properties (e.g., gradient, quality of the snow) *and* the abilities and dispositions of the individual to interact with these properties. This is particularly important in flow because it is these higher-order, relational properties of the performer-environment system that underpin adaptive action. For action to succeed, the

skier must be able to perceive the actionable properties (affordances) of the slope. Fluctuations in experience might be expected to correspond to fluctuations in higher-order properties, very loosely characterised as “ski-down-ability".

For example, the experience evoked by a looming obstacle such as a tree is not so much a “subjective evaluation” as much as a recognition of the real possibility of injury afforded (affordances can be “for good or ill” (Gibson, 2014)). In many flow activities, the emergence and dissolution of affordances provide clear insight into the fluctuating dynamics of experience. This affordance-experience relationship is clearly evident in high-risk activities. Flow researchers would not disagree that an affordance to navigate around an obstacle and avoid a high-speed collision will result in a sense of exhilaration and relief.

From an ecological perspective, it is the meaning-laden performance environment, rather than an internal model, that is the object of experience. Because the affordances performers perceive as they adapt to the performance environment are inherently meaningful, additional processes which assign subjective value are not required. An obstacle approaching in a manner which does not afford avoidance *means* collision. The ecological conception of experience is, therefore, able to refer to both the individual performer and the performance environment through an impredicative entailment that connects wholes to parts (Chapter Two; Chemero & Turvey, 2007; Rosen, 1991). Importantly, this conception of experience is also not reducible to verbal reports (Seifert et al., 2022). In many flow activities (e.g., sports), the meaningful fluctuations in the affordances perceived by performers are so transient, subtle, or complex that they challenge verbal description.

Consider an attacker-defender dyad in a team invasion game (e.g., football, hockey, basketball). The distance, angle, and relative velocity between the players are recognised to be important variables that describe state of the dyadic system (Passos et

al., 2008). In simple terms, an attacker who is closer to the goal, or accelerating away from a defender gains an advantage related to the objective of scoring a goal. The many scales of fluctuations which occur in these order parameters (Passos et al., 2009) are, therefore, highly meaningful to performers. Experience in all sport is filled with such fluctuating dynamics of complex variables relating to meaningful outcomes (i.e. eco-physical variables; Araújo et al., 2021; Seifert et al., 2022). While these dynamics have been recognised as a significant gap in the understanding of flow, they are difficult to access via verbal reports or methods which require participants to be immobilised (Peifer & Tan, 2021). It is quite possible that the difficulty of describing these complex, higher-order variables verbally has contributed to the notion that flow is subjective or internal.

An ecological dynamics theory of flow in sport, therefore, begins with a fundamentally different conception of experience that cannot be understood within a subject-object framework. Crucially, this conceptualisation of experience can support explanations of precise performer-environment relations and the meaningful nature of flow states. Given the significant challenges faced by theories underpinned by dualistic ontologies (see Chapter Two), this alternative metatheory utilised by the ecological dynamics framework is considered to be essential to scientific progress in the understanding of flow. In the following, the ecological understanding of experience is used to consider the *subset* of experience described by the concept of flow.

3.7.1 Intentionality and the Role of Constraints in Shaping Flow Experiences

Intention is implicated in two of the original dimensions of flow (clear goals, autotelic experience) (Csikszentmihalyi, 1990) and remains an important aspect of any theory of flow. In flow, performers engage with a task under certain intentional conditions. Flow experiences are only plausible for agents capable of *caring* about the tasks they engage with (Hodges, 2009). This intentional dimension of caring about a task is fundamental to all sports and also creates the epistemic conditions for an explanation of flow. Here,

intention is construed broadly to capture multiple scales such as motivation, goals, and the prospective (future-oriented) quality of behaviour within flow activities. Generally, intentional behaviour is understood to have the quality of *aboutness* (being directed towards objects) (Turvey, 2018).

Csikszentmihalyi (1975) was unconvinced by the prevalent narratives which construed behaviour as the logical outcome of some external factor such as reward or punishment and left no role for the intentions of the individual. As noted previously, the tension between internal and external or subjective and objective is a repeating theme in current flow research. As has generally been the case in flow research, the observed limitations of exclusively objective explanations have been understood to necessitate subjective explanations of intentions in flow. Accordingly, Csikszentmihalyi's (1990) account construes intention as a mental representation of a desired outcome.

Traditional explanations of intentionality (e.g., mental representation of an outcome) have faced significant challenges finding their place in scientific theories (Juarrero, 1999). If the prevailing framings of intention and causality are conserved, theorists are forced to choose between a deterministic physical science and the insertion of an immaterial self or 'ghost in the machine' (Ryle, 2009; see also Juarrero, 1999). Further, approaches that locate the origin of intentions in a mental realm have struggled to explain how these immaterial entities are able to cause the action of physical bodies (Kloos & Van Orden, 2010; Kugler et al., 1990) and lead to a muddled dichotomy between voluntary and involuntary actions (Van Orden & Holden, 2002). While discussions around the nature of intention will no doubt continue, flow researchers could adopt a metatheoretical framework which propose radically different responses to the problem posed by intentional behaviour (Dixon et al., 2015; Shaw & Kinsella-Shaw, 1988).

The ecological perspective on intention in flow rejects the assumption that intentions are mental entities exerting *efficient* cause on a linear chain of contiguous

reactions (Juarrero, 1999). Rather, intentional contents exemplify a form of *circular* causality in which longer timescales of behaviour *constrain* (Umerez & Mossio, 2013) system degrees of freedom at shorter timescales in a continually evolving hierarchy (Kloos & Van Orden, 2010; Van Orden & Holden, 2002). Notably for flow research, the view of intentions as constraints dissolves the distinct categories of voluntary and automatic actions. The vertical coupling between scales (as opposed to vertical separation required by the efficient causality account, see Van Orden & Holden, 2002) that underpins the ecological conceptualisation of intention also motivates specific empirical predictions discussed in section 3.11.

From this perspective, the nestedness and relatedness of constraints play an important role in the explanation of skilled behaviour and the experiences therein (Balagué et al., 2019). The interaction between these nested scales (Kelty-Stephen & Wallot, 2017) is characterised by impredicative entailments that define complex systems (Rosen, 1991) and signifies the irreducibly embedded nature of performance (Araújo, Davids, et al., 2019). In practical terms this means that a set of constraints governing a flow activity can both arise out of interactions and serve to constrain behaviours emerging at shorter timescales. These nesting of constraint ecologies holds an important implication for constraint manipulations targeting flow experience. The role of a given constraint manipulation (e.g., the mass of a cricket bat) in facilitating flow is not inherent to the constraint itself (predicatively entailed) but defined in relation to (impredicatively entailed) other constraints (e.g., the strength of the batter, mass of the ball).

3.7.2 The Integrated Model and Evolving Task Constraints

An ecological dynamics perspective on the nested nature of constraints may also provide additional insight into the recent distinction between flow and clutch states in the context of sport (Swann et al., 2017). The integrated model of flow (Swann et al., 2017) considered flow states and clutch states as overlapping, but distinct, experiences arising

due to the openness of goals, among other contextual factors. An ecological dynamics approach could provide the tools to explore the intentional dynamics of behaviour emerging under these differing networks of constraints. More precisely, empirical analyses of the variability of movement in potential flow and clutch states could quantify potential differences in the use of perceptual information (Kelty-Stephen & Dixon, 2014; Palatinus et al., 2013).

More generally, an ecological dynamics approach seeks to shed light on the relationship between flow and the continually evolving structure of flow activities or sports considered as sets of replicable task constraints (Rączaszek-Leonardi, 2012), as discussed in chapter one. Such a relationship is suggested in (Massimini et al.'s, (1988) paper on the role of flow in biocultural evolution, but the framing of a mimetic process operating in a subjective landscape has not supported further research, thus far. It is expected that flow plays a significant role in the constraint selection process defining the genesis and subsequent evolution of a sport. For example, it is intuitively apparent that children at play adapt the constraints of their activities to foster certain (perhaps flow) experiences.

Returning briefly to the relationship between physical energy flows and psychological flow discussed in section 3.4, the role of selected constraints in flow activities enables flow experiences to be situated socially and historically and qualify as a psychological phenomenon. For example, catching a fly ball means something in the context of a baseball game because of the constraints which have been selected, but the constraints of the game only acquire meaning when they constrain dynamic flows of energy (e.g., participating athletes). As such constraints and dynamics shape experiences such as flow collectively rather than independently (Pattee & Rączaszek-Leonardi, 2012).

3.8 Adaptivity and Skill in Flow Activities

It is uncontroversial that flow involves skilled performance. While passive activities such as watching a movie or enjoying a sunset may generate some features of flow, they are not considered to be flow experiences due to the lack of skilled performance and activity on the part of the participant (Barthelmäs & Keller, 2021). The way in which skills and activity challenges are construed is, therefore, an important part of any theory of flow. While the relationship between skills and challenges were originally considered to be orthogonal dimensions, Barthelmas and Keller (2021) have questioned this framing, as skills and challenges are inherently relative to one another. However, from an ecological dynamics perspective, a deeper critical investigation into the concept of skill used in flow theories is still required. Empirical research in ecological dynamics has revolutionised the contemporary understanding of skill acquisition (Araújo et al., 2006; Davids et al., 2008; Hristovski et al., 2006; Passos et al., 2008). Here, we emphasise the aspects of that body of work with the greatest relevance for flow in sport.

Theories of flow developed within the cognitive metatheory have traditionally conceptualised skills as some form of mental representations, neurally encoding actions (e.g., Dietrich, 2004; Gold & Ciorciari, 2021). These may be referred to as representations, programmes, scripts or schemata. Regardless, all posit some local organising entity that is stored within the organism and then executed. Such explanations of skilful behaviour have been termed *component-dominant* views and can be contrasted with the ecological view that behaviour is not generated by centralised components but rather dominated by interactions connecting many scales of events (Balagué et al., 2019; Van Orden et al., 2005).

Ecological dynamics, therefore, conceptualises skilled performance as a functional, *adaptive* relationship with a performance environment, rather than originating in a stored representation of an ideal technique (Davids et al., 1994). Skill is not a “thing”

that can be “acquired” and “possessed” by someone, but rather is contextually defined, providing an “adaptive, functional relationship between an organism and its environment (Araújo & Davids, 2011, p. 18). It is stressed that behaviour can be “regular without being regulated” (Gibson, 2014, p. 215) due to the natural laws that govern self-organisation (Kelso, 1995) and the degeneracy inherent to neurobiological systems (Seifert, Komar, et al., 2016). The emphasis on soft-assembled coordinative structures in ecological dynamics is well summarised by the proposal that, “[d]exterity is the ability to create a perfect key for any emerging lock” (Bernstein, 1996, p. 215). The ecological understanding of skill as adaptivity-in-context also suggests reconsideration of the commonly utilised concept of automaticity.

3.8.1 Issues with the Concept of Automaticity

The word automatic is commonly invoked to describe a sense of control and effortlessness experienced in flow (Csikszentmihalyi, 1990). However, explanation via automaticity creates several problems. First, if the actions performed in flow are truly automatic programs executed from within, intense concentration would not be required and the link between action and perception is severed. Second, it is unclear how skills conceptualised as pre-existing and automated programs might be able to deal with the unique contextualised challenges likely to be encountered in each flow activity (Van Orden et al., 2011) or effectively constrain the abundant degrees of freedom available to the movement system (Latash, 2012). The emphasis on automaticity of skills in flow may create an unhelpful organismic asymmetry (Seifert et al., 2022) in which the decontextualised movement patterns are analysed, rather than the movement-context relationships that hold consequences for performance outcomes. When intentions are not expected to exert efficient cause, the dichotomy between automatic and consciously controlled movement is resolved.

3.8.2 The Dynamics of Adaptive Action in Flow

Thus far, this chapter has discussed general differences between ecological and cognitive approaches to skills in flow. In the following section, the nature of skills in flow implied by an ecological dynamics rationale is explored more deeply. It is possible that rejecting the narrative of automatically executed motor programmes will enable a more nuanced discussion of both the phenomenology and dynamics of skills in flow. An ecological dynamics account emphasises that control of action cannot be localised in either the performer or environment alone but is co-determined by the emerging relationship between them (Araújo, Hristovski, et al., 2019).

It is anticipated that the experience of fluid adaptation in flow is likely to emerge in metastable performer-environment systems (Kelso, 1995, 2012) which remain open to multiple latent patterns of coordination by hovering close to regions where multiple affordances are present (Hristovski et al., 2006, 2011) and multiple scales of events are tightly linked by multiplicative cascades (Kello et al., 2008; Kelty-Stephen & Wallot, 2017). For example, as an attacker-defender dyad in a football/soccer match draws closer to system reorganisation (e.g., tackle or successful dribble), surrounding attackers and defenders influence the affordances available to players in the 1v1 system. However, the surrounding players are also influenced by the unfolding 1v1 as they hover between continuing to attack/defend or transitioning to defence/attack. These “extended critical transitions” (Longo & Montévil, 2014) reflect continual symmetry breaking of the system and indicate the emergence of new forms of order (Kelso, 1995). Metastability not only maximises each performer’s sensitivity to the demands of context, but it has also been recognised as a bridging point between phenomenology and dynamics of skilled action (Bruineberg et al., 2021) since first-person experiences can be used to help identify meaningful variables (i.e., eco-physical variables). Because an ecological dynamics approach posits an entangled relationship between action and perception, the type of

perceptual information needed to support this account of adaptive action, and its implications for attention in flow is discussed next.

3.9 Information for Action and Attention in Flow

Some of the difficulty explaining flow may relate to its proximity to the concept of 'attention'. While attention is intuitively accessible, it has proven to be a difficult phenomenon to study empirically (Hommel et al., 2019). Despite frequently mentioning the close relationship between flow and attention, Csikszentmihalyi, (1978) expressed dissatisfaction with extant theories of attention and suggested that a new conceptual paradigm might be required for scientific progress. It is imperative, therefore, that an account of attention in flow goes beyond the relatively trivial statement that attention is focused on the task at hand, or that it is not directed elsewhere.

The ecological approach situates attention as "an adaptive relationship between performing and procuring information to guide and support that performance" (Gibson & Rader, 1979, p. 6). A central question, therefore, concerns the process by which performers in flow attend to information for action. The ecological definition of attention makes three important claims. First, effective attention cannot be defined in isolation from the demands of the task (e.g., as a larger general reservoir or stronger spotlight). The effective structure of the attentional process reflects the structure of the information needed to support successful performance in each task. Second, procuring information is considered to be, itself, an active process. Finally, and more subtly, the instantaneous present moment and trichotomy of past, present, and future are rejected; perceiving is continuous. It is claimed that the ecological information that enables performers to perceive affordances (Wagman & Blau, 2019) will clarify the nature of attention in flow.

Information, as conceptualised by the ecological approach, exists in the relationship between a performer's exploratory movement and the lawful structure of the

ambient energy arrays (e.g., light structured by surfaces) (Gibson, 2014; Kugler & Turvey, 2015). Transformations created by exploratory movement reveal invariant properties of the performer-environment system. For example, as an individual approaches an object, the centre of optical expansion is lawfully related to heading direction and the rate of optical expansion specifies the time to contact (Lee & Reddish, 1981; Silva et al., 2019). Because the information perceived is generated actively, the regulation of action is explained without the need for additional steps or intermediary mental processes. The information variables used in the prospective control of action have been the subject of a robust and fruitful empirical research programme both in sport (Fajen et al., 2009; Hristovski et al., 2006; Passos et al., 2008) and psychology (Lee & Reddish, 1981; Kelty-Stephen & Dixon, 2014; Kugler & Turvey, 2015).

At this point, it is worth reflecting on what this extant body of research implies for the study of attention in flow. First, the adaptivity of a given attentional process depends on the way it is situated within a longer timescale of events, denoting an impredicative entailment (Chemero & Turvey, 2007; Rosen, 1991). For instance, the same sidewards glance at a doorway provides information that guides and supports performance when one proceeds to exit the room, but functions as a distraction if one remains in the room and maintains a conversation; the longer sequence of events contextualises the shorter. As such, attention can be observed in the way the action-perception process relates to itself as it unfolds over many nested timescales. Second, the ecological emphasis on multiscale dynamics provides a general framework for the empirical study of information use across different cognitive phenomena (for an overview, see Dixon et al., 2012).

The multiscale dynamics approaches motivated by an ecological perspective have already shed light on attention (Avelar et al., 2019), anticipation (Stephen et al., 2008; Stephen & Dixon, 2011), executive function (Anastas et al., 2014), task engagement

(Bennett et al., 2022), adaptivity (Nonaka & Bril, 2014), and insight (Stephen et al., 2009), offering a compelling account of the general prospective or future-facing nature of intentional behaviour. It is proposed that understanding attention in flow may be supported by the concept of "strong anticipation" (Dubois, 2003; Stephen & Dixon, 2011; Stepp & Turvey, 2010) in which performers couple to long-range temporal correlations that give lawful structure to seemingly chaotic events (e.g., evasive opponents). Additionally, fractal fluctuations in gaze behaviour have been shown to accelerate visual search (Stephen & Anastas, 2011), suggesting further study of hyper-diffusive gaze behaviour in the context of flow in sport. Empirical research on multiscale dynamics in flow has already made a promising start with Montull et al.'s (2021) study which found that ecological information describing the stability of the performer-environment system reliably co-varied with measures of flow experiences in a slackline task.

The multiscale dynamics of information use may also offer a parsimonious explanation of selective attention, a key aspect of flow. Expert performers may stay close to the jagged edges of system reorganisation to maintain flexibility (Hristovski et al., 2006). In these critical regions, extremely small fluctuations may be sufficient to break the symmetry of the delicately poised system, however, only events related to the relevant opportunities for action (i.e., affordances) can perturb the organisation of the system (Kloos & Van Orden, 2010). Thus, Csikszentmihalyi's (1990) recognition that flow increases as performers become able to make "finer and finer distinctions in the challenges involved in the activity" (p. 97) may have much to do with the fact that affordances are exquisitely nested and contain further affordances (Stoffregen & Wagman, 2024). Esteves et al. (2011) found that basketball players differentiated between dribbling affordances that allowed them to beat a defender with enough time to take a shot and those that did not also afford shooting. Hence, highly focussed attention in flow may be the result of nested systems that hover close to the edges of reorganisation.

To summarise so far, it has been argued the explanations of information and attention espoused by ecological dynamics enable flow to be more than an efficient internal process. On the present account, flow in sport reflects the infinite richness of the environment and the real possibilities for action created when "perceiving gets wider and finer and longer and richer and fuller" (Gibson, 2014, p. 244).

3.10 Temporality and Self-Consciousness Reconsidered

The original nine-dimension model of flow (Nakamura & Csikszentmihalyi, 2014) includes transformation of time (i.e., speeding up or slowing down) and the loss of self-consciousness as characteristics of the flow experience. More recently, however, limited support has been found for these dimensions (Swann et al., 2018). While the present work makes no commitment to the nine-dimension model, a brief comment on these two dimensions may help illustrate the way metatheoretical stances have directly constrained flow research and demonstrate the utility of an ecological dynamics approach.

The nature of time and (self-)consciousness have been the subject of philosophical musings for millennia. Participants offering verbal reports on the transformation of time or loss of self-consciousness in flow are situated within the history of these terms and will likely reflect received views that are culturally pervasive. At issue in both temporality and self-consciousness is the question of unit. A unit gives a system a characteristic scale and separates above (embedding context) from below (sub-components). However, the ecological approach raises important questions about the nature of units:

> There are forms within forms both up and down the scale of size. Units are nested within larger units. Things are components of other things. They would constitute a hierarchy except that this hierarchy is not categorical but full of transitions and overlaps. Hence, for the terrestrial environment, there is no special proper unit in terms of which it can be analyzed once and for all. There are no atomic units of

> the world considered as an environment. Instead, there are subordinate and superordinate units. (Gibson, 2014, p. 5)

These insights about nesting hold important implications for understanding both temporality and self-consciousness.

An ontologically distinct self (i.e., unit as "one") requires an unchanging atomic unit that reliably divides the subjective internal world from the objective external world. Systems that display nested structure (of either objects or events) may not have a *single* appropriate unit. At one extreme, an idealised self-similar (fractal) structure completely obscures the notion of unit; the same pattern stretches to infinity in both directions of scale. By contrast, a classical Euclidean object (e.g., a triangle) has a single, obvious level of wholeness that defines its characteristic scale. The ecological approach does not expect the units of time and self in flow to be limited to either of these extremes. Rather, multiple scaling laws (i.e., multifractality) are needed to reflect the coexistence of scale-invariant natural laws and scale-dependent constraints (Kelty-Stephen, 2024; Mandelbrot, 1999; Stoffregen & Wagman, 2024).

From this perspective, the loss of self-consciousness would not be expected to be a binary phenomenon where the absolute unit of self is either present or absent. Rather, the unit of self may shift fluidly as performers couple and de-couple from the task context. For example, a hockey player's stick may be experienced functionally as part of the "self" during play. Alternatively, an athlete directing their intention toward their own body (e.g., stretching a stiff muscle or massaging a bruise) sub-divides their own body into "subjective" and "objective" parts, demonstrating the fluidity of unit (Gibson, 2014). Similarly, nested events provide the basis for any conception of time (Gibson, 1975). Because perception is necessarily extended in time, the distinction between present and past or perception and memory cannot be made rigorously (Gibson, 1975). In both cases, the structure of events in potential flow activities can be investigated empirically (Kelty-

Stephen, Lane et al., 2023) and the need for participants to verbally interpret complex philosophical topics is avoided.

In conclusion, an ecological perspective holds that consciousness only exists at the level of the performer-environment relation. Research cannot reduce such a relation – or else only matter exists, nor only focus on the relation - or else only idealisation exists. (Physical) performers can directly perceive their (physical) situation and themselves in that situation without needing a 'consciousness copy' of the environment, nor a 'consciousness copy' of themselves (Shaw & Kinsella-Shaw, 2007). As Gibson (2014) put it " [perception] involves awareness-of instead of just awareness. It may be awareness of something in the environment or something in the observer or both at once, but there is no content of awareness independent of that of which one is aware" (p. 228).

3.11 Implications for Empirical Research

For a theory of flow in sport to be maximally impactful, it should have consequential implications for empirical research. The following outlines some empirical expectations this theory motivates.

3.11.1 Interaction-dominant dynamics will be pervasive in flow activities

A key hypothesis that emerges from an ecological dynamics theory of flow in sport is the expectation that interaction-dominant dynamics (Ihlen & Vereijken, 2010; Kelty-Stephen, Lane et al., 2023) will be pervasive in flow activities. Current research in flow typically seeks to identify the *components* responsible for generating flow experiences. By contrast, the current account seeks to identify the *interactions* responsible for flow. Component-dominant and interaction-dominant systems have empirical signatures that can be clearly distinguished (Kelty-Stephen & Wallot, 2017; Mangalam et al., 2025). Flow is not expected to exhibit a simple, monotonic relationship with the degree of cross-scale interactivity in all activities. Rather, the multiplicative cascades

modelled by multiscale dynamics approaches (Kelty-Stephen, Lane et al., 2023) may support differing demands on context-sensitivity under different task constraints (Kelty-Stephen, Similton et al., 2023).

3.11.2 Intermittency of flow experiences and context-sensitivity

Intermittency is entailed by the cross-scale interactivity and multiplicative cascades found in interaction-dominant systems. The difficulty of predicting or controlling flow is a well-noted issue in flow research (Swann et al., 2012). Intuitively, if the antecedents of flow were well understood, they could be manipulated to induce flow experiences. However, the present theory predicts that no *single* scale of analysis will be adequate to provide necessary and sufficient conditions for flow. Not only are the multiple scales of the performer-environment system considered necessary conditions for flow, but multiplicative cascades across these scales may have important implications for when flow occurs.

Processes involving multiplicative cascades are typically marked by *intermittent* patterns (Mandelbrot, 1999). Because an ecological dynamics theory of flow in sport predicts that these cascades support context-sensitivity and adaptation in many activities, it is expected that flow will arise intermittently. Dormant periods reflect the product of small multipliers, while sudden spikes arise from large multipliers (Ihlen & Vereijken, 2010). The difficulty predicting and controlling flow is, therefore, understood to result from the broad range of scales likely implicated in flow and the nonlinear interactions between them.

3.11.3 Non-ergodicity: the distribution and markers of flow experiences

Because the symmetry-breaking transitions and multiplicative cascades (see section 3.8.2) expected in flow activities often break ergodicity (Longo & Montévil, 2014; Mangalam & Kelty-Stephen, 2022), the present theory also finds it likely that flow may

be non-ergodic. A process is ergodic when variability between individuals (i.e., ensemble data) is equivalent to variability within an individual across time (i.e., time series data; Mangalam & Kelty-Stephen, 2021; Molenaar & Campbell, 2009). For example, ten fair dice cast once should result in similar outcome distributions to one fair die cast ten times. The question of ergodicity has great practical significance for research on flow in sport. The successful identification of reliable psychophysiological correlates of flow (Peifer & Tan, 2021) in inter-individual trends would likely require flow to meet the ergodic assumptions (for a review of ergodicity in psychological research, see Meyer-Lindenberg, 2023). The absence of such correlates indicates that flow might not meet such assumptions. This question has already been raised in the study of flow at work (Ceja & Navarro, 2017), and it is expected that flow in sport will also be non-ergodic. Evidence of ergodicity-breaking in flow activities would also suggest the limitation of internal predictive models which require a constrained form of variation (Mangalam et al., 2023). Non-ergodic processes will likely benefit from intra-individual forms of analysis that can assess continuous fluctuations in time (e.g., Correia et al., 2013; Molenaar & Campbell, 2009) and nonlinear descriptors that are, themselves, ergodic (see Kelty-Stephen & Mangalam, 2022).

3.12 Avenues for Future Research

In the following, several general suggestions for future research on flow in sport are suggested.

3.12.1 Enhancing understanding of constraints on co-adaptation in flow experiences

As noted in chapter one, a comprehensive theory of flow should utilise general concepts to explain how the domain-specific conditions for flow (e.g., flow in sport) are created. Presently, we consider constraints (Umerez & Mossio, 2013) and co-adaptation (Kauffman & Johnsen, 1991; Passos et al., 2016) to be key scientific concepts for future

research into how flow experiences are shaped in the context of sport. When athletes participate in a sport, they abide by a set of task constraints that limits the use and availability of system degrees of freedom. For example, football/soccer players are constrained to not control the ball with their hands, while basketball players may not control the ball with their feet. While the laws of nature do not change from sport to sport, these specific constraints provide exceptional boundary conditions that complement the natural laws governing the self-organisation of behavior (Pattee & Rączaszek-Leonardi, 2012).

While task constraints comprising an official format of a sport appear fixed at the short timescales (e.g., a single game), they change over longer timescales and can also be manipulated to create a wide range of training activities (Davids et al., 2008). While constraint manipulation has typically been considered in the context of skill acquisition (Button et al., 2021), it can also be used to shape experience. However, the effective manipulation of constraints on experience in sport requires an understanding of *what* is constrained, and the way constraints exert influence.

To understand what is constrained in sport, the concept of co-adaptation (Kauffman & Johnsen, 1991) is introduced. Co-adaptation refers to bi-directionally coupled relationships in which the adaptive movements of one agent transform the affordances available to another agent (Passos et al., 2016). Co-adaptation spans both cooperative and competitive coordination. The relevance of co-adaptation is most obvious in sports that feature direct competition between athletes (e.g., invasion games, net sports, martial arts), but actions in individual sports are also co-adaptive in nature. We propose that constraints on co-adaptation (e.g., Torrents et al., 2016) will be most relevant for studying flow in sport. Furthermore, the need to constraint co-adaptive processes strongly suggests that the constraint selection process introduced in chapter one (see Figure 1.1.) involves perceivable information that supports social coordination of constraint selection

(Heft et al., 2014).

A key tendency observed in co-adapting systems is attraction to critical or metastable regions in which the organisation of the system fluctuates as it approaches a transition to a different state of organisation (Passos et al., 2009). As noted in section 3.9, we theorise that this delicate balance is related to the nature of attentional processes in flow in sport. The way constraints influence these tightly coupled interactions (e.g., the 1v1 sub-phase of invasion games) may, therefore, be central to the study (and facilitation) of flow in sport. Constraints do not exert *efficient* causality (Juarrero, 1999). For example, the presence of a basketball hoop does not force a player to take a shot. Rather, it is one of many conditions *supporting* this possibility (Turvey, 2018). Suppose the diameter of the hoop is doubled. The immediately obvious effect is an increase in affordances to shoot. However, this constraint manipulation will ripple throughout the entire structure of the nested affordances available to the athletes as they co-adapt. An affordance to shoot can nest within it a region in which a performer may choose to shoot or fake a shot and dribble.

The effect a given constraint will exert on a system cannot be determined a priori because the value and meaning of a constraint is always relative to the dynamic flow of action it constrains (Pattee & Rączaszek-Leonardi, 2012). While this makes it difficult (if not impossible) to suggest constraints that will necessarily result in flow experiences in all contexts, multiscale dynamics are well positioned to analyse the relationship between specific cascading flows (e.g., co-adapting athletes) and constraint manipulations. Constraints may be likened to stones placed in a small stream while building a dam. It may be expected that a given stone will fill a gap in the dam, but this is contingent on the flow of the water and the co-positioning of the other stones. The role of a specific stone may change if these other factors change. The context-dependent nature of the stone does not hinder children from building dams in streams, and neither does the context-

dependent nature of constraints on co-adaptation (Balagué et al., 2019) hinder practitioners from manipulating constraints conducive to flow experiences.

3.12.2 The role of eco-physical variables in future research on flow

Because flow emerges in skilled, intentional performance, the identification of the variables that are meaningful to performers is crucial. Eco-physical variables "express the fit between the environment and the performer's adaptations" (Araújo et al., 2021, p. 76). For example, a football/soccer player approaching the ball in the run-up to a penalty kick may experience rapid fluctuations in experience as the higher-order relationship between their body position (e.g., angle of hips, timing of steps) and momentum (constraining the possible trajectories of the shot) and the movement of the goalkeeper (constraining the shots they can block) tilts the system towards a goal or a miss/save. In short, there are eco-physical variables (perhaps relative phase between both player-ball-goal angles over time) that can describe the rapidly unfolding shooter-goalkeeper relationship as it teeters between outcomes. It is expected that the identification of eco-physical variables in such a task would provide insights into the dynamic contours of experience to the extent that the performer is invested in the task.

3.12.2.1 Avoiding a symbol-dynamics dualism

The uncrossable divide between symbols and dynamics posited by cognitive-computational approaches (Pylyshyn, 1980, p. 111) has had a clear influence on psychological research methods. When symbolic and dynamic processes are assumed to be different in kind, ecological dynamics might be mistakenly associated with only the dynamic side of this presumed divide, while psychological processes are considered to be symbolic operations. It is noted that this proposed division of labour is, itself, situated within the cognitive metatheory and rests on the questionable assumption of near-decomposability (see Wallot & Kelty-Stephen, 2018). Additionally, the restriction of (sport) psychology to non-dynamic processes would render it largely useless for assessing

the experiences during the dynamic flow of action.

Because ecological dynamics rejects symbol-dynamics dualism, it is asserted that it can support a thoroughgoing psychology (e.g., Carvalho & Araújo, 2022). Eco-physical variables, therefore, do not oppose subjective-qualitative and objective-quantitative approaches, and have employed mixed-methods research designs to good effect (Seifert, Adé, et al., 2016). Verbal reports or other qualitative methods are not discouraged by an ecological dynamics perspective (see Seifert et al., 2022) and can be an important part of identifying eco-physical variables in flow activities (Jackman et al., 2023). It is only suggested that verbal reports are poorly prepared to support advances in flow research when situated as reports on subjective internal processes (Seifert et al., 2022).

3.12.3 Flow research could benefit from ecologically empowering tasks

One of the most important outcomes of an ecological dynamics theory of flow in sport is the relationship between events and experiences:

> The basic assumption of this approach is that ecologically significant events will be accompanied by ecologically significant experiences. By an ecologically significant event or experience we mean those events or experiences which possess sufficient efficacy to significantly modify the adaptive lifestyle of the organism if they are but occur or are omitted. The sign or value of such events and experiences can, of course, be either positive (supportive) or negative (damaging), such as the event of falling off a cliff or the experience of vertigo that prompts a hasty retreat from the cliffs edge. (Shaw et al., 1974, p. 280)

The implications for flow research are clear: the ecological significance of an event cannot be faked. The difficulty of inducing flow in the laboratory (Moller et al., 2010) is likely the result of the limited situational significance many common research tasks hold for the participants. The holistic context must be considered in the design of the study. It

should not be surprising when the actions of a participant who stops by the laboratory to participate in an unfamiliar or highly constrained task to receive extra credit in a class do not provide deep insights into the nature of flow (Durcan et al., 2024).

Two boxers engaged in a friendly sparring match may execute similar movements to two strangers engaged in a physical altercation, but the ecological significance of the events could not be more different. The dynamics are not differentiated by contrasting subjective evaluations, but by the differing consequences that become apparent when the longer scales of nested events are considered. The necessity of considering multiple scales aligns with our suggestion in the previous chapter that flow is better studied through "vertical" relationships linking nested events than "horizontal" chains exerting efficient cause at a single scale. An empowering task needs to present affordances that solicit participants' actions, implying perceptual and action variability that draws individuals to become, and remain, physically, psychologically and/or emotionally embedded in activity (Araújo, Brymer, et al., 2019). Future research should explore how sports can be situated as positive ecologically empowering (significant) experiences.

3.13 Conclusion

The ecological dynamics framework can provide a parsimonious account of existing descriptions of the flow experience while resolving problems that have been intractable thus far within the traditional cognitive psychology framework. While exact claims about the antecedents or causal mechanisms of flow cannot be made without further empirical support, there is sufficient evidence to posit the ecological dynamics framework as well positioned to guide this empirical research. An ecological dynamics rationale significantly reconceptualises some aspects of flow, which may appeal to Csikszentmihalyi's (1978) hope that "a new conceptual paradigm will be able to inspire new research, direct it along the most promising paths, and then relate findings to each other and explain them in a meaningful context" (p. 356).

Ultimately, it is argued that flow must be more than an internal process if it is to be remain a meaningful concept in psychology. Internal subjective framings of flow may motivate the search for "hacks" presumed to enable the direct manipulation of experience once some central control panel is found. It is asserted that this perspective is antithetical to an understanding of flow that would promote meaning in life through earnest engagement with the world we share. The ecological approach identifies "the constraints on action as the fundamental basis for the reality of experience" (Flach & Holden, 1998, p. 93). In sport, athletes are presented with many opportunities to confront this reality in a direct and courageous manner.

The next chapter begins the empirical portion of this thesis. Because the expectation of cross-scale interactivity is central to much of this thesis and only has initial empirical support in sport (i.e., evidence of power-law behaviour in the fluctuations of one-vs.-ones (Passos et al., 2009) the next chapter focusses on the multiscale dynamics of a one-vs.-one activity in order to test the hypotheses put forward in section 3.11 and identify eco-physical variables whilst chapter five builds on these findings to model flow in the same activity. Although the next chapter may seem to represent a brief detour from flow, dividing the analysis in this manner contributes to understanding of a form of competitive coordination (i.e., antagonistic coupling) that is common in sport and enables a more thorough treatment of flow in the chapters that follow.

Chapter 4:

Multifractality in Antagonistic Couplings: Cross-Scale Interactions in 1v1 Futsal Dyads

4.1 Introduction

This chapter tests the hypothesis that the dexterity or fluidity of performance in competitive contexts is underpinned by interaction-dominant dynamics (section 3.11) and develops on the directions for future research proposed in section 3.12. Although nonlinear cross-scale interactivity in sporting behaviour has been *suggested* by previous results (e.g., Freitas Cruz & Sampaio, 2020; Passos et al., 2009) previously utilised methods are not able to conclusively distinguish between component-dominant and interaction-dominant dynamics (Kelty-Stephen & Wallot, 2017). This chapter utilises surrogate analysis to provides a definitive test of cross-scale interactivity in a dyadic futsal task while introducing two new quantitative methods to the domain of sports science. Multifractal nonlinearity (Mangalam et al., 2025a) and a measure of intermittent anticipating synchronisation (Senthilkumar & Lakshmanan, 2007a) are employed here to identify eco-physical variables within the multiscale dynamics of antagonistic coupling and support the modelling of flow in this task in chapter five.

Social coordination involves a rich interplay of pursuing goals and evading obstacles—often with other agents, but sometimes against them. In the latter case, the obstacles may even be other agents pursuing their own goals. Sport offers a variety of competitive or "antagonistic" (De Poel, 2016) coordination. For instance, invasion games pit opposing players against each other to manipulate an object, such as a ball, into goals or target areas at opposite ends of a symmetrical playing area. The one-v.-one sub-phase (henceforth 1v1) of invasion games arises when the interpersonal distance between an

attacker and a defender decreases, and their movements as a dyad become increasingly coupled (Passos et al., 2016). The 1v1 phase exemplifies antagonistic coupling in which the attacker attracts the defender, and the defender repels the attacker (De Poel, 2016). The present work examined the 1v1 futsal dyad to probe for underlying dynamics of antagonistic coupling. The 1v1 dyad is methodologically simplifying without losing touch with what is fundamentally challenging about antagonistic coupling. In 1v1s, opposing objectives unfold according to a set of selected constraints whose interaction with the movement of participants defines a particular sport (see Chapter One, Chapter Three).

Antagonistic couplings unfold at many timescales, ranging from predator-prey pursuit to co-evolutionary "arms races" and often complement more affiliative coordination (Dotov & Paxton, 2024). Mutual cooperation between agents is not always guaranteed, so the processes supporting adaptation in antagonistic couplings may be implicated in a variety of the complex intelligent behaviours of evolved organisms. Although the generality of antagonistic couplings provides ample motivation to study them, progress has been a challenge. Antagonistic couplings appear in such a wide variety of organisms that explanation will not find simple grounding in any specific process or structure of a nervous system (Turvey, 2018). Indeed, a comprehensive framework for studying the neurobiology and biomechanics of perceptual and motor processes which underpin antagonistic couplings such as predator-prey interactions remains elusive (Peterson et al., 2021). Despite their ubiquity, antagonistic couplings raise complex epistemological questions. For example, the need to relate the movements of an individual to the dyad within which they participate raises several difficult questions. These questions include the locus of intentionality, the structure of temporality, and the nature of unit or self. It is thus advantageous to investigate these couplings in less anatomical and more functional terms, using nonlinear-dynamics tools for modelling interactions

across time scales, considering both individual and collective variability (Kelso, 1995). The present work addressed antagonistic coupling in a dyadic sport paradigm, examining how each agent led or followed the other and effected nonlinear interactions across time scales.

Much of the difficulty understanding antagonistic co-adaptation is in the modelling of nonlinear interactions across scale. These interactions appear both at the scale of individual agents and at the scale of the dyad. Any context-independent strategy, defined at the level of the individual (e.g., a specified pattern of zigs and zags), is susceptible to exploitation by counteracting moves. Behavioural science's bias towards methodological individualism means that the contribution of independent actors and independent processes has overshadowed interactive, dyadic, and collective actions (Davids & Araújo, 2010; Dunwoody, 2006). The prevailing assumption has been that compiling the discrete and isolated actions of the individual would explain more complex or interactive contexts (Vargas, 2024). Growing interest in extended cognition has entailed growing interest in individual-environment interactions. However, individual-environment interactions have been an acceptable focus of study only "[i]nsofar as this thesis requires only that one attend to the interactions of cognitive processes with noncognitive environmental processes" (Adams & Aizawa, 2008, p. 79). The challenge of explaining how multiple agents might model each other's models *ad infinitum* (e.g., recursive theory of mind) usually only appears as a curiosity "yet to be unpacked" (Friston et al., 2012, p. 4).

Explaining antagonistic coupling mainly in terms of individual agents may reflect the broader commitment to explaining behavior as the sum of independent component factors. Indeed, the foregoing suggestion that antagonistic coupling may depend on nonlinear interactions across scale verges beyond more conventional approaches to sport. Influential models of the "mental chronometry" of processing stages in sport envision

chain-like sequences (e.g., perceive-decide-execute) at a *single* timescale (e.g., Poplu et al., 2003; Ripoll et al., 1995). Such models hinge on assuming independent or decomposable timescales (i.e., 'vertical separation') separating, say, the cellular from organismic behavior and both from longer timescales on which cultures develop games. Orthogonal to this vertical separation, decomposability of timescales gives permission to propose 'loose horizontal couplings,' i.e., the chain-like sequences operating at a single scale (Simon, 1977). Because the stages in horizontal processing-stage models reflect the contributions of pre-defined, independent components, systems operating in this fashion are characterised by *component-dominant dynamics* (Van Orden et al., 2003; Wallot & Kelty-Stephen, 2018). Fortunately, this assumption of decomposable scales and independent processes is not simply personal preference but generates empirically testable features which can be queried in behavior in 1v1 competitions. Specifically, independent processes producing component-dominant dynamics should yield classical indicators of linearity: time-symmetry and additivity, built only of independent oscillations, producing often uncorrelated white noise (Kelty-Stephen, Lane et al., 2023; Kelty-Stephen & Wallot, 2017).

The possibility of nonlinear interactivity in antagonistic couplings opens the possibility that 1v1 player behaviour is no horizontal chain, but fluid coordination unfolding across many scales. As scale-dependent componential constraints loosen, a process may exhibit *interaction-dominant dynamics* (Van Orden et al., 2003) in which functions are soft-assembled or fluidly defined within an unfolding multiscale synergy (Turvey, 2007). In the case of 1v1s, fine-scale events include the action potentials and tendon stretching supporting muscle contractions. Medium-scale events might include synergistic muscular co-contractions and scanning eye movements, and longer-scale events might be decisions to dribble the ball right or left or to change tack. Coarser scales would include changes in possession, adjustments to strategy or formation, and even the

glacial change of tactical trends (Balagué et al., 2019). Curiosity about and inclusivity of multiple scales may be necessary to avoid "scale-blindness" in theorising (McGann, 2024) and to prevent scale-dependent logic from trivialising adaptive behaviour (Kelty-Stephen, 2024). Interaction-dominant dynamics in behavioural data are consistent with the principle of nested organism-environment reciprocity endorsed by ecological psychology (Gibson, 2014; Wagman & Miller, 2003). This principle implicates a stance of "methodological direct perception" in which the contributions of the individual and the surrounding context are ontologically entangled (Van Orden et al., 2003, 2010).

Nonlinear interactions across timescale manifest in measurements as a power-law relationship between amount and frequency of behaviour. Behavioural science in sport has already begun unearthing these signatures of nonlinear interactions across timescale. For instance, Passos et al. (2009) showed that the fluctuations of 1v1 dyads exhibit power-law scaling. The power-law signature is crucial because the interactions in interaction-dominant systems involve cascades – fluid configurations which build multiplicatively across multiple scales of events (for a comprehensive treatment of cascades see Kelty-Stephen et al., 2013; Kelty-Stephen & Farrokh, 2025; Kelty-Stephen & Mangalam, 2022; Yaglom, 1966). So, invasion game 1v1s between two bipedal humans entail a hierarchy of constraints and multiple scales (Balagué et al., 2019). Gameplay produces fluctuations which flow through this multi-scaled hierarchy of constraints and engender a fractal structure in which small fluctuations are nested within larger fluctuations. The relationship between the magnitude (i.e., amount) and timescale (i.e., frequency) of fluctuation very often appears as a power-law (Kelty-Stephen, Lane et al., 2023; Mandelbrot, 1999). The scale-invariant structure of a power law might seem at first like a denial of the heterogeneity and nuance in antagonistic coupling. However, nonlinear cross-scale interactions create unevenness and heterogeneity in the form of multiple such power-law relationships. Each power-law relationship expresses a slightly different

parametrisation of the scale-invariant relationship. The dyad is not a zero-sum exchange, and each player is leveraging ongoing variety in their own, and their opponent's, behaviour to exploit emerging fluctuations and amplify opportunities. So, one power law never suffices, and the variability of play—within or across individuals—is best understood nonlinearly through a family of power laws.

Multifractal modelling of player and of dyad in the 1v1 format offers three major contributions toward clarifying how nonlinear interactivity in antagonistic coupling translates to the competitive outcome. First, it leans on previous insights (e.g., Passos et al., 2008; 2009) to find a place in the nonlinear-interactivity formalism to express individual differences in player behavior across a dyad. Multifractal formalism allows player, or dyad, behaviour to have multiple power-laws which are estimable as part of a multifractal spectrum. The width and height of this spectrum reflect the number and strength of those power laws (Chhabra & Jensen, 1989; Ihlen, 2012; Kelty-Stephen, Lane et al., 2023). Specifically, wider multifractal spectra should correspond to greater exploratory variability, e.g., as a defender tries to search out the most advantageous place to stop the attacker. Second, multifractal modelling allows us to test quantitatively the validity of the horizontal chain-like stage models of 1v1 play. Whereas single power laws or "monofractal" results are *suggestive* of nonlinear interactivity, they have never been independently capable of distinguishing these interaction-dominant models from linear approximation. We can make this linear approximation using synthetic surrogate-data series representing the best linear model (i.e., iterated amplitude adjusted Fourier transform [IAAFT]; Schreiber & Schmitz, 1996). Comparing multifractal results between original measured movement and surrogate data can clearly demonstrate nonlinearity (Kelty-Stephen & Wallot, 2017; Mangalam et al., 2025).

Blending multifractal modelling with surrogate series allows a third contribution that could substantially strengthen nonlinear-dynamical models of performance. Beyond

refuting linear chain-like models of behaviour, this original-vs.-surrogate difference in multifractal spectrum width allows expressing specifically how a player or dyad's exploratory variability makes use of nonlinear interactions. This specific difference in multifractality from surrogates has been immensely useful in understanding movement control (Deligiannis et al., 2024; Mangalam, Chen, et al., 2020). More to the point of 1v1 antagonistic coupling, this multifractal nonlinearity predicts perceptual-motor outcomes in learning how to respond to perturbation (Carver et al., 2017) even under uncertain circumstances (Kelty-Stephen, Lee, et al., 2023; Stephen & Dixon, 2011). Effectively, the growth and attrition of multifractal nonlinearity appear to correspond with the release and constraint of motoric degrees of freedom (Kelty-Stephen & Mangalam, 2024). Variations in multifractal nonlinearity reflect the unfolding of broader, more destabilised variability (i.e., with high multifractal nonlinearity) as well as the more focused, more certain constraint of variability (i.e., with lower multifractal nonlinearity (Bell et al., 2019; Booth et al., 2018; Jacobson et al., 2021; Kelty-Stephen, 2018; Kelty-Stephen et al., 2021, 2024). So, it is possible that multifractal nonlinearity could offer new leverage on modelling and predicting the outcomes of antagonistic coupling in 1v1 games.

Revisiting the format of a successful performance in 1v1 futsal might sharpen hypotheses about how and when multifractal dynamics predict successful task completion. First, the successful futsal attack begins with anticipatorily synchronising with the defender, i.e., watching where the defender is moving and creating enough space to get there in advance. More generally, we can expect the defender to (temporally) follow the lead of the attacker. Hypothesis 1 was that classical metrics of anticipatory synchronisation (Senthilkumar & Lakshmanan, 2007; Rosenblum et al., 1996) would show that, between the 1v1 dyad, the attacker was leading the synchronisation, and the defender was following. Next, following an ecological dynamics rationale (Araújo et al., 2006), Hypothesis 2 was that movements in a 1v1 task would exhibit interaction-

dominant dynamics. In finer detail: Hypothesis 2a was the prediction of non-zero multifractal spectra widths, and Hypothesis 2b was the prediction of significant differences between the spectra widths of original data and the populations of surrogates. The presence of multifractal dynamics and nonlinear difference from surrogates was expected in both players as well as in a collective dyadic variable encoding interpersonal angle (Passos et al., 2009). These hypotheses follow neatly from wide evidence of multifractal nonlinearity in various demonstrations (Kelty-Stephen & Mangalam, 2024).

More exploratorily, we predicted that the attacker score could be associated with a divergence of multifractality nonlinearity between attacker and defender (Hypothesis 3). We exploratorily entertained two exclusive alternatives regarding the role of this potential divergence in attacker score. In the first alternative, attackers would have higher scores when attackers showed more nonlinearity contributing to multifractality than defenders (Hypothesis 3a). This alternative would follow the heuristic understanding that more multifractality is healthy and potentially more robust than less or no multifractality (Ivanov et al., 2001). The second possibility is rooted in the foregoing description of the antagonistic coupling of a 1v1. That is, the successful attacker will destabilise the defender, encouraging wider variability in their defending movements before exploiting this instability by constraining their own behaviour into an attack. In this latter case, attackers might show less multifractal nonlinearity than defenders (Hypothesis 3b).

4.2 Method

4.2.1 Participants

Twenty male football and/or futsal players aged 18 to 38 years (M = 23.55, SD = 4.88) participated in this study on a voluntary basis. They had three or more years of self-reported experience playing football (M = 11.05, SD = 4.73) or futsal (M = 1.05, SD = 1.23) at any level. The study was approved by the Sheffield Hallam University ethics

committee (Converis ID ER47422746) with each participant providing informed consent before taking part in the study. Beyond a criterion level of ball control, the specific skill level of the participants was not a primary consideration of the study because the research question concerned the emergence of domain-general coordination dynamics. However, the need to maintain control of the ball was an essential selection criterion for this study, reflecting basic amateur experience levels.

4.2.2 Design

A 1v1 "futsal" (i.e., an adaptation of football played on a hard surface) task met several practical constraints. 1v1 attacker-defender dyads exemplify antagonistic coupling (De Poel, 2016): the attacker attracts the defender, while the defender repels the attacker. The task engaged the experiential qualities of 1v1s in competitive matches, and the futsal format enabled the use of a high-precision motion capture system. All participants completed at least one match (i.e., two trials: one attacking, one defending) and no participants completed more than 12 trials (M = 5.3, SD = 3.06). Pairings were assigned randomly, with no pairings repeated across the data collection, so all dyads were unique.

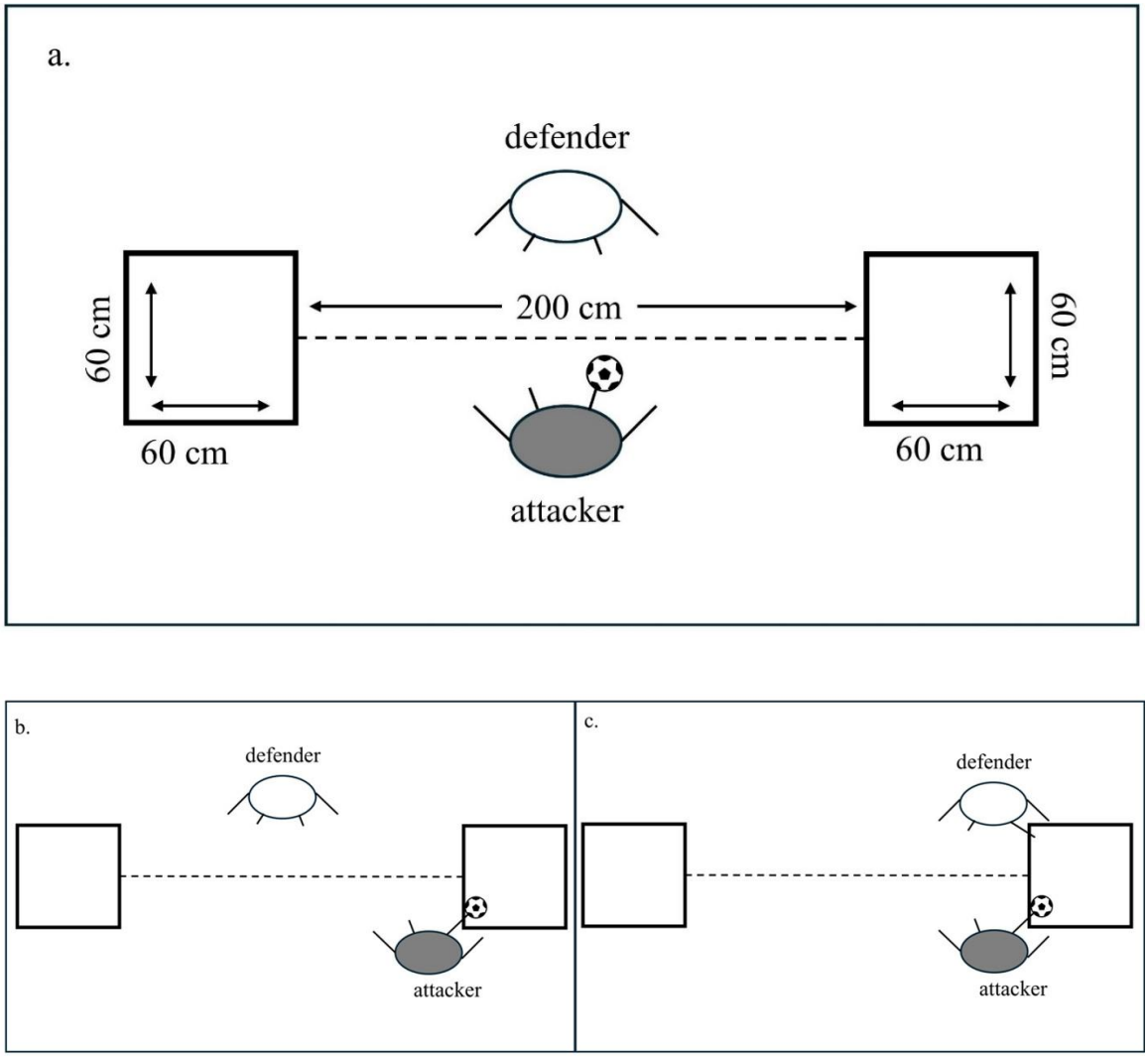
4.2.3 Procedure

Player movements were recorded by a motion capture system (Cortex 6.0, Santa Rosa, CA) tracking the trajectory of a sacral marker (120hz). All participants wore tight-fitting Lycra shorts to ensure consistent and stable fixture of a sacral marker. Video footage of all trials via a video camera (Panasonic HC-V770, Newark, NJ) allowed confirmation of match scores and maintenance of play within capture volume. Sacral-marker position along a transverse axis between target zones would effectively encode task engagement. As explained below, reaching and occupying the target zones with their foot or the ball entailed players moving laterally to fulfil their roles.

The experimenter read task rules and objectives aloud to all participants prior to their first trial. White tape demarcated playing area on the carpeted floor. Matches were played with official size and mass Nike Pro futsal balls. Attacking required manipulating a futsal ball into either of two 60x60cm targets marked with white tape 200cm apart on the floor (see Figure 1a). Defending required participants to occupy target zones by maintaining foot contact with the target zone (see Figure 1c). Scoring a point involved meeting three conditions simultaneously. First, the attacker had to have foot contact with the ball. Second, the ball contacted the target zone. Third, the defender's foot had no contact with the target zone (see Figure 1b). Attackers could score consecutive points in the same zone if the ball fully exited and then re-entered the zone. The experimenter asked each participant to stay on their side of the white-tape dashed line connecting target zones to avoid physically obstructing their opponent's movements. The experimenter also asked participants to stay within the larger marked area denoting the motion-capture capture volume. All participants completed an unscored 15-second warm-up in each role, i.e., attacker and defender prior to their initial trial. Each match lasted 60 seconds marked by an audible tone synchronised with the start and end of recording. Participants switched attacker/defender roles after 2-4-minute rest periods.

Figure 4.1

Depiction of (a) the basic experimental setup, (b) an attacker scoring a point by controlling the ball in a target zone while the defender is not in contact with the zone, and (c), a defender preventing the attacker from scoring a point by placing their foot in the target zone before the attacker controls the ball in the zone.

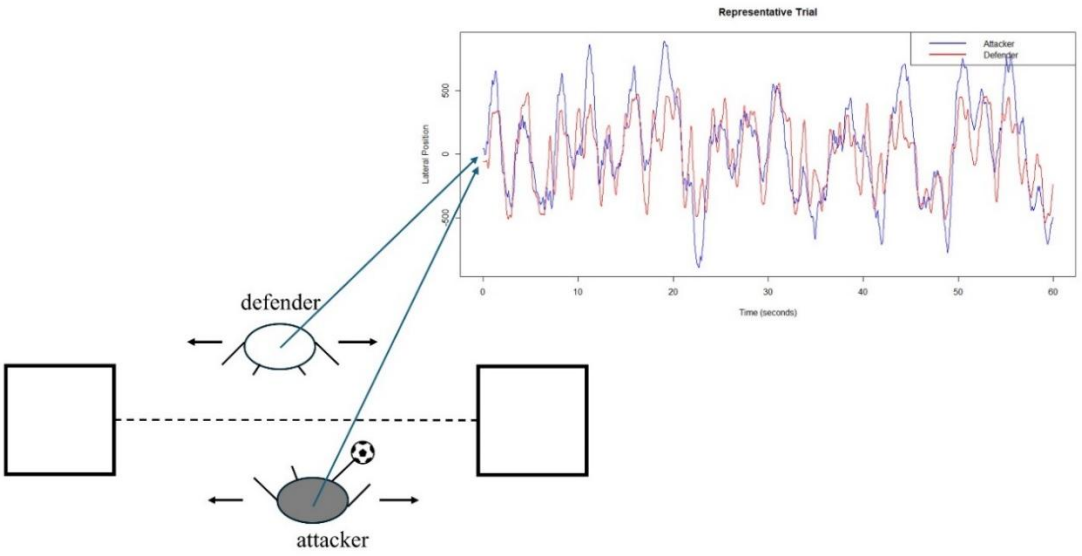


4.2.4 Data Processing and Variable Calculation

28 matches (56 trials) were recorded. After excluding four matches due to marker dropout, data analysis addressed sacral-marker trajectories along an axis connecting the two target zones (i.e., the dashed line in Figure 1).

Figure 4.2

Data capture process for the position of the sacral marker of an attacker and defender in a representative trial.



An interpersonal angle was defined by the line-of-sight between attacker and defender and the goal line (see Figure 4.3; Passos et al., 2009). This measure encodes variation in coupling, where 90 degrees would entail face-to-face mirroring between defender and attacker. Above and below 90 degrees entails the attacker to the left and right, respectively, of the defender. Hence, this collective variable was used to capture important aspects of the dyad's co-adaptation over time.

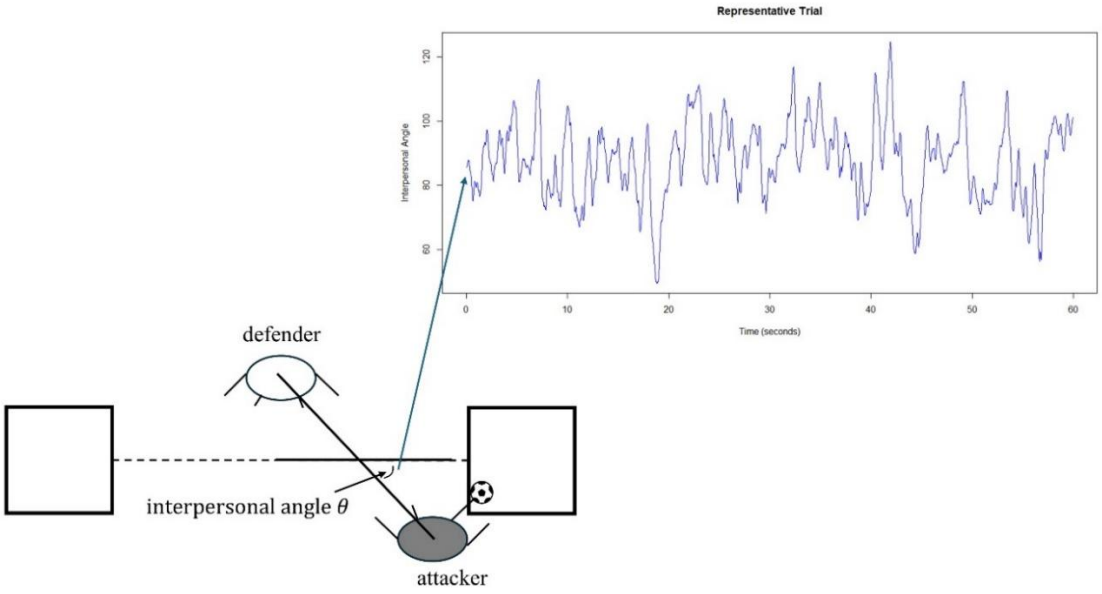
4.2.5 Data Analysis

All statistical analyses were conducted in R-Studio (Posit Team, 2022; R Core Team, 2021). Senthilkumar and Lakshmanan's (2007) measure of intermittent anticipating synchronisation (see supplemental materials), based on previous work by Rosenblum et al. (1996) was used to confirm and assess the anticipatory synchronisation of attacker with defender movements. Multifractal detrended fluctuation analysis (MFDFA; Kantelhardt et al., 2002) was conducted and iterative amplitude adjusted Fourier-transform (IAAFT; Schreiber & Schmitz, 1996) surrogates were produced with the package 'multifractal' (Schadner, 2023). An ANOVA (R Core Team, 2021) was used to address basic differences in multifractal spectra before fitting a regression model for attacker score. The regression model was fit with the package 'glmmTMB' using the function

'glmmTMB' with family set to 'nbinom2' (Brooks et al., 2017). Conceptual outlines of these analyses appear in the subsequent paragraphs.

Figure 4.3

Data capture process for the interpersonal angle θ for a representative trial.



4.2.5.1 Anticipatory Synchronisation for Testing Hypothesis 1

The similarity function $S_a(\tau)$ is the time-averaged difference between two mean-centred signals x_1 and x_2 for a time shift $|\tau|$, divided by the product of their standard deviations

$$S_a^2(\tau) = \frac{\langle [x_1(t+|\tau|) - x_2(t)]^2 \rangle}{[\langle x_1^2(t) \rangle \langle x_2^2(t) \rangle]^{1/2}}, \quad (1)$$

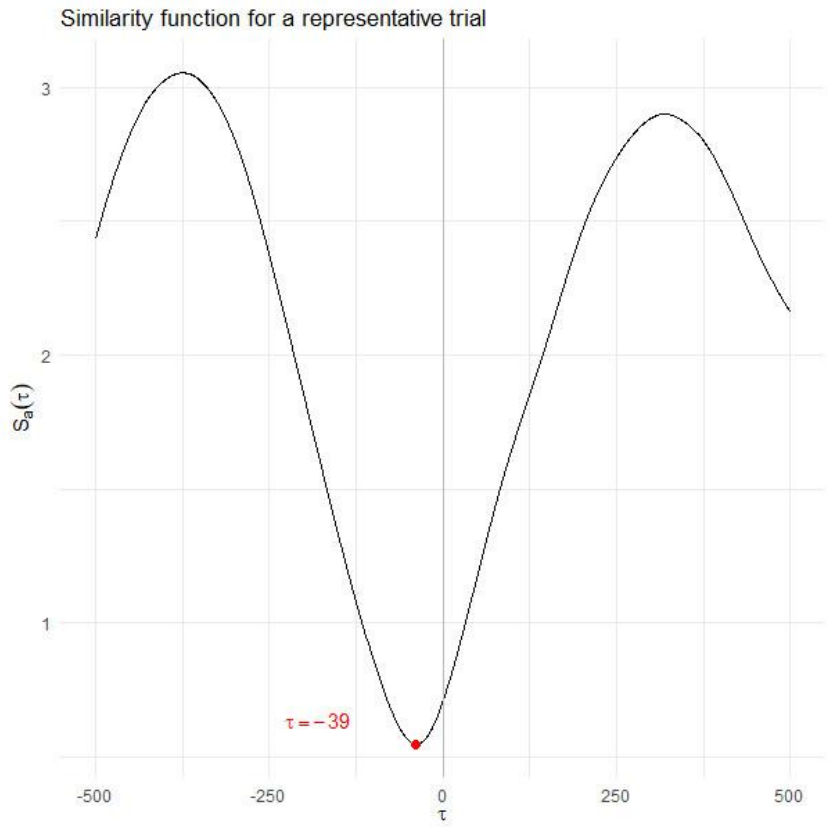
where $\langle x \rangle$ is the time average of the signal.

This function assessed the average subtractive difference between the sacral-marker lateral-position series for the attacker x_1 and for the defender x_2. The value of τ that minimises $S_a(\tau)$ for -500 ≤ τ ≤ 500 (i.e., approximately 4.2 seconds) served as an

estimate τ_{AS} of the time lag at which the attacker coordinates with the defender (see Figure 4). A negative value of τ at the minimum of the similarity function indicated that the attacker's movements were most similar to the defender's later movements (i.e., defender is lagging the attacker). Positive τ indicated that the attacker's movements were most similar to defender's earlier movements (i.e., attacker is lagging the defender).

Figure 4.4

Plot of the similarity function $S_a(\tau)$ for different values of τ for a representative trial. The negative value of τ at the minimum reflects a tendency for the attacker's movements to lead or anticipate the defender's movements.



4.2.5.2 Multifractal Analysis for Testing Hypothesis 2a

For each trial, MFDFA estimated multifractal-spectrum width for three raw time series, i.e., attacker and defender's sacral-marker lateral movement series (Figure 4.2) and the interpersonal angle series (Figure 4.3). MFDFA quantifies the scaling behaviour of

fluctuations in nonstationary time series (Kantelhardt et al., 2002). Standard, non-multifractal DFA divides the time series into segments, and, within each segment, it applies polynomial detrending and computes the residual standard deviation. The slope of the relationship between residual standard deviation $F(s)$ and segment size s on double-logarithmic plots is an estimate of the Hurst exponent h. DFA's use of the second moment (i.e. standard deviation) hinges on the use of the exponent 2. For instance, standard deviation involving first squaring of difference scores and then taking the square root of their sum. MFDFA generalises this approach by explicitly manipulating moment as a parameter q. Whereas non-multifractal DFA quantifies a single power law using the second moment (i.e., standard deviation; $q = 2$), MFDFA generalises standard deviation $F(s)$ from its canonical $q = 2$ to a continuum qth-order standard deviations, i.e., standard deviations $F(q, s)$ reflecting the raising of difference scores to the qth power and taking the qth root of their sum.

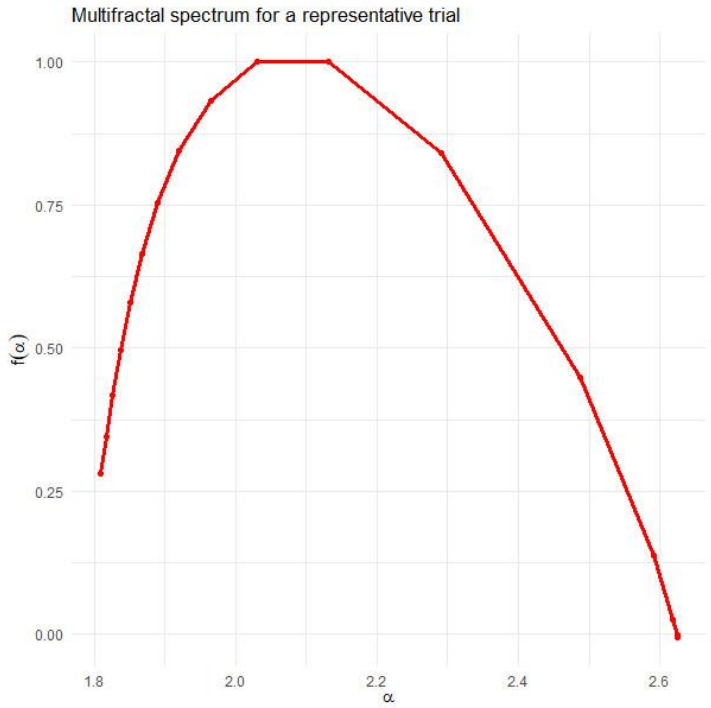
$$F_q(s) = \left\{ \frac{1}{2N_s} \sum_{v=1}^{2N_s} \left[F^2(v,s)^{q/2} \right] \right\}^{1/q}, \quad (2)$$

where N_s is the number of segments, and $F^2(v,s)$ is the local variance of the vth segment of size s.

Positive values of q emphasise large-amplitude fluctuations while negative values of q emphasise small-amplitude fluctuations. Consequently, MFDFA uses the slope of the relationship $F(q, s)$ and s as an estimate of $h(q)$, i.e., a Hurst exponent for each value of q. Variation of $h(q)$ yields a multifractal spectrum $(\alpha(q), f(\alpha(q)))$ via a Legendre transform $\alpha(q) = h(q) + q(\frac{h'(q)}{dq})$, and $f(q) = [\alpha - h(q)] + 1$ (see Figure 4.5). The difference between the maximum and minimum values of $\alpha(q)$ is the multifractal-spectrum width (MFW). For a comprehensive tutorial on multifractal analysis, refer to (Ihlen, 2012; Kelty-Stephen, Lane et al., 2023).

Figure 4.5

The multifractal spectrum α(q), f(α(q)) representing the range of power-law exponents α(q) for different qth-order moments and the Hausdorff dimension f(α(q)) of the subset of the time series characterised by α.



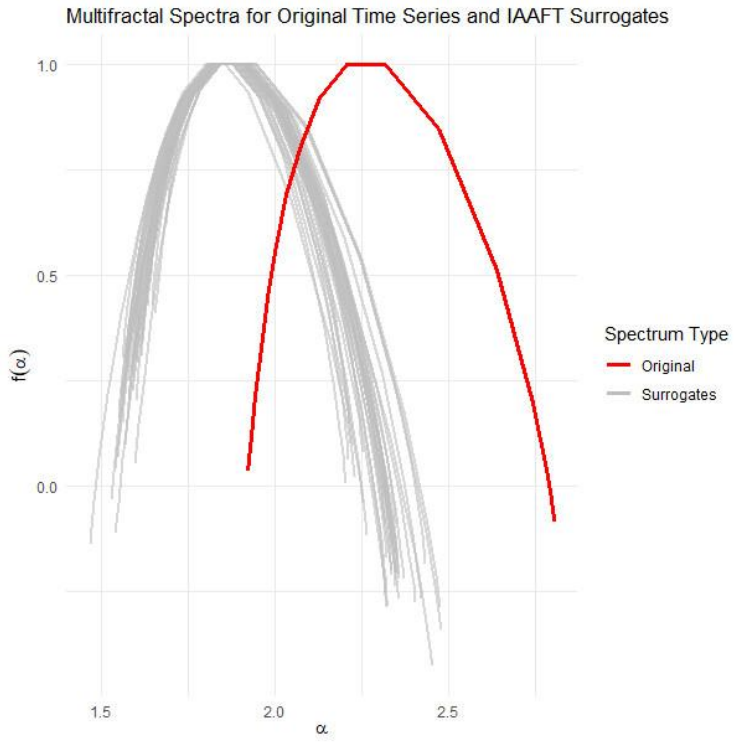
MFDFA requires selecting three primary parameters: range of scales (i.e., minimum and maximum segment sizes), polynomial order of detrending, and range of q moments. Minimum scale must exceed polynomial order of detrending to prevent overfitting. Maximum scale is typically $N/4$ or $N/8$ where N is the time-series length. Present analysis used scale range of 24 to 899 (N/8) and quadratic detrending to avoid both small-sample bias at larger scales and overfitting at short scales, respectively (Ihlen, 2012). The q-range was decided on trial-by-trial basis beginning with $-10 \leq q \leq 10$ and only used q values for which the fluctuation function on double-logarithmic axes had $R^2 >$ .980 to ensure robust scaling (Kelty-Stephen, Lane, et al., 2023)

4.2.5.3 Surrogate Analysis for Testing Hypothesis 2b

IAAFT surrogate analysis involves preserving the linear features (mean, variance, autocorrelation) of the data while shuffling the temporal order and thus removing the interactions between scales (Schreiber & Schmitz, 1996). The multifractal spectra width is computed for each of a sample of surrogates (see Figure 6). A one-sample *t*-test (henceforth t_{MF}) quantifies the difference in multifractality due to nonlinearity absent from the linear structure embodied by the surrogates. This multifractal nonlinearity statistic t_{MF} is a robust estimator of nonlinear interactivity across scales (Kelty-Stephen, Lane et al., 2023; Mangalam et al., 2025). Multifractal nonlinearity t_{MF} also serves as significant predictor in regression models of adaptive behaviour across a wide range of perceptual, cognitive, and motoric domains (Kelty-Stephen & Mangalam, 2024). For each trial, 32 IAAFT surrogates were generated for the attacker lateral-position series, defender lateral-position series, and interpersonal angle series (e.g., Figure 4.2 and Figure 4.3) and t_{MF} was computed for each.

Figure 4.6

Multifractal spectra for original time series (red) and 32 IAAFT surrogate time series (grey) for a representative trial.



Note: Original and IAAFT surrogate time series were found to exhibit a similar range of Hurst exponents.

4.2.5.4 Generalised Linear Mixed-Effects Model to Test Hypothesis 3

Addressing attacker score as the dependent measure required at least two considerations in choosing a regression strategy. First, attacker score is a count variable, typically requiring Poisson modelling. Second, because this variable was overdispersed (i.e., with higher variance than its mean), negative binomial regression was a necessary alternative because it relaxes assumptions of equal mean and variance. A random-effect intercept was included for each attacking participant. Multicollinearity between MFW and t_{MF} variables (variance inflation factors greater than 10) motivated the use of principal component analysis to generate orthogonal covariates for multifractal estimates (see Table 4.1). The measure of anticipating synchronisation (τ_{AS}) was included along with all six principal components (PCs) in an initial negative binomial mixed-effect model. This initial model revealed significant statistical effects for τ and the first and fifth PCs. All other PCs were removed as they did not significantly improve model fit (see Table 4.2).

The first principal component loaded onto all six multifractal variables with a slightly stronger influence for the interpersonal angle. The fifth principal component represented the contrast between multifractal spectra width (MFW) and multifractal nonlinearity (t_{MF}), with the strongest influence again coming from the interpersonal angle followed by the defender. A linear mixed effects model also returned comparable results (see supplemental materials).

Mixed effect modelling is a departure from standard ANOVA treatments of the present dependent measures. Whereas ANOVA estimates fixed effects for balanced designs using ordinary least-squared modelling, mixed-effect modelling uses maximum likelihood to estimate fixed effects for covariates while nesting response behaviours and covariate values by participant even for unbalanced designs. An ANOVA is included next to detail the group differences in multifractal spectra before presenting the regression models.

Table 4.1

Loading Values for Significant Principal Components

	PC1	**PC5**
Interpersonal angle t_{MF}	-0.533	-0.532
Attacker t_{MF}	-0.310	-0.133
Defender t_{MF}	-0.348	-0.443
Interpersonal angle MFW	-0.493	0.605
Attacker MFW	-0.389	0.214
Defender MFW	-0.324	0.302

Table 4.2

Negative Binomial Mixed-Effects Model for Attacker Scores

Attacker Score

Predictors	*Estimate (β)*	*std. Error*	*Conf. interval*	*z-value*	*p*
(Intercept)	0.557	0.246	0.074 – 1.039	2.259	0.024
τ_{AS}	-0.034	0.007	-0.047 – -0.021	-5.068	>.001
PC1	-0.161	0.053	-0.264 – -0.058	-3.054	0.002
PC5	-0.647	0.265	-1.167 – -0.127	-2.439	0.015
Random Effects					
σ^2	0.20				
$\tau_{00\ Attacker}$	0.61				
ICC	0.76				
$N_{\ Attacker}$	20				
Observations	44				
Marginal R^2 / Conditional R^2	0.360 / 0.844				

4.3 Results

4.3.1 Hypothesis 1: Attackers Lead Anticipating Synchronisation

The analysis of anticipating synchronisation showed that attackers' movements tended to lead or anticipate defenders' movements, based on the values of τ that minimised the similarity function $s_a(\tau)$ in each trial (*M*= -13.8, *SD* = 15.5). This result indicates a mean lead time of roughly one-tenth of a second for attackers across all trials.

4.3.2 Hypothesis 2a: Non-Zero Multifractal Spectra Widths

All roles in all trials exhibited non-zero multifractal spectra widths (attackers *M* = 0.869, *SD* = 0.312; defenders *M* = 1.151, *SD* = 0.419; interpersonal angles *M* = 0.851, *SD* = 0.337). Non-zero multifractal spectra widths entail the presence of a range of power-laws at work in contrast to the single power-law exhibited by monofractal processes.

4.3.2.1 Hypothesis 2b: Significant Differences Between Original and Surrogate Spectra Widths

IAAFT surrogate analysis revealed MFW for the original data differed significantly from MFW of 32 linear surrogates in all trials and roles t_{MF}(attackers M = 5.709, SD = 13.784; defenders M = 17.184, SD = 16.25; interpersonal angles M = 9.879, SD = 14.905). Significant differences between the multifractal spectra widths of original and surrogate data in each trial provides clear indication that performance in the 1v1 task involves nonlinear cross-scale interactivity.

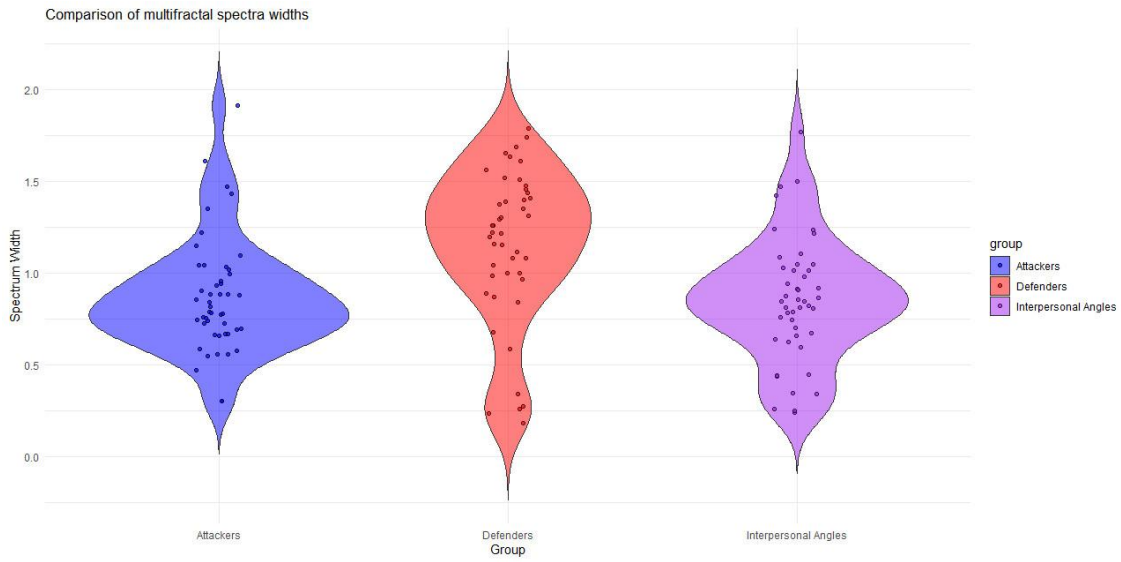
4.3.3 Hypothesis 3: Diverging Multifractality Relating to Attacker Score

4.3.3.1 Analysis of Variance

Prior to testing more specific hypotheses about the role of attacker and defender multifractality in attacker score, a one-way Analysis of Variance (ANOVA) was utilised to compare spectra widths and multifractal nonlinearity in attackers, defenders, and the collective variable, interpersonal angle. The results indicated a significant effect of role on spectrum width $F(2, 137) = 10.52$, $p < .001$ (see Figure 7). The effect size (η^2) value was 0.13 indicating a medium effect. A post-hoc Tukey test indicated that defenders displayed significantly wider spectra than attackers ($p < .001$) and interpersonal angle values ($p < .001$). The spectra widths of attackers and the interpersonal angle values did not differ ($p = .882$).

Figure 4.7

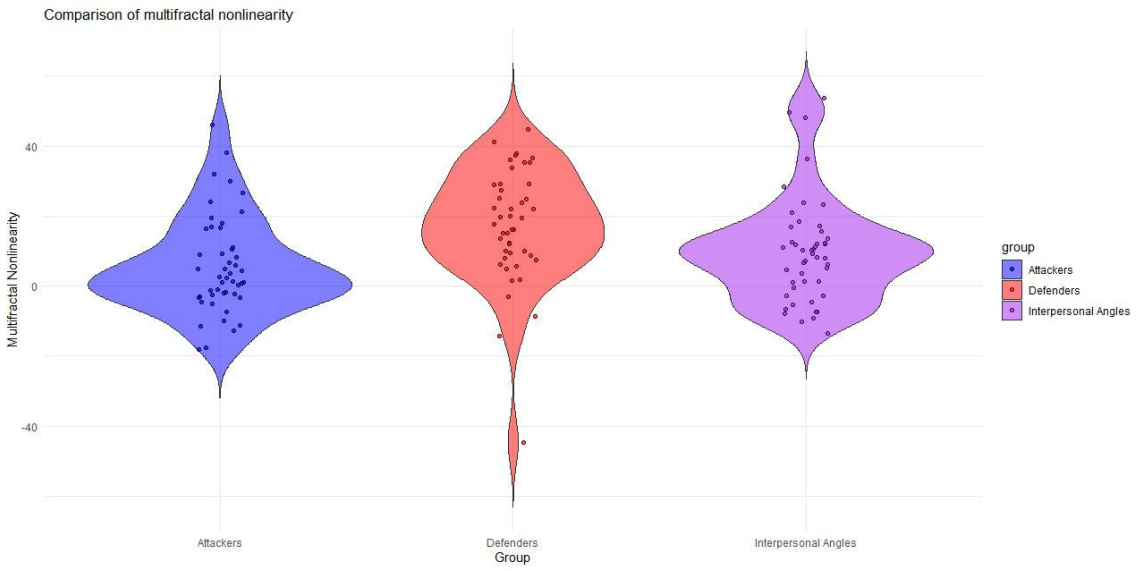
Violin plot comparing multifractal spectra widths for attackers, defenders, and interpersonal angles.



Multifractal nonlinearity (t_{MF}) also differed significantly by role $F(2, 137) = 6.793$, $p = .002$ (see Figure 8). The effect size (η^2) was 0.09, indicating a medium effect. A post-hoc Tukey test indicated that defenders displayed significantly more multifractal nonlinearity than attackers ($p = .001$), marginally significantly more multifractal nonlinearity than interpersonal angles ($p = .058$), and there was no significant difference in multifractal nonlinearity between attackers and interpersonal angle values ($p = .375$).

Figure 4.8

Violin plot comparing multifractal nonlinearity (t_{MF}) for attackers, defender, and interpersonal angles.



4.3.3.2 Hypothesis 3a and 3b: Multifractality and Attacker Score

The generalised linear mixed-effects model revealed main effects of anticipating synchronisation (τ), global multifractality (PC1), and the contrast between MFW and t_{MF} (PC5) on attacker score. Specifically, higher attacker scores were related to greater temporal anticipation (more negative values of τ), greater global multifractality (lower values of PC1) reflecting stronger nonlinear interactions between scales, and a higher proportion of multifractality owing to nonlinear interactions between scales (PC5). Notably, the effect of PC5 entails that attacker success depended less on the attacker's own multifractality and more on their ability to foster multifractality in the defender and interpersonal angle. The loadings of PC5 showed greater contribution of defender and interpersonal values of t_{MF}. The wider spectra and more multifractal nonlinearity displayed, on average, by defenders suggested that attackers constrained degrees of freedom as they control the ball. These results suggest that attackers exploited widened exploratory variability of the defender's movements with sharp, piercing attacks, lending support to the latter of the two exploratory hypotheses (3b).

4.4 Discussion

The present study tested three primary hypotheses. The results supported the predictions of all three. First, attackers exhibited temporally anticipating synchronisation with defenders (Hypothesis 1). Second, all trials for all players and dyads exhibited non-zero multifractal spectra widths (Hypothesis 2a) and significant multifractal nonlinearity (Hypothesis 2b), confirming the presence of interaction-dominant dynamics. Two exploratory hypotheses considered how multifractal nonlinearity would be associated with attacker score. Results failed to support the possibility that attacker score would be associated with greater attacker multifractality than defender or dyad multifractality (Hypothesis 3a). Instead, results supported the alternative hypothesis, i.e., that attackers scored more points when they fostered increased multifractal nonlinearity in the defender and interpersonal angle (Hypothesis 3b). The present findings develop on work by Passos et al. (2009) which found power-law distributions in the interpersonal angle values in antagonistically coupled 1v1 dyads while adding confirmation of nonlinear interactions between scales (i.e., multifractal nonlinearity) and modelling its role in attacker score. Passos et al. (2009) interpreted power-law distributions in fluctuations in 1v1s as a form of *self-organised criticality* (SOC) (Bak, 1996) which arises when multiple agents co-adapt to "the edge of chaos" (Kauffman & Johnsen, 1991). The present results confirm the presence of power-law behaviour in the fluctuations of 1v1s and lend support for the general interpretation of self-organisation under nested constraints. However, the role of multifractal nonlinearity t_{MF} in attacker scores generalises nonlinear interactivity beyond SOC models to the broader class of cascade models capable of generating heterogeneity (Ivanov et al., 2001; Kelty-Stephen & Wallot, 2017; Mandelbrot, 1999; Stephen et al., 2012). Furthermore, t_{MF} revealed the cascade model's ability to predict individual 1v1 outcomes.

These results suggest sport performance may rely on a lawful fluidity allowing players to act and respond on multiple time scales in a way that carries the events at one scale into adjustments and corrections at another. Classically, scholars have attempted to model sport as unfolding at two distinct levels: a local space of immediate interactions governed by superficial action-perception processes and a global "form space" of rules and tactics governed by representational knowledge structures (Ripoll, 2009). Such claims fall back on an older tradition of cognitive psychology that presumes a mental "knowledge level" housing and operating upon mental representations about events unfolding on a physical level of sensorimotor process (Newell, 1982). In such a framework, the antagonistically coupled dyad becomes a drama of duelling representational systems each trying to predict and outwit the other. Independence appears both within each player, separating knowledge from sensorimotor levels, and between each player, with each intentionally misleading the other. Consequently, from this perspective, it has made sense to address skill development in 1v1 contexts strictly through the movement patterns of the individual (Gearing & Bridge, 2022; Parry et al., 2025).

The present results show that there is more that warrants modelling in dyadic antagonistic coupling that the representational account can address. Understanding attacker success requires reckoning with multiple spatial (i.e. individual and dyadic) and temporal scales that overlap and thus prevent such clean fracturing of the antagonistically coupled dyad. In a 1v1, an individual's intention to successfully attack or defend refers to an outcome at the level of the dyad. To underscore the challenge in barer form: the player must respond to their own body and the dyad at the same time. For example, when an attacker A intends to evade a defender D, A's actions must refer to multiple scales of events, not just their current bodily state but to the dyadic set {A, D}. The dyad is a coordinative structure that becomes potentially another synergy in which A's movement

system must participate. Crucially, the dyad constitutes another scale beyond A's body in which A must achieve an outcome $O_{\{A, D\}}$. Hence, the dyadic-level definition of the goal must include an entailment that has the logical structure $A(\{A, D\}) \rightarrow O_{\{A, D\}}$. Mathematical theory has attempted resolve how to define independent members of a set that act according to the set they belong to. A century later, this program appears to be logically impossible (George, 1987; Russell & Whitehead, 1910; Turvey, 2018). Atomic components cannot approximate a distributed fluid process in which a single event has forking entailments that diverge across scales (Dewey, 1896; Gibson, 1960; Mandelbrot, 1999; Van Orden et al., 2010). The present evidence of cross-scale interactivity in 1v1 dyads suggests that this issue is more than a logical abstraction.

By contrast, advancing Passos et al.'s (2009) work to go beyond SOC toward the broader class of cascades, fluid dynamics affords a means of articulating lawful regularities in a way that avoids scale-bound approximations (Buckingham, 1914; Kelty-Stephen, 2024; Weyl, 2015). The lawful fluidity of the cascades provides a ready link between scales spanning both the individual and the dyad. Cascade-like interplay between laws and constraints governing and shaping flow, respectively, relaxes the need for a local, centralised point of control and suggests that intentionality may be expressed through an ecology of distributed constraints, rather than chain-like efficient causes (Juarrero, 1999; Kloos & Van Orden, 2010; Turvey, 2007). Eminent movement scientist, Nikolai Bernstein, observed that movement was better analysed as an integrated meshwork rather than a chain of independent details (see Bernstein, 1967, p. 69). The fluid adaptivity of movement manifests in intermittent, sweeping reorganisations stemming from non-obvious, non-local causes. Beyond the intuition that discretised, piecewise analyses fail to capture this form of system (re)organisation, multifractal cascade modelling provides a robust contemporary framework for the quantitative analysis of the nonlinear structures constraining and releasing degrees of freedom in

dexterous behaviour (Kelty-Stephen & Mangalam, 2022). The current results build on previous research showing that multifractal cascades may be the mechanism which enables attunement to this lawful, global structure and supports anticipatory coordination (Stephen et al., 2008; Stephen & Dixon, 2011). Rather than "weak" contingence on private predictive models (e.g., Ripoll, 2009; Rosen, 2012), this anticipation would be "strong" (Dubois, 2003). It would ground the prospectivity of adaptive behaviour in both the lawful invariant ecological structure and the exploratory behaviour which supports the discovery of this structure (Arzamarski et al., 2010; Kelty-Stephen et al., 2023; Stephen et al., 2012; Turvey, 2018).

Nested in the ecology of a sport dyad, the struggle between attacker and defender unfolds as a competition for affordances, i.e., the possibilities for action (Gibson, 2014; Kelty-Stephen, 2024). For instance, the distance between targets in the present 1v1 task presses upon the classical affordance of reachability (Carello et al., 1989; Choi & Mark, 2004), a tradition which might cast the reachability affordance in the 1v1 as some ratio of leg length to inter-target distance (e.g., Warren, 1984). However, the 1v1 task objective nested reachability within the added constraints posed by antagonistic coupling. The classical ratio of bodily to context lengths thus accrue a dizzying number of time-varying denominators. To score a point, an attacker needed to perceive *where* they could contact the target with foot on ball *when* the defender could not reach the target first. So, it is not just reachability but a murkier "reach-first-ability" affordance which is highly specific to ebbing and flowing task constraints of 1v1 contexts in competitive sports. The crucial role of anticipating synchronisation in attacker success suggests that this temporal relationship is a primary concern for both players. The "reach-first" affordance is not simply the nesting of the body within a static task. Reaching first abuts and indeed conflicts with the defender's leg length: a scoring opportunity is equally a defending inopportunity. Another denominator looms as attacker or defender's previous movements

constrain their future possibilities. The classical sense of affordance-as-single-ratio falters as the nesting relationships change the constraints on reachability. Furthermore, these time-varying constraints on reachability likely only compound with other affordances like controllability of the ball. The attacker's search for a strategic marginal difference beyond the defender's affordances are most likely nested sequences unfolding amidst the ebbing and flowing constraints rather than discrete movements.

Multifractality offers new traction on understanding 1v1 because it addresses the nested complexity of affordances. With fluid accumulation of constraints, the affordance as a body-context ratio quickly yields to a cascade of successive divisions—that is, multiplicative relationships—among constraints at multiple scales. If 1v1 coupling complicates the single body-context ratio sense of affordance, it may be time to consider multifractality as means to formalise the affordance relationships supporting competitive coordination in sport. Multifractality of head movement has been shown to increase near the action boundaries in judgements of the stand-on-ability of slopes (Hajnal et al., 2018). So, multifractality may offer a generic means to model the movement variability allowing players to explore the nesting relationships supporting affordance perception. Multifractal-spectrum width and multifractal nonlinearity are ways of indexing how much and why, respectively, the fluid meshwork of the Bernsteinian movement system releases its degrees of freedom (Kelty-Stephen & Farrokh, 2025). Attackers may thrive by cultivating proximity to the defender's action boundaries, provoking defenders to widen their exploratory variability in an attempt to maintain poise. Deceptive moves executed near the boundary of the defender's affordance to reach a target may generate uncertainty and support the attacker's objective of destabilising the dyad. One-v.-ones may require attackers to narrow and, therefore, direct nonlinearity in movement towards the marginal excess of attacking affordances beyond a defender's affordances. The relative narrowing

of attacker's nonlinear multifractal variability may reflect a transition from exploring for this marginal excess to zeroing in on and exploiting it.

4.5 Limitations and Directions for Future Research

The present work represents a first step towards understanding the dynamical flows of antagonistic couplings in invasion games. This study was able to measure and model an extended period of antagonistic coupling with precision. However, this precision came at the cost of limiting play to a single axis in 1v1 exchanges divorced from any team coordination and from any broader match context. The very rhetoric about the force of interactions across scales entails that future research should be ready to extend the present modelling to contexts of game play across broader scales. That is, future research might investigate the 1v1 dynamic between specific pairs of players within the context of a full match, potentially examining how specific dyads develop their antagonistic coupling with successive encounters. Future research including ball tracking could also investigate progressively higher-order collective variables encoding player-ball-goal angles (e.g., Carrilho et al., 2020).

Future work might also address a more distributed network of coupled agents. This distributed-network approach could expand beyond 1v1 to whole-team dynamics, e.g., towards a multifractal portrayal of a "group tensegrity" (Caldeira et al., 2020). This network approach might also focus inward to within-player dynamics. Longer-term data collections across full-body marker sets allow the modelling the flow of fractal-fluctuations across the body (Mangalam et al., 2020a, 2020b; Carver et al., 2017), reflecting body-wide tensegrity organisation (e.g., Turvey & Fonseca, 2014). The present limited data collection could only find that local Hurst exponent values for attackers, defenders, and interpersonal angles appeared to covary closely within trials. Similar network modelling has shown that multifractality helps to classify social coordination across groups or swarms of organisms as attractive or repulsive for resources (Carver &

Kelty-Stephen, 2017; Dixon & Kelty-Stephen, 2012). The nonlinear interactions across scale may entail consonant cascades both within and among organisms in social interactions. Multifractality offers a potentially common framework for understanding coordination within and among organisms (Kelty-Stephen, 2017). Sport offers a diverse array of progressively more complex circumstances and coordinative modes for understanding pursuit-evasion interactions.

The present work was exploratory of one sport-specific pursuit-evasion interaction, but experimental manipulation of the affordance layout would generalise this work towards wider ecological frameworks for pursuit-evasion interactions. Specifically, experimental manipulation of inter-target distances as ratios of attacker's or defender's leg length could clarify the role of reachability. Explicit manipulation of the affordances could reveal how attackers might cultivate proximity to the defender's action boundaries. Crucially, attackers might be exploiting the pursuing defenders' action boundaries to encourage more exploratory variability. Changes in the affordance layout might change the evading attacker's capacity to fake out the pursuing defender. If indeed multifractal modelling can formalise affordance relationships, then experimental manipulations might influence the multifractal results and their relationships with antagonistic outcomes.

Multifractal modelling could also enable further empirical exploration of the claim that sports emerge as sets of replicable task constraints that players select for their ability to foster enjoyable experiences (see Chapter One, Chapter Three). Multifractality has already demonstrated leverage into the dynamics of experience in computer games (Bennett et al., 2022; Dotov et al., 2017), and it is anticipated that similar analyses could help inform the constraint selection process in competitive contexts such as sports. Future work might aim at optimal or "flow" experiences (Csikszentmihalyi, 1990) more precisely by triangulating between constraint manipulation, flow measures, and cascade modelling. Flow experiences might reflect precisely those fluid aspects of cognitive

process that cascade dynamics are best suited to predict. Multifractal analysis might show flow and cascades to be more than a coincidental pun.

4.6 Conclusion

Multifractal modelling of 1v1s suggests that competitive co-adaptation rests on the nonlinear interaction across time scales and not a simple sequence of independent events. Attacker success increased with greater anticipatory synchronisation and less multifractal nonlinearity than for the defender and interpersonal angle. More broadly, present findings encourage future study of the nesting in affordance layouts and network relationships unfolding across individuals, teams, and competitive interactions. Multiscale approaches to ecological dynamics approach might allow stepping beyond performance analysis towards querying the values (Hodges & Rączaszek-Leonardi, 2022) guiding the selection of constraints for athletic participation and the self-organisation of group-tensegrity structures. This strategy might allow a more active and responsible role in shaping the future of sport.

The supplemental materials which include the R code for the anticipating synchronisation metric and regression models as well as the data used in the regression models are available at: https://osf.io/8f7gt/?view_only=b966a43f45e74668b03ec286a9062516

Chapter 5:

The Multiscale Dynamics of Flow in Competition

5.1 Introduction

Chapter 4 analysed the multiscale dynamics of antagonistic couplings in a 1v1 task, finding strong evidence of nonlinear interactions between scales of events in this performance context. Furthermore, this nonlinear release or constraint of degrees of freedom supported successful performance in both attacking and defending roles. This outcome provides some support for the possibility raised in chapters two and three: that is, much of the difficulty understanding flow would be explained if flow activities are often characterised by interaction-dominant dynamics while many theoretical explanations of flow assume component-dominant dynamics. More simply, explaining the emergence of flow experiences via sequences of mental processes becomes difficult in activities that exhibit interaction-dominant dynamics and suggests the need for an alternative strategy. However, the contraindication of a common form of explanation does not provide a positive account of flow. Hence, the objective of this chapter is to demonstrate the potential of multiscale eco-physical variables to explain the emergence of flow experiences in the same 1v1 activity.

Since the inception of the concept, sports have been recognised as a prominent class of flow activities (Csikszentmihalyi, 1975; Jackson, 1996). Sports can be divided into branching families such as martial arts, endurance sports, net sports, and invasion games. Invasion games are team sports in which two teams compete to manipulate a ball or similar object into goals or zones on opposite ends of a playing area. Invasion games involve one-v.-one sub-phases (henceforth 1v1s) which emerge when the distance between an attacker and a defender becomes small and the movements of both players becomes tightly coupled (Passos et al., 2016). 1v1s exemplify antagonistic coupling, a form of competitive coordination in which one member of a dyad repels while the other attracts (De Poel, 2016). Antagonistic coupling is a form of competitive coordination which can be observed in evolutionary processes such as predator-prey relationships

(Dotov & Paxton, 2024). Although not all flow experiences occur in sports and not all sports are characterised by antagonistic coupling, the present work explored the relationship between flow and antagonistic coupling in a 1v1 futsal task.

Flow has traditionally been conceptualised as an internal, subjective experience (Csikszentmihalyi, 1990; Engeser et al., 2021), leading flow researchers to prefer the individual as the primary unit of analysis. The study of flow beyond the individual has largely been dedicated to teams or *collaborative* groups (e.g., Van Den Hout & Davis, 2019). While several studies have examined the relationship between flow and the dispositions or attitudes (e.g., confidence, anxiety) of individual performers during competition (Koehn, 2013; Koehn et al., 2013; Sodhi et al., 2016), the competitive relationship itself (e.g., antagonistic coupling) has less often been the explicit focus of study. This may be because the concept of flow has roots in *positive* psychology while the competitive relationship may carry a *negative* connotation, as evidenced by the somewhat unfortunate term 'antagonistic coupling'. Nevertheless, it is possible that competitive coordination holds important insights for flow research and positive psychology.

The motivation for making the antagonistic coupling an explicit focus in the study of flow can be expressed as follows. Chapters Two and Three highlighted two related issues which might contribute to the difficulty studying and explaining flow scientifically. First, it was suggested that flow researchers had struggled to frame the skill-challenge relationship in flow activities tractably because they lacked the key concept of affordances (i.e., lawfully supported possibilities for action; (Gibson, 2014)). An affordance-based approach to flow research entails an emphasis on the lawful nesting of the performer within the performance environment (Kelty-Stephen et al., 2025) and, therefore, motivates testable hypotheses about the multiscale dynamics of nested events in flow activities. Second, a multiscale, affordance-based perspective on flow diverges

from a tradition in flow research which seeks to ground explanations of flow in stable neural, physiological, or mental markers (e.g., Peifer & Tan, 2021). Whereas modelling flow as the sum of independent component factors requires that flow arise due to the contribution of pre-defined modules, an ecological approach suggests that nonlinear interactions between scales and the ergodicity breaking entailed (Molenaar & Campbell, 2009) might confound this strategy. Giving the multiscale dynamics of competitive coordination a central role in the study of flow relaxes the assumptions required for the linear modelling of independent factors while opening the door to identifying more fluid, functional markers that enable ergodic description of non-ergodic processes (see Mangalam & Kelty-Stephen, 2022).

Antagonistic coupling also highlights the always-present mutuality between individual and environment. In terms more familiar to flow research, antagonistic coupling means that the skills of one individual are challenges to the other and vice versa. Analyses which are tied to the scale of the individual must break this symmetry by arbitrarily designating one agent as the individual and the other as the environment. However, as discussed in section 4.4, the supra-individual level of the dyad can be shown to factor into the intentions of both individuals since common sporting objectives (e.g., scoring, preventing scoring) refer to mutually exclusive states of the dyad (see section 4.4 in the previous chapter). Notably, affordances possess the required logical structure (i.e., impredicative entailment) to describe relationship between an individual and the individual-environment system they participate in (Chemero & Turvey, 2007, 2008) and, therefore, provide a necessary link between personal experience and the external performance environment.

In addition to rectifying the issue of organismic asymmetry, the present use of multiscale dynamics to explore flow experiences addresses another methodological concern raised in chapters one and three: the treatment of the relationship between lawful

dynamics and rule-like constraints in the shaping of (flow) experience. Although sports and games are commonly equated with their rules (e.g., formalism (Suits & Hurka, 1978), rules, as such, are not experienced. As suggested by the term *flow*, the object of experience is a dynamic, if intermittent, stream of events (Heft, 2001; James, 1890). However, traditional analyses of dynamics alone do not permit consideration of the way in which constraint selection shapes experiences. For instance, a constraint manipulation such as doubling the diameter of the hoop in basketball game might reasonably be expected to change the experience of gameplay, although the diameter of the hoop is treated as a constraint in the analysis of the dynamics. Furthermore, it is not the diameter of the hoop that is experienced per se, but its impact on the dynamics of participants as they explore new lawful possibilities (i.e., affordances) to shoot the ball into the bigger hoop. Thus, a method capable of assessing the texture of the dynamics under the constraint ecology of the activity becomes an important desideratum for flow research.

By way of analogy, consider an individual in a small boat on a river. A large rock in the riverbed may create ripples or eddies in the stream of water. Although the rock is not experienced *directly*, its presence may be perceived *through its impact on the dynamic flow* of the water. More literally, the cascade modelling techniques utilised here were originally developed in the field of fluid dynamics to support analysis of very similar scenarios (Kelty-Stephen et al., 2013; Mandelbrot, 1974; Yaglom, 1966). Cascades involve the successive multiplication of random variables over progressively finer or coarser scales with the influence of contextual factors or constraints at one scale being carried through to the next in this successive splitting (Kelty-Stephen & Farrokh, 2025). Far from deterministic automatism of movement (e.g., Dietrich, 2004), cascade models estimate the *context-sensitivity* of a dynamic processes such as dexterous behaviour in flow. As such, cascade modelling provides an ideal tool for exploring how flow

experiences might emerge as performers release and constrain their degrees of freedom during competitive coordination.

An initial hypothesis implicit in the design of this study was the expectation that an activity constrained to generate tight antagonistic coupling would likely be conducive to flow experiences. Therefore, hypothesis 1 was that that the activity would generate Flow Short Scale (FSS; Rheinberg et al., 2016) scores significantly greater than the 7-point scale's midpoint of four. Based on the understanding that individuals within the antagonistically coupled dyad both continually transform the possibilities available to each other, hypothesis 2 was that participants' flow scores would be sensitive to the multifractal properties (MFW and t_{MF}) of both their own and their opponents' movement. In more detail, hypothesis 2a considered the possibility that participants' flow scores would relate positively to their own multifractal nonlinearity t_{MF} and negatively to their opponents'. Hypothesis 2b was that participants' flow would relate negatively to their own multifractal spectra width MFW and positively to their opponents'. Continuing this relational emphasis, hypothesis 3 was that greater (attacker) anticipatory synchronisation (more negative values of τ) would be associated with higher flow scores for attacker and lower flow scores for defender.

5.2 Method

5.2.1 Participants

Twenty male football and/or futsal players aged 18 to 38 years (M = 23.55, SD = 4.88) with three or more years of self-reported experience playing football (M = 11.05, SD = 4.73) or futsal (M = 1.05, SD = 1.23) at any level participated in this study on a voluntary basis. The study was approved by the Sheffield Hallam University ethics committee (Converis ID ER47422746) with each participant providing informed consent before taking part in the study.

5.2.2 Situational motivation and contextual considerations

Facilitating flow in the laboratory has been likened to "trying to make someone to relax in a dentist's chair" (Moller et al., 2010, p. 192). One explanation for this difficulty is the possibility that tasks commonly used to solicit flow in experiments (e.g., Tetris, Pacman, arithmetic tasks) may not inhabit sufficiently meaningful roles in the lives of participants to support genuinely intrinsic motivation (Durcan et al., 2024). Alternatively, flow researchers have prioritised the richness of the flow activity in career-based methods, such as interviewing an athlete about a long-past championship match (Jackson, 1992) while accepting the limitations of retrospective recall (Jackman et al., 2017, 2022). Experimental studies of flow which carefully consider the autonomy and motivation of the participants are, therefore, critical if both task representativeness and empirical precision are to be maintained (Durcan et al., 2024; Jackman et al., 2017).

To address these pressing concerns, both the nature of the task and the broader context of participation were considered in the design of the study. Participants were recruited from student recreational sports activities on campus and by word of mouth. Participation was on a voluntary basis, and no extrinsic rewards were offered. Additionally, participation was restricted to individuals with three or more years of self-reported experience playing either football (M = 11.05, SD = 4.73) or futsal (M = 1.05, SD = 1.23) in part to ensure that the activity (which represented aspects of futsal and football) bore some relationship to the interests of the participants' personal lives. To test these motivational attitudes, participants were asked to complete the situational motivation scale (SIMS; Guay et al., 2000) once following their initial trial. The SIMS is a 7-point Likert scale which contains four subscales (intrinsic motivation, identified regulation, extrinsic regulation, and amotivation) to reflect different attitudes towards a specific situation (Guay et al., 2000).

5.2.3 Design

Please refer to section 4.2.2. for the design of the 1v1 activity.

5.2.4 Procedure

The procedures for the 1v1 task can be found in section 4.2.3. In addition to the procedures detailed there, all participants completed the FSS (see Appendix 5.1) (Rheinberg et al., 2016) immediately after the conclusion of every 60-second trial. The FSS contains ten core items which assess flow experience in an activity (Rheinberg et al., 2016). The shorter FSS was preferred to the longer (36-item) Flow State Scale due to the need for participants to complete a flow measure after each trial. Participants also completed the SIMS scale once after their initial trial. Upon completion of the FSS, participants switched attacker/defender roles and completed another 60-second trial before completing a second FSS questionnaire. Each match therefore consisted of two trials: (A) participant 1 attacker vs. participant 2 defender, and (B) participant 2 attacker vs. participant 1 defender. This structure yielded four FSS questionnaires per match, capturing each participant's experience in both attacking and defending roles.

5.2.5 Data processing and variable creation

28 matches (56 trials) were recorded. Twelve trials were excluded due to marker dropout, leaving 44 trials for data analysis. Each trial produced two FSS questionnaires, however, one participant did not complete an FSS for one trial, so the total number of FSS scores for data analysis was 87. As calculated and detailed in sections 4.2.5.2 and 4.2.5.3, the multifractal spectra width (MFW), multifractal nonlinearity (t_{MF}) for both players and the interpersonal angle, the anticipating synchronisation measure (τ), and the attacker score corresponding to each FSS were also calculated.

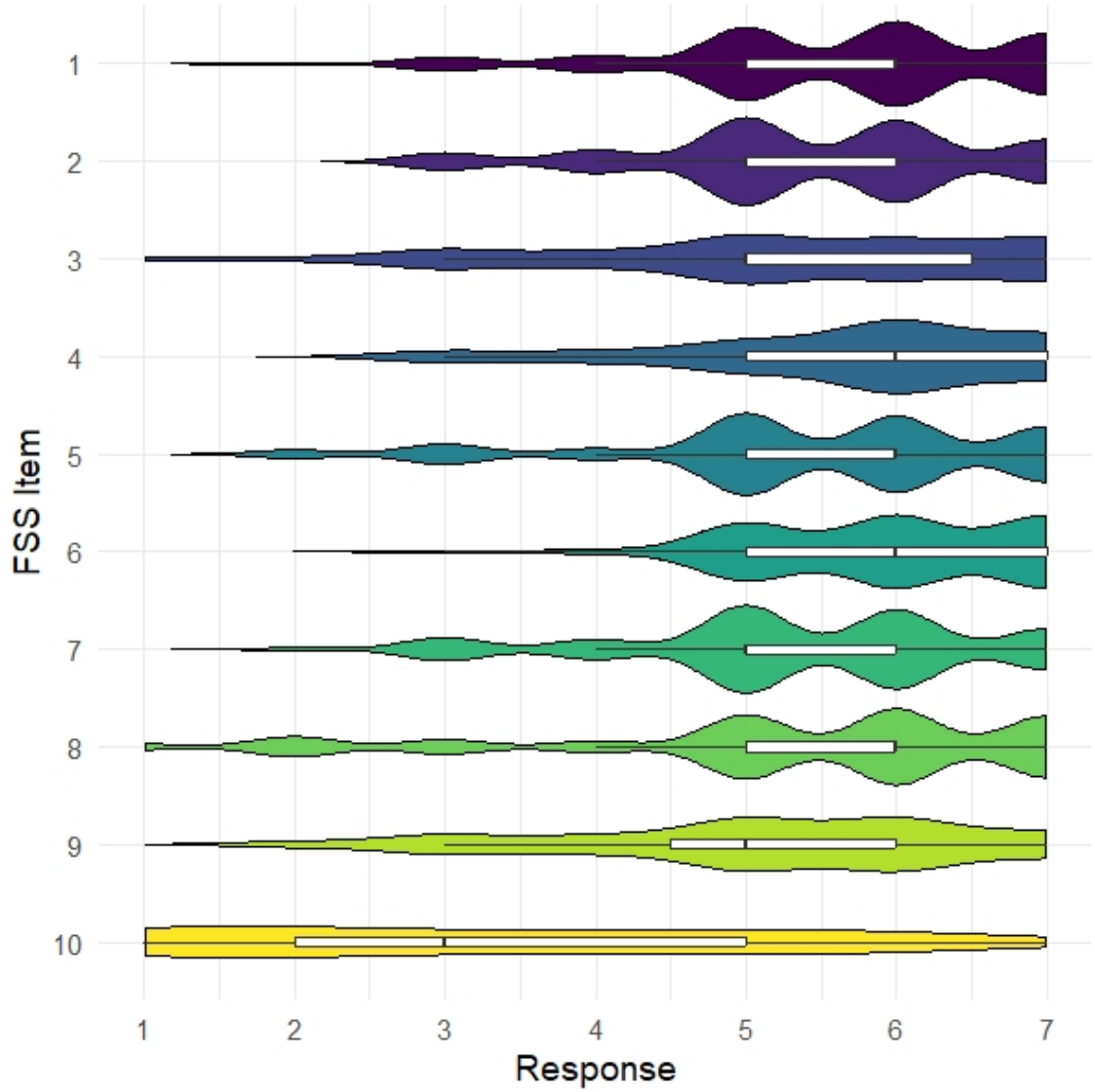
5.3 Data Analysis

5.3.1 Flow scores for testing hypothesis 1

To assess the internal reliability of the flow scores in the present study, Cronbach's alpha was computed with the function "alpha" from the package "psych" (Revelle, 2024). The ten core items of the FSS displayed sufficient internal reliability (α = .79) as well as the fluency subscale (α = .82), but the absorption subscale displayed a lower consistency (α = .37), likely due to item 10. Item 10 asks participants to agree or disagree with the statement "I am completely lost in thought", with higher agreement contributing to a higher score on the absorption subscale. The lower reliability of the absorption subscale has been previously recognised and attributed to the potentially ambiguous wording of item 10 (Kyriazos et al., 2018; Laakasuo et al., 2022). Dropping this item from the results was considered, however, the primarily unidimensional behaviour of the full 10-item FSS motivated the conservative choice of including all responses and assessing flow as a single factor. As such, the mean of the 10-item FSS was compared to the scale's midpoint of four with a one-tailed one-sample t-test to test hypothesis one. Although the FSS assesses flow as a graded rather than dichotomous variable, comparison to the scale's midpoint supported differentiation between episodes of "micro-flow" reflecting mild attentional engagement in trivial tasks (Csikszentmihalyi, 1990) and deeper experiences of flow which we hypothesised would be common in tightly coupled competitive coordination demanded by the futsal task.

Figure 5.1

Violin plots of responses to the ten core flow items of the FSS.



5.3.2 Generalised linear model for testing hypotheses 2, 2a, 2b, and 3

The mean of the 10-item FSS for each participant in each trial was modelled as the dependent variable "flow score" to test hypotheses 2, 2a, 2b, and 3. A generalised linear model was fitted with the package 'glmmTMB' using the function 'glmmTMB' with an identity link and family set to 'Gaussian' (Brooks et al., 2017). Attackers were defined as the reference group. Whereas Chapter Four utilised principal component analysis, variance inflation factors under ten enabled the use of the raw multifractal statistics in the modelling of flow score. Multifractal spectra width (MFW) and multifractal nonlinearity ($t_{MF)}$ for attackers, defenders, and the interpersonal angle, anticipating synchronisation (τ), attacker score, role, and their interactions were initially

included. The model presented here was selected based on predictor stability across alternative specifications and parsimony to avoid overfitting. Removing item 10 of the FSS (a consideration discussed in section 5.3.1) did not cause any significant alterations to the results of this model. Visual inspection of the Q-Q plot and residual diagnostics indicated approximate normality (Shapiro–Wilk $W = 0.99$, $p = 0.91$) and homoscedasticity (Breusch–Pagan $BP = 6.41$, $df = 8$, $p = 0.60$).

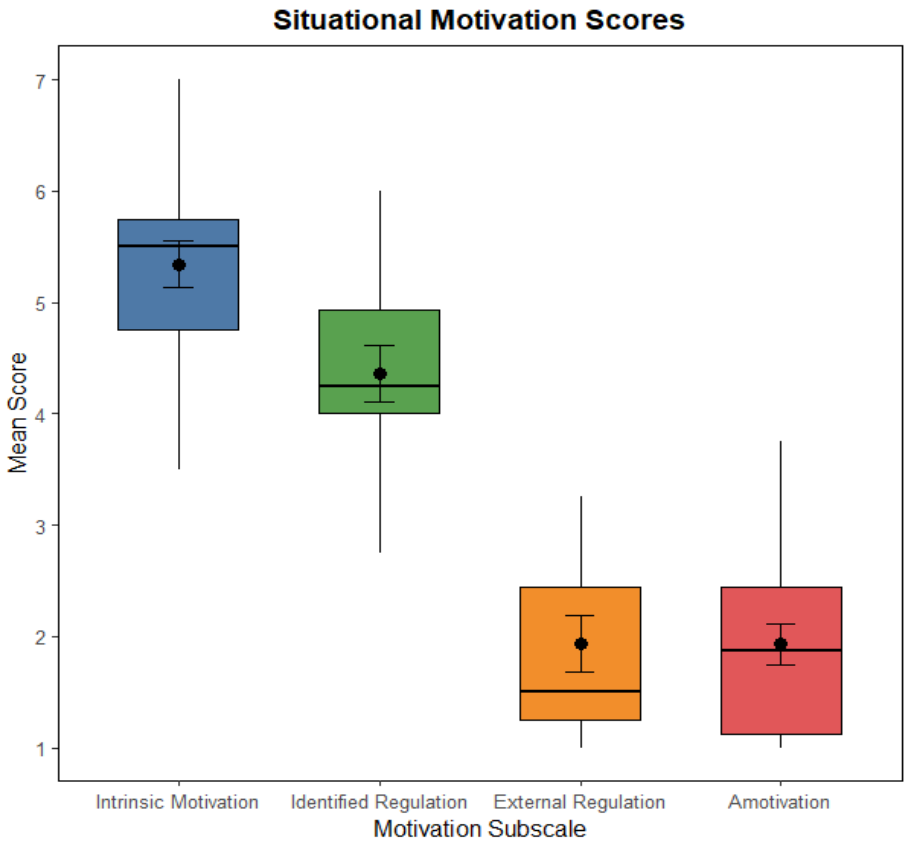
5.4 Results

5.4.1 Situational motivation

The situational motivation (SIMS) questionnaire revealed a high degree of intrinsic motivation ($M = 5.34$, $SD = .87$) with low degrees of extrinsic regulation ($M = 1.94$, $SD = 1.07$) and amotivation ($M = 1.93$, $SD = .80$) (see Figure 5.2). These results indicate that participants generally expressed positive attitudes towards the task, which was deemed to be intrinsically motivating.

Figure 5.2

Box and whisker plots of the SIMS questionnaire results.



5.4.2 Hypothesis 1: Antagonistic coupling will generate above-average flow scores

The results of the FSS indicated high flow scores (M = 5.27, SD = .79). A one-tailed one-sample t-test supported hypothesis 1, which expected that flow scores would be significantly higher than the scale's midpoint of four, $t(86) = 15.09$, $p < .001$). A Wilcoxon signed-rank test further supported the hypothesis that flow scores were significantly higher than the midpoint of the scale ($V = 3527$, $p < .001$).

5.4.3 Hypothesis 2: Flow scores will be sensitive to multifractal properties of both individuals

The results of the generalised linear model (Table 5.1) indicated that flow scores for both attackers and defenders were sensitive to the multifractal properties of their opponent's movement. Defenders' flow appeared to be less sensitive to their own movement than that of their opponents, while attacker flow depended on both their own and their opponents' movements. These results support hypothesis 2 fully for the

attacking role but only partially for the defending role. Model results relating to the more detailed sub-hypotheses, 2a and 2b, are reported in the following sections.

Table 5.1

Generalised linear model for flow scores

	Flow Score				
Predictors	*Estimate (β)*	*std. Error*	*Conf. interval*	*z-value*	*p*
(Intercept)	5.61	0.55	4.54 – 6.69	10.26	**<0.001**
Defender MFW	0.95	0.24	0.48 – 1.43	3.94	**<0.001**
Defender t_{MF}	-0.02	0.01	-0.03 – -0.01	-2.87	**0.004**
Anticipating synchronisation (τ)	-0.01	0.00	-0.02 – 0.00	-1.63	0.103
Attacker MFW	-1.89	0.65	-3.15 – -0.62	-2.92	**0.003**
role [defender]	-1.16	0.72	-2.57 – 0.24	-1.62	0.105
Attacker t_{MF}	0.04	0.01	0.01 – 0.07	2.50	**0.013**
Attacker MFW * role [defender]	2.13	0.90	0.37 – 3.88	2.37	**0.018**
Attacker T_{MF} * role [defender]	-0.05	0.02	-0.09 – -0.01	-2.29	**0.022**
Observations	87				
R^2 / R^2 adjusted	0.301 / 0.220				

5.4.3.1 Hypothesis 2a: Flow scores will relate positively to participant's own t_{MF} and negatively to opponent's t_{MF}

Attackers' flow increased when their own multifractal nonlinearity was greater (β = 0.04, SE = 0.01, 95% CI [0.01, 0.07], z = 2.50, p = .013) and decreased as defender multifractal nonlinearity increased (β = −0.02, SE = 0.01, 95% CI [−0.03, −0.01], z = −2.87, p = .004). Defenders' flow scores decreased with greater attacker multifractal nonlinearity as revealed by the significant interaction with the defending role (β = −0.05,

SE = 0.02, 95% CI [−0.09, −0.01], z = −2.29, p = .022), but their own multifractal nonlinearity was not a significant predictor. These results fully support Hypothesis 2a for attackers and partially for defenders.

5.4.3.2 Hypothesis 2b: Flow scores will relate negatively to participant's own MFW and positively to opponent's MFW

Similarly, attackers' flow decreased as their own spectra widened (β = −1.89, SE = 0.65, 95% CI [−3.15, −0.62], z = −2.92, p = .003) and increased as defenders' spectra widened (β = 0.95, SE = 0.24, 95% CI [0.48, 1.43], z = 3.94, p < .001). Again, the significant interaction with the defending role indicated that defenders' flow increased as attacker's spectra widened (β = 2.13, SE = 0.90, 95% CI [0.37, 3.88], z = 2.37, p = .018) but their own spectra width failed to significantly predict their own flow scores. These results support hypothesis 2b with respect to attackers and, again, only partially with respect to defenders.

5.4.4 Hypothesis 3: Attacker flow and defender flow will relate positively and negatively to anticipatory synchronisation, respectively

The anticipatory synchronisation metric τ trended towards a positive relationship with attacker flow (note that more negative values of τ reflect greater attacker anticipation) but was not significant at α = .05 (β = -0.01, SE = 0.00, 95% CI [-0.02, 0.00], z = -1.63, p = .103) and did not exhibit a significant relationship with defender flow. Despite not being a significant predictor of flow, τ improved model fit (AIC), warranting its inclusion. Concerns about model overfitting suggested against including an interaction between τ and role. Thus, hypothesis 3 was not supported.

5.5 Discussion

The present study tested three hypotheses. The results of the t-test supported hypothesis 1 while the generalised linear model supported hypotheses 2, 2a, and 2b fully

with respect to attackers and partially with respect to defenders. Hypothesis 3 was not supported. The present findings lend support to three broader claims developed in this thesis. First, flow activities may often exhibit interaction-dominant dynamics which could explain the difficulties experienced within popular component-dominant explanatory strategies. Second, if explanations of flow are limited to a single scale, such as the internal states of the individual, vital information is lost since flow scores in both roles were sensitive to properties of opponent movement. Finally, and most critically, multifractal cascade dynamics provided strong predictors of flow during competitive coordination.

The consistently above-average scores on the FSS taken together with the high degree of intrinsic motivation indicated by the SIMS scale suggest legitimate and non-trivial experiences of flow often occurred during completion of the 1v1 task. However, explaining these experiences presents a challenge for traditional approaches to flow research. Although it might be observed that the activity fits the three traditional antecedents of flow (i.e., clear goals, immediate feedback, balance of challenges and skills (Nakamura & Csikszentmihalyi, 2014)), these broad descriptors of the pre-conditions of flow have not, thus far, supported reliable facilitation of flow experiences in sport (Goddard et al., 2021; Swann et al., 2012). Furthermore, match scores - the most intuitive marker of these conditions - did not provide a significant predictor of flow in this task.

To supplement course-grained verbal descriptions of potential antecedents, flow researchers have often appealed to yet-to-be-discovered neural or physiological markers (e.g., Peifer & Tan, 2021), with many proposals of these markers on offer (Dietrich, 2003; Gold & Ciorciari, 2021; Harmat et al., 2015; Harris et al., 2017; Weber et al., 2009) but little progress towards consensus in the neuroscientific study of flow (Alameda et al., 2021). Although the difficulty of conducting brain imaging during immersive activities has been cited as a practical limitation on the identification of these markers (Moller et al., 2010), the present results suggest that a deeper dilemma may be hindering progress

within this paradigm. As elucidated in chapter two and briefly here in the introduction, the assumption that the psychological experience of flow is generated centrally from some combination of identifiable independent factors within the nervous system requires that different spatial and temporal scales of the performer-environment system are "vertically separated" and thus additively decomposable (Simon, 1977). However, the time series of performance in the present task all exhibit clear signatures of cross-scale interactions (significant differences between MFW of original and linear surrogates), indicating that this assumption is violated in the context of the present activity. More generally, multifractal nonlinearity has also been linked to the breaking of ergodicity (Kelty-Stephen & Mangalam, 2022; Mangalam & Kelty-Stephen, 2021, 2022), supporting the hypothesis in section 3.11.3 which expected the difficulty identifying stable markers of flow may be related to nonlinear interactivity-induced non-ergodicity.

The same cross-scale interactions that create difficulty for component-dominant explanations of flow open the door to the intriguing possibility of cascade-based explanations, which may have been implicitly suggested by the term "flow" all along. In the present study, the cascade model provided strong predictors of flow experiences beyond what was evident in self-report or performance measures. The flow scores of both participants increased when their opponents' movements displayed wider spectra and decreased when their opponents' movements exhibited stronger multifractal nonlinearity. Attackers' scores also increased with greater multifractal nonlinearity in their own movements and decreased with wider spectra. These findings permit theoretical interpretation of how the nonlinear release and constraint of degrees of freedom may lead to the experience of flow during competitive coordination.

Competitive coordination highlights the psychological significance of the jagged multifractal structure of affordances and their boundaries. Attackers experienced the most flow when their deceptive movements were able to force their opponent to produce

higher-variability exploratory behaviour (e.g., wider spectra) around affordance boundaries but not effectively release degrees of freedom to maintain poise (lower t_{MF}). Meanwhile attackers' flow increased when they generated more precise attacks with lower variability (narrower spectra) while still leveraging multifractal nonlinearity (higher t_{MF}) to unleash their own movement system degrees of freedom (see Kelty-Stephen & Farrokh, 2025) towards the boundaries of defenders' coverage. Rather than a static cut-off point, affordance boundaries in competitive contexts present a moving target that is continually redefined and renegotiated in the fluctuations of play (see section 4.4). Maintaining an advantageous relationship to these co-defined affordance boundaries thus requires players to coordinate their own movements across multiple scales with higher dexterity relative to the opponent.

Defender flow displayed slightly different characteristics to attackers. Whereas attackers' own movements factored into their flow, defenders' own movement did not significantly predict their own flow. This may be because defenders did not have the added constraint of dribbling the ball and may have been able to focus more exclusively on the movement of their opponents. Although not a significant predictor in the model, defenders' MFW did display a positive relationship with their own flow, indicating that defender MFW may have been the only variable that did not display a role-specific reversal in its relationship to flow score. Trials in which defenders displayed wider spectra were strongly associated with higher attacker flow without inhibiting (and perhaps weakly supporting) defender flow. This pattern may be explained with recourse to the constraints of the task. Attacking the two targets without being able to leverage other affordances (e.g., shooting, passing) that are present in full football and futsal matches made destabilising the defender a considerable challenge. Thus, trials in which attackers were able to provoke higher variability in defender movements may have been more engaging for both participants.

Situated within ecological theory, the cascade-dynamical model of flow presented here may also offer access to an aspect of flow that has been difficult to capture empirically. Flow experiences often involve embodied sensations that can be difficult to measure or convey. Phenomenological research, for instance, highlights qualities such as "bounciness" in runners' descriptions of optimal experiences (Jackman et al., 2023). Scientific analysis of such sensations was long hindered by the absence of a clearly identified *medium* (cf. Gibson, 2014) for haptic perception. The *multifractal tensegrity hypothesis* addresses this gap by locating the medium for haptic perception in the nested interplay of tensile and compressive elements that structure biological organisms (Turvey & and Fonseca, 2014). This tensegrity architecture spans scales from microscopic extracellular matrices to the macroscopic skeletomuscular and connective tissue systems, enabling mechano-sensitivity through the global distribution of force (Ingber, 2003, 2008; Levin, 2011). Ecological theorising has proposed that all perception engages this tensegrity-based haptic medium (Cabe, 2019), which might provide new insight into aspects of flow experiences during competitive coordination.

The present study tracked the position of a marker affixed to participants' sacra. Rather than resting on the surface of support via continuous compression (like a tower of blocks), the sacrum relates to the pelvis through a suspensory system which more closely resembles the hub and spokes of a bicycle wheel (Levin, 2007). This taut pre-stress of tensegrity architecture explains the documented phenomenon of "ultra-fast cognition" or "preflexes" – adaptive responses which occur too rapidly to leave time for information processing (Wallot & Van Orden, 2012) – and likely plays a role in competitive coordination. In antagonistic coupling, probing affordance boundaries may require perceiving the tuning of a competitor's tensegrity-based movement system as expressed in the multifractal fluctuations of their motion. Accordingly, the predictive role of opponent multifractality for flow experiences may stem from participants' judgments

about how their opponents' action capabilities interacted with their own to shape the affordances available to them.

Several predictors are notable by their absence in this model. Hypothesis 3 predicted a role-specific relationship between τ and flow. Although this relational variable provided information on attacking performance in chapter four, it did not serve as a significant predictor of flow. Likewise, neither MFW nor t_{MF} of the interpersonal angle displayed clear relationships with the flow scores of participants in either role. The lack of information provided by these variables may indicate that the cascade dynamics of the players play a more central role in the determination of flow experiences in this activity. Given that τ and the multifractal characteristics of the interpersonal angle did help predict attacker score, their absence in the model of flow also suggests that the predictors of flow in this task are not identical to the predictors of performance.

5.6 Limitations and Directions for Future Research

The primary aim of the present study was to test the feasibility of cascade-dynamical models of flow and provide initial insights into the multifractal properties which related to flow in antagonistic coupling — a form of competitive coordination common to many sports. Demonstrating the potential of cascade dynamics to model flow was a necessary step before experimental manipulation of task constraints could be undertaken. In this initial step, the ecological dynamics framework demonstrated the ability to guide the selection of task constraints leading to flow experiences, as reflected in hypothesis 1 and the results of the FSS. The crisis in flow research suggested against experimental constraint manipulations with no empirical precedent for the relationship between the cascade dynamics and flow experience. Now that this link has been established, future studies could build on this work with experimental manipulation of task conditions to explore how constraint manipulations leading to different cascade dynamics might increase or decrease flow.

A second limitation that might be clarified in future work concerns causal relationships in the evolution of multifractality across the dyad. Although defenders' flow scores were more sensitive to their opponents' movements than their own, the present results supported the theoretical gist of hypothesis 2: that flow scores would be sensitive to properties which extend beyond the individual. As noted in section 4.5 of the previous chapter, the length of the time series in this study permitted only visual observation of co-variation of local Hurst exponents of attackers and defenders. Therefore, it is presently unclear to what extent individuals adapt their (multi)fractality with respect to an opponent during competitive coordination. Future studies should analyse the time variation of local Hurst exponents to examine causal relationships in the spread of multifractal fluctuations. This objective could be supported by vector autoregression modelling methods such as those implemented by Mangalam, Carver et al. (2020a, 2020b) to explore the spread of fractality across the body.

The link between multifractal cascade dynamics and flow experiences open another intriguing possibility for flow research and interventions. Kelty-Stephen, Similton et al. (2023) showed that (auditory) stimulation with varying degrees of multifractal nonlinearity interacted with multifractality of postural sway to influence perceptual judgments. Given this empirical demonstration of the ability of exogenous multifractal stimulation to influence endogenous multifractality and the present link between multifractality and flow experience, the application of multifractal stimulation in various media formats presents an interesting opportunity to future flow research. Although the relationship between exogenous stimulation, endogenous multifractality, and flow is unlikely to be simple or monotonic, it warrants further empirical consideration. Multifractal stimulation could also be explored through tasks which require participants to cooperate or compete with digital avatars exhibiting manipulated

degrees of multifractality. More broadly, exploring the spread of multifractality may be a promising direction for flow research.

Finally, sports leagues and national governing bodies could utilise cascade modelling to better understand the impact of proposed rule changes or age-related adaptations. As the cascade-dynamical markers of flow are developed in different sports and activities, the relationship between constraint manipulation and experience may further clarified in these contexts. As discussed in section 3.7.1, the manipulation of a single constraint may initiate a range of sometimes unpredictable cascading effects, making cascade modelling an ideal tool for assessing the impact of constraint manipulations. Coaches might also utilise this information to design engaging training sessions to support participation and player experience. For instance, Freitas Cruz and Sampaio (2020) found that multifractal spectra widths tended to increase with task complexity across a range of football training activities (e.g., jogging, circuit training, small-sided games, full match play). Cross-referencing these results with subjective self-report might inform constraint selection in curriculum design. Notably, it is not claimed that multifractal spectra width or multifractal nonlinearity have universally positive or negative meaning or relationship to flow. A task-specific approach is suggested due to the different constraint ecologies involved in different sports.

5.7 Conclusion

Despite the connotation of antagonism, the etymology of the word competition refers to a process of *seeking together*. The ecological metatheory motivating the present use of cascade modelling supports a clearer picture of what it is that competitors seek together. As competitors probe for the boundaries of their opponents' affordances, they also reveal their own abilities. In this reciprocal exchange, competitors are known through their attempts to know. While the score of a match is typically zero-sum, this process of mutual revelation of self and other during competition is not. Competitors who engage

one another in competitive coordination may share in psychologically significant experiences such as flow. As sets of replicable constraints, sports provide a context for these interactions to occur. The richly textured, nested structure of affordances, and the boundaries at which players contact each other, are shaped both by the capabilities of the individual competitors and the selected constraints of the activity. As such, modelling the cascading dynamics of competition that are co-determined by these factors provides a window into the ontological core of sport just as it provides insight into the best experiences sport can enable.

Chapter 6:

Group Tensegrity and Group Flow: Network Modelling of Time-Variation in Local Hurst Exponents

6.1 Introduction

Following the theoretical and metatheoretical analysis of the first three chapters, Chapter Four established the ability of multiscale dynamics to analyse performance in competitive coordination, while Chapter Five utilised these findings to provide a cascade-based explanation of flow experiences antagonistically coupled dyads. The congruence between the initial theorising and empirical results, thus far, demonstrate the practical utility of the ecological dynamics rationale in the scientific analysis of flow in sport. To support future ecological dynamics research on flow in sport, this chapter briefly demonstrates how the multiscale dynamics of larger groups might be analysed with network modelling (e.g., vector autoregressive analysis (VAR)). This strategy was suggested in section 4.5 of this thesis and Araújo et al.'s (2025) review of directions for future research in ecological dynamics, and provides a novel approach to investigating group flow in team sports.

The inspiration for vector autoregressive modelling of time-variation of local Hurst exponents is drawn from empirical demonstration of the utility of this approach in the domain of movement science. Previous research has demonstrated that the global broadcasting of local fractal fluctuations supported perception via effortful touch (Mangalam, Carver, et al., 2020a). This work found that perceptual accuracy increased with the flow of fractal fluctuations across the body, with network modelling able to identify key relationships such as the elbow and the hand (Mangalam, Carver, et al., 2020a). These results lend empirical support to ecological theorising which has proposed a key role for the multifractal tensegrity structure of the body in perception and dexterity (section 5.5; Cabe, 2019; Turvey & Fonseca, 2014). The relevance of these ideas for understanding and explaining flow experiences are expressed in the following.

Chapter Two proposed that, since the meaningful consequences of flow activities are inextricably linked to the performer's affordances (i.e., action possibilities supported by natural law), understanding the structure of flow experiences may entail understanding the structure of affordances in flow activities. Chapter Three developed this possibility further by drawing on the ecological understanding that attention exists in the "adaptive relationship between performing and procuring information to guide and support that performance" (Gibson & Rader, 1979, p. 6) to hypothesise that analysis of the ecological information supporting perception of affordances will play a critical role in understanding flow in sport, since flow is recognised to be an attentional phenomenon (Csikszentmihalyi, 1990). A significant body of empirical evidence supports the idea that the tensegrity architecture of the myo-fascial-skeletal system helps couple the active exploration of invariant properties of ambient energy arrays to the mechanical force production and effectivities of the performer, with multifractal analysis providing a suitable empirical method for examining this use of ecological information (Hajnal et al., 2018; Kelty-Stephen et al., 2023; Kelty-Stephen & Dixon, 2014; Mangalam, Carver, et al., 2020b, 2020a; Mangalam, Chen, et al., 2020; Palatinus et al., 2013). Building on these findings, Chapters Four and Five of the present thesis analysed multifractal fluctuations of movement coordination during competitive performance and used these insights to model flow experiences arising in this context.

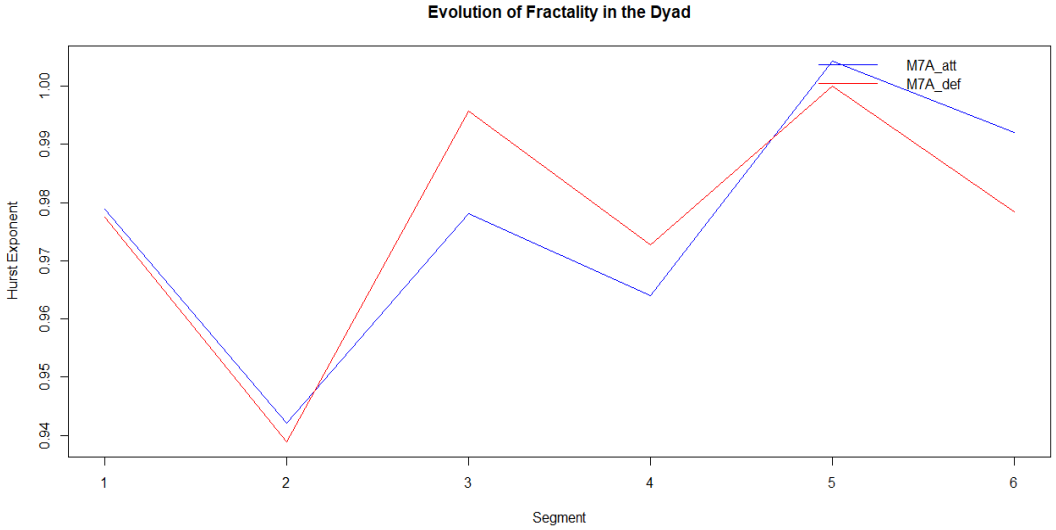
Although empirical work on multifractal tensegrity has, thus far, primarily addressed individual coordination, the appeal of this ecologically inspired framework has also motivated the hypothesis that *group* tensegrity may support team synergy formation as physiological and informational constraints provide a pre-stressed structural organisation from which teams adapt and explore (Caldeira et al., 2020). While the group tensegrity proposal is well-grounded theoretically, it awaits a suitable quantitative method and empirical demonstration. This chapter takes the method developed by (Mangalam,

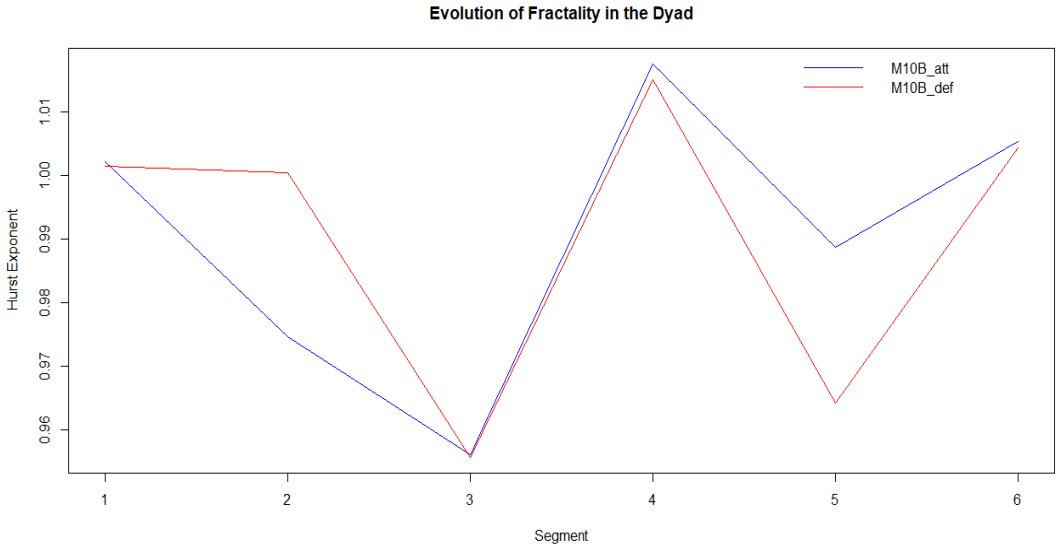
Carver, et al., 2020a) to explore the spread of fractality across an *individual's* body and adapts it to examine the spread of fractality in intra- and inter-team dynamics. Although previous implementations of this method assessed perceptual accuracy as a dependent variable, the results of chapter five indicate that multifractal cascade dynamics also reflect psychologically meaningful properties of dexterous behaviour. Hence, modelling the diffusion of these dynamics within competing and cooperating groups supports the possibility of future research on group and individual flow in team sports. Such research follows from the suggestion offered throughout this thesis that flow research would benefit from analysis of more relational markers or "eco-physical variables" (Seifert et al., 2022) which consider psychological experience by identifying the support for goal-directed behaviour.

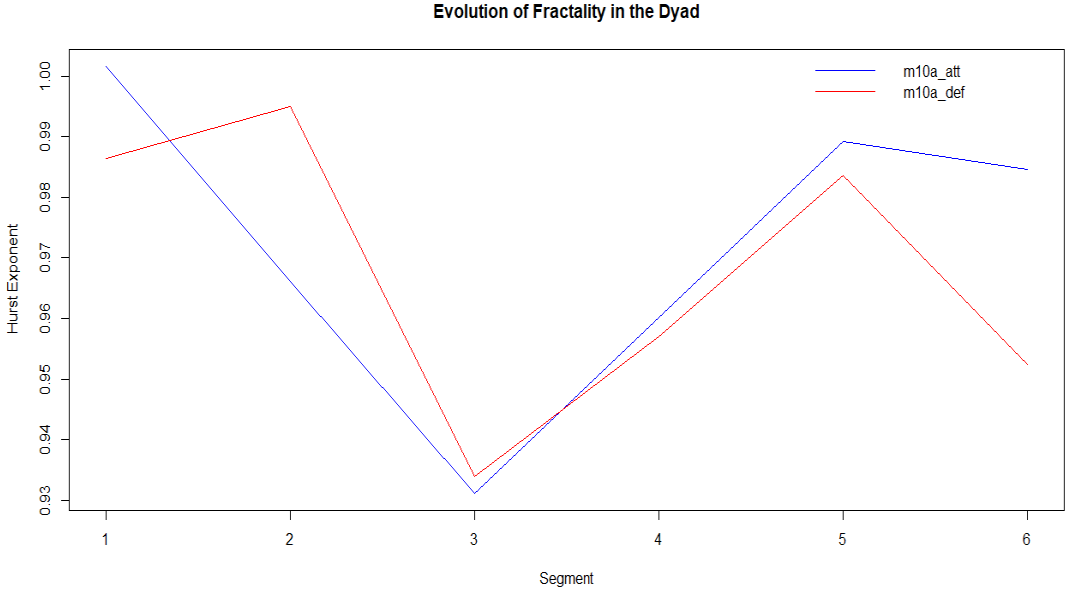
As noted in chapters four and five, the local Hurst exponents of attackers and defenders appeared to covary within trials (see Figure 6.1). In this previous exploratory analysis, the local Hurst exponents for both attackers and defenders were estimated for each 10-second interval within a trial. However, this intra-trial covariation of fractality in the dyad could not be explored further because reliable estimation of the Hurst exponent requires approximately 1,000 data points (Zhao et al., 2022), which enabled the estimation of Hurst exponents for a maximum of six binned segments within the 60-second trials. Although visual observation suggests some form of covariation, more formal quantification of these intertemporal relationships was not supported by the length of the time series data (i.e., six data points per trial). Thus, identification and analysis of longer time series data drawn from a 90-minute football match supported several aims, outlined next.

Figure 6.1

Variation of the local Hurst exponent for attacker and defender across six segments in three separate trials.


Evolution of Fractality in the Dyad
M7A_att
M7A_def
Hurst Exponent
0.94
0.95
0.96
0.97
0.98
0.99
1.00
1
2
3
4
5
6
Segment


Evolution of Fractality in the Dyad
M10B_att
M10B_def
Hurst Exponent
0.96
0.97
0.98
0.99
1.00
1.01
1
2
3
4
5
6
Segment


Evolution of Fractality in the Dyad
m10a_att
m10a_def
Hurst Exponent
0.93
0.94
0.95
0.96
0.97
0.98
0.99
1.00
1
2
3
4
5
6
Segment

First, the empirical analysis of multiscale dynamics and flow during competitive coordination was limited to analysis of performance in a dyadic task. The theoretical commitment to *multiscale* dynamics motivated by the ecological dynamics rationale suggests that analysis should not be restricted to any particular scale and makes extension to group dynamics an important objective. Second, evidence of directional influence between the multiscale dynamics of competing or coordinating individuals further consolidates the theoretical interpretation of previous results in the thesis. Simply, dismissals of fractal fluctuations as some type of statistical artefact (Wagenmakers et al., 2005) become highly implausible when these properties show some form of non-local temporal sensitivity (e.g., Granger causality) between multiple agents (Marmelat & Delignières, 2012). Evidence that competitive coordination is not limited to local reactive adaptation or contemporaneous correlation but involves the spread of multifractal fluctuations between individuals further supports the ecological hypothesis that anticipatory behaviour common to flow activities is strong rather than weak (Dubois, 2003; Stephen & Dixon, 2011).

In the initial step of demonstrating the feasibility of network modelling of the diffusion of fractality during interpersonal coordination, it was not possible to directly assess the relationship between the network model and flow experiences. However, given the demonstrated potential of multiscale dynamics to predict flow in chapter five, extending this analysis to the level of teams provides an important methodological contribution to future studies of flow in sport by identifying network relationships that may later be used in cascade-dynamical markers of flow. Based on the results of (Mangalam, Carver, et al., 2020b, 2020a; Mangalam, Chen, et al., 2020) and chapter five of the current thesis, hypothesis 1 was that fractality (e.g., local Hurst exponents of players) in a football match would spread both within (Hypothesis 1a) and between

(Hypothesis 1b) teams, evaluated by the presence of significant impulse-response functions obtained from the VAR model.

6.2 Method

Tracking data from a professional football match was obtained from an open data repository made freely available for the purpose of research under the condition of source acknowledgement in public usage (Metrica Sports, 2019). All data were anonymised, so the identity of the teams, players, and competition were unavailable. This study was approved by the Sheffield Hallam University ethics committee (Converis ID: ER83220189). Of the three sample matches provided, *sample game 2* was selected following preliminary inspection, as it offered the highest data quality and a substitution pattern that ensured consistent player participation across longer phases of play. These features made it the most suitable dataset for investigating the research questions, allowing for more reliable analyses of continuous player interactions.

6.2.1 Data processing and variable creation

The Metrica dataset “sample game 2” included values of the x and y coordinates for all players (25hz) with home team players being assigned player numbers 1-14 and away team players 15-26 (Metrica Sports, 2019). The planar coordinates for each player were provided in a 0-to-1 format along each axis but were rescaled to meters by multiplying the original units by the dimensions of the pitch (105 x 68), which were provided along with the data (Metrica Sports, 2019). The present interest in the spread of fractality, within and across teams using VAR, motivated the exclusion of goalkeepers, substitutes, and players who were substituted during the match to obtain the longest possible time series of complete observations for analysis. In line with the methods reported by Mangalam, Carver, et al., (2020a), the planar Euclidean displacement (PED) series for each of the remaining seven home team players and nine away team players were calculated as:

$$PED(t) = \sqrt{(x_t - x_{t-1})^2 + (y_t - y_{t-1})^2} \quad (1)$$

where $x = (x_{t-1}, x_t)$ and $y = (y_{t-1}, y_t)$ are coordinates of the player's position in consecutive frames. Following displacement, the PED series for each player was separated into 1,000-datapoint (40-second) bins (preserving temporal order) for data analysis. A segment length near the minimum required for stable Hurst exponent estimation was selected to maximise the length of the time series for VAR modelling.

6.2.3 Data analysis

All statistical analyses were conducted in R-Studio (Posit Team, 2022; R Core Team, 2021).

6.2.3.1 Detrended fluctuation analysis to estimate local Hurst exponents

The Hurst exponent for each player bin was estimated using detrended fluctuation analysis (DFA) (Peng et al., 1995) implemented with the function "dfa" in the package "NonlinearTseries" (Garcia, 2022). As outlined in section 4.2.5.2, DFA first constructs the profile of a time series $Y(k)$:

$$Y(k) = \sum_{t=1}^{k}(x(t) - \bar{x}), k = 1, \dots, N \quad (2)$$

where $\bar{x}$ is the mean of the time series and *N* is the total number of data points in the time series. The profile $Y(k)$ is divided into non-overlapping segments with equal lengths *n*. Within each segment, a linear least-squares trend is fit and then subtracted from the profile, yielding the detrended series. The root-mean-square (RMS) fluctuation function for scale *n* is then calculated as

$$F(n) = \sqrt{\frac{1}{N}\sum_{k=1}^{N}[Y(k) - y_n(k)]^2} \quad (3)$$

For standard scales (i.e., $n < N / 4$), $F(n)$ follows a power law $F(n) \sim n^H$ with the Hurst exponent *H* obtained as the slope of $log\, F(n)$ versus $log\, n$ (Peng et al., 1995).

Note that DFA represents a base from which the multifractal detrended fluctuation analysis (MF-DFA,) utilised in chapters four and five, generalises. Whereas DFA only estimates H for the second-order moment (i.e., RMS), MF-DFA generalises this process for a range of q-order moments. Although DFA represents a step backward from the multifractal detrended fluctuation analysis (MF-DFA) utilised in the previous chapters, temporal variation of monofractal scaling exponents is one of the sources of multifractality (i.e., the spectrum of scaling exponents generated by different values of q) (Ihlen, 2012). Thus, analysis of these temporal variations can provide an alternative window into multifractality, even though a monofractal scaling exponent is estimated at each time step.

To avoid overfitting in small bins and instability in large bins (see section 4.2.5.2), a conservative scaling range of 8-100 was utilised. The mean r^2 across all estimated Hurst exponents was .981, indicating robust scaling. A time series of 141 Hurst exponents (estimated for each 40-second interval of 1,000 data points) was obtained for the 16 players (see Figure 6.2). Hurst exponents varied widely between 0.19 and 1.87 with a mean of 1.53 across all bins. Customarily, the original player trajectories would be classed as fractional Brownian motion (fBm) while the first-order derivative is considered to be fractional Gaussian noise (fGn), with the scaling exponents derived from each typically denoted as H_{fBm} and H_{fGn}, respectively. However, exponents $1 < H < 2$ are consistent with H_{fBm}, which can be related to H_{fGn} by subtracting one. Nevertheless, the interpretation as H_{fBm} or H_{fGn} has no bearing on the outcome of the VAR model, as the relative fluctuations across players are preserved under either interpretation. Visual inspection revealed that Hurst exponent values dropped close to zero around the midpoint of the match, coinciding with poor fits of the fluctuation function. To address the discontinuity associated with half-time, the three bins (120 seconds) spanning and

surrounding half-time were excluded, yielding a time series of 138 Hurst exponents for each player for VAR modelling.

Figure 6.2

Hurst values for each 40-second bin for each player included in the VAR model

6.3.1 Vector Autoregressive Analysis for testing Hypothesis 1

Vector autoregressive modelling is a multivariate time-series framework which extends univariate autoregressive analysis to estimate a system of regression equations which predict each variable as a function of lagged versions of itself and other variables (Lütkepohl, 2013). For the simplified bivariate case with no exogenous variables, the structure of a VAR model is:

$$f(t) = A_1 f(t-1) + B_2 g(t-1) + \varepsilon_f(t),$$

$$g(t) = B_1 g(t-1) + A_2 f(t-1) + \varepsilon_g(t) \quad (4)$$

where A_j and B_j are coefficients which quantify the effects of past values of f and g with error terms $\varepsilon_f(t)$ and $\varepsilon_g(t)$, respectively (Lütkepohl, 2013). Suitably for the present purposes, VAR modelling requires little prior knowledge about the influences impacting

variables. VAR goes beyond simple correlation by considering temporal ordering and cross-lagged dependencies, enabling analysis to address whether fluctuations in one variable provides unique predictive information about the future of another variable. Although experimental manipulation is needed to discuss mechanistic causality, the directionality of significant impulse-response function is consistent with the concept of Granger causality and goes beyond what can be explained by simple synchronisation or contemporaneous correlation.

The aim of vector autoregressive analysis was to test whether fluctuations of the local Hurst exponents of each player were directionally influenced by fluctuations in the local Hurst exponents of teammates and opponents. All 16 Hurst exponent time series were included as endogenous variables, and no exogenous variables were included. Analysis of Akaike and Bayesian information criteria and the relatively large number of variables suggested a lag-1 VAR model. A Portmanteau test (asymptotic) for serial correlation did not find any autocorrelation in the model residuals ($\chi^2(2816) = 2780.3$, $p = .68$), supporting the lag selection. The stationarity of each time series of Hurst exponents was tested with an Augmented Dickey-Fuller test which rejected the null hypothesis of a unit root in all cases (all $p < .05$) and indicated the suitability of the data for VAR modelling. Residual diagnostics did find significant deviation from multivariate normality (Jarque–Bera $\chi^2(32) = 516.18$, $p < .001$), due to both skewness ($\chi^2(16) = 319.05$, $p < .001$) and kurtosis ($\chi^2(16) = 197.14$, $p < .001$), which is common in high-dimensional VAR models. Importantly, however, the inverse roots of the characteristic polynomial were all found to be within the unit circle (max = .43), indicating that the VAR model was dynamically stable and permitting reliable interpretation of the impulse response function.

The impulse response function (IRF) estimates how a one standard deviation "shock" or impulse to one variable impacts the current and future values of other

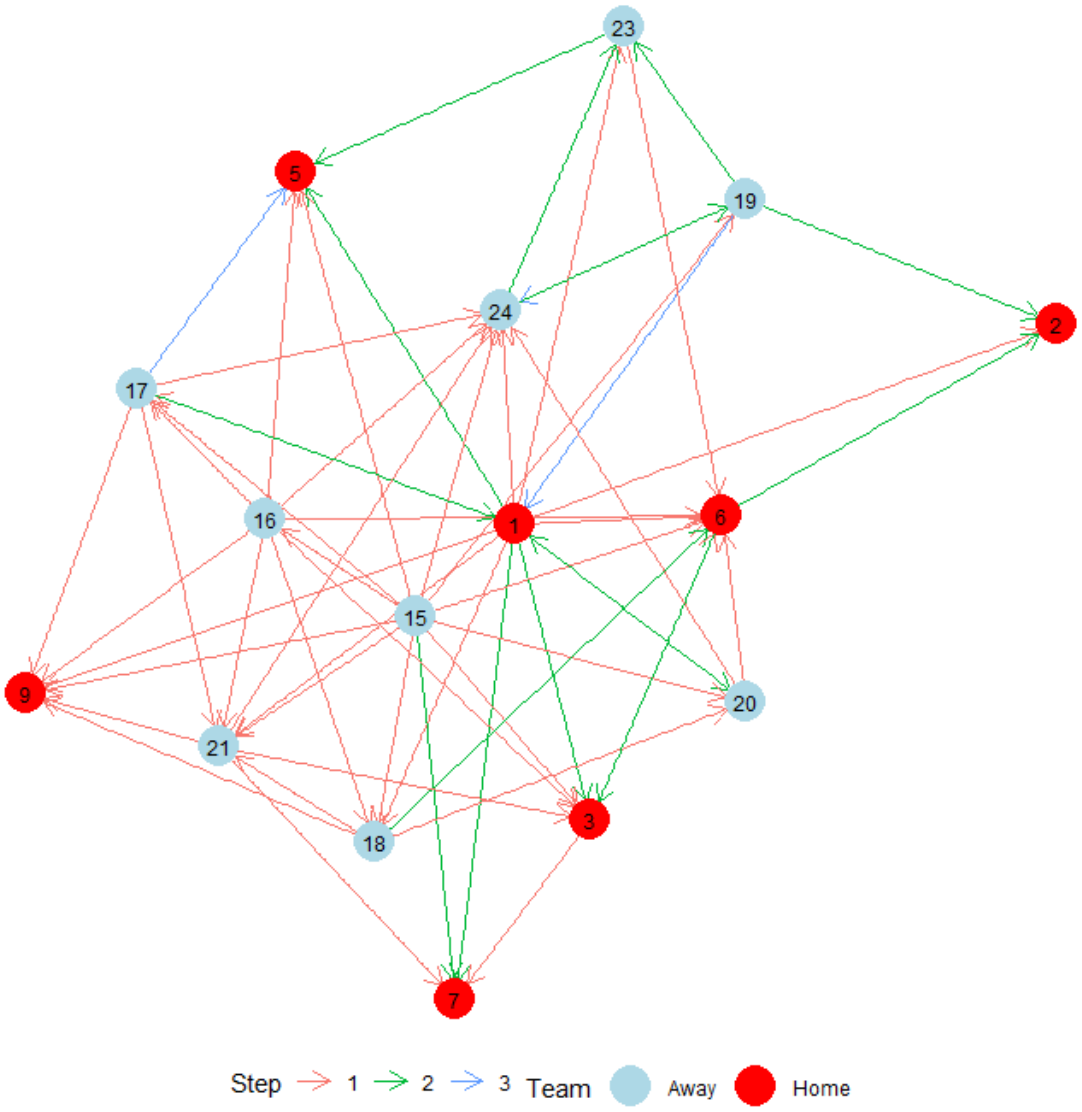
variables. The IRF was calculated for a maximum of ten future steps for all 256 pairwise relationships. Following Mangalam, Carver, et al.'s (2020a) approach, a response was considered significant when the 95% confidence interval of the response variable fell entirely above or below zero, indicating that the shock to the impulse variable creates a substantial change in the response variable. Because the residual diagnostics indicated deviation from multivariate normality, a bootstrapping procedure was used to generate robust confidence intervals. One thousand bootstrap replications of the VAR model were generated by resampling residuals, re-fitting the model, and recalculating the IRF at each iteration. The empirical distribution of these bootstrapped IRFs was then used to construct the 95% confidence interval for each impulse-response pair. Because the objective of the study was to analyse the spread of fractality between individuals, auto-responses were not included in the results of significant IRFs.

6.4 Results

The results of the IRFs from the VAR model revealed that the local Hurst exponents of players in a football match were dynamically responsive to one another, supporting hypothesis 1 which predicted interpersonal diffusion of fractality. Each of the 16 players modelled exhibited at least one significant IRF relationship with another player (see Figure 6.2). The home team displayed 13 significant intra-team IRFs, while 23 intra-team IRFs were found for the away team, summing to a total of 36 significant intra-team IRFs, supporting hypothesis 1a which anticipated spread of fractality within teams. Thirty-one significant IRFs were found between players on opposing teams, supporting hypothesis 1b which predicted that fractality would also spread between competing players. Out of the 67 significant IRFs, 49 were significant at the first forecasted step, 15 were significant at the second forecasted step, and three were significant at the third step (see Figure 6.3).

Figure 6.3

Network graph displaying players as nodes and significant impulse-response functions as edges. Edges representing significant IRFs are coloured based on the number of future steps at which the IRF was significant.



6.5 Discussion

The aim of this study was to examine whether fractal fluctuations propagated between individual football players as they interacted with each other over a 90-minute football match. The IRF results from the VAR model indicated that fractality spread between individuals during both cooperative and competitive coordination, supporting both hypotheses 1a and 1b. Whereas visual inspection suggested that the fractality of attackers and defenders co-varied within 60-second trials in the previous study, this

observation could not differentiate between simple synchronisation and directional influence. The present results build on those reported in previous chapters by providing initial evidence that fluctuations in the local Hurst exponents of interacting individuals not only correlate contemporaneously but may also exert Granger-causal influence on one another.

The present results also add some context to those of the previous two chapters. Analysis of performance (Chapter Four) and flow experiences (Chapter Five) in the antagonistically coupled 1v1 task revealed an important role for the multifractal properties of *both* individuals within the dyad. For instance, attacker flow was highest when attackers' t_{MF} were higher, attackers' spectra were narrower, defenders' t_{MF} were lower, and defenders' spectra were wider. Although these multifractal properties supported modelling of performance and flow at the level of an entire 60-second trial, they could not determine how the temporal co-evolution of these properties may have contributed to performance or flow during the task. Evidence that fractality of both cooperating teammates and competing opponents exert directional influence on each other during play, therefore, creates the possibility of more continuous markers of flow through analysis of fluctuations in such fluid, cross-scale coordination.

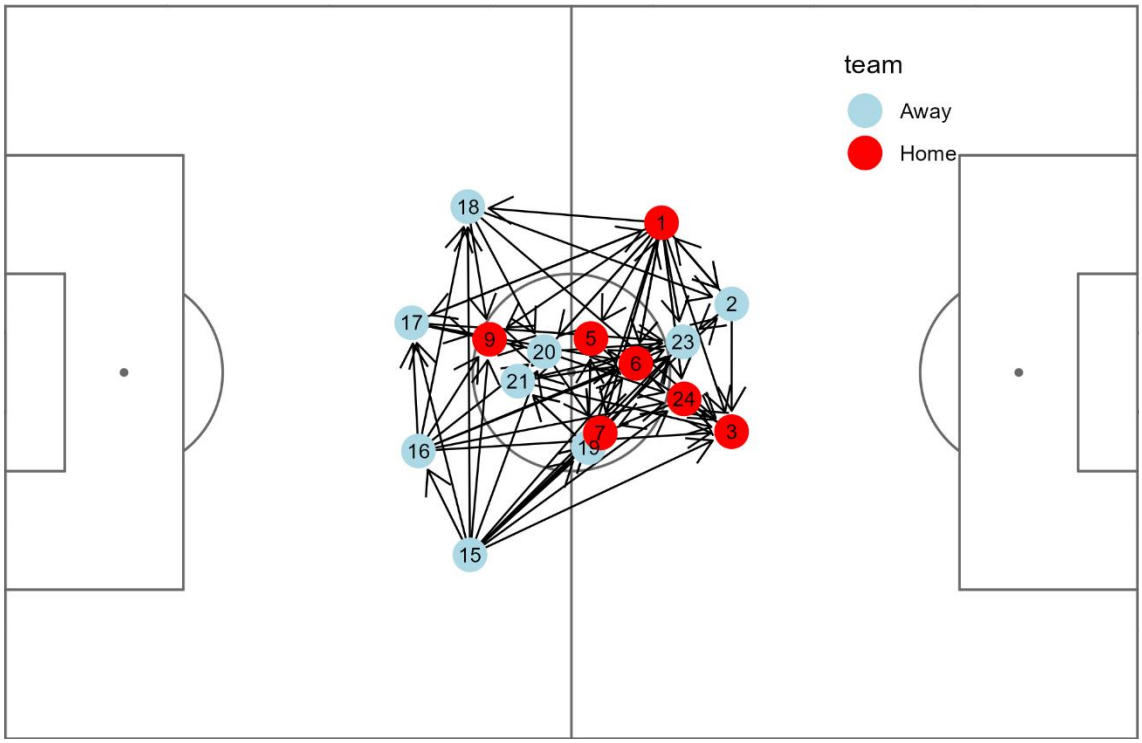
Evidence consistent with Granger-causal influence in the co-evolution of fractal fluctuations also has implication for utilising cascade dynamics as ecological markers of flow. Although the potential of multiscale cascade-dynamical markers of flow has been endorsed throughout this thesis, a simple monotonic relationship (e.g., stronger interactions between scales always relating to greater experience of flow) has also been cautioned against (see section 3.11.1). Instead, it is likely that the nonlinear interactions between scales support both performance and experience differently under different task constraints (Kelty-Stephen et al., 2023). Due to the tight coupling which often characterises competitive coordination, it is possible that the way multifractal fluctuations

spread throughout co-adapting performer-environment systems will be more informative than their absolute values. In team sport contexts, group flow could relate to the group tensegrity hypothesis, underpinned by the diffusion of multifractality.

The results of Chapter Six demonstrate the utility of developing concepts and methods which are not bound to a particular scale of analysis (Kelty-Stephen, 2024). Although Mangalam, Carver, et al., (2020a) analysed the scale of an individual body, the concepts of synergy and multifractal tensegrity which motivated their specific quantitative approach are both equally applicable at the scale of interpersonal coordination. The previous implementation of this method analysed IRFs between the local Hurst exponents of 13 markers situated across the bodies of individual participants to identify network relationships that supported greater perceptual accuracy. For instance, Mangalam et al. (Mangalam, Carver, et al., 2020a) found that absolute error in a perceptual judgement task was lower when the impulse to elbow fractality led to a significant (positive) response in hand fractality. The present work could only confirm that such a network of directed responses was present in the analysed football match, as it was not possible to model performance or flow experience as a dependent variable. Although the identity of the players and teams were not available, plotting the network graph with the nodes aligned to each player's average position enables visualisation of the results within the more familiar shape of a football team (see Figure 6.4).

Figure 6.4

Network graph of significant impulse response functions with each player positioned in their average position throughout the match.



More broadly, these findings also contribute to an ongoing theoretical discussion regarding the nature of anticipatory behaviour during skilled performance. Whereas some common explanations of anticipation (e.g., predictive processing frameworks (Hohwy, 2013)) rely on inferential processes supported by internal models (e.g., weak anticipation), ecological approaches have suggested the alternative possibility that anticipation is underpinned by the lawful nesting of performers within performance environments and may, thus, be considered "strong" (Dubois, 2003; Stephen & Dixon, 2011). Although the weak anticipation (e.g., model based) account may be stretched (if somewhat uncomfortably) to accommodate local synchronisation of monofractal scaling exponents, directional influence between these multiscale properties is only expected by the strong anticipation account (Marmelat & Delignières, 2012). Coupled with Chapter Four's finding of significant differences between original and surrogate spectra widths in *all* trials, the results of this thesis provide empirical support for the ecologically motivated strong anticipation account of skilful behavior. Notably, strong anticipation has primarily been studied in the context of *cooperative* coordination, thus far (Davis et al., 2016;

Marmelat & Delignières, 2012). The empirical studies conducted within this thesis represent initial work on strong anticipation during *competitive* coordination.

6.6 Limitations and directions for future research

Although this chapter represents an initial step in the utilisation of network modelling of fractal fluctuations in the study of flow in sport, the presence of directional influence in a football match suggests the feasibility of this novel approach. At this early stage, many questions remain unanswered. As the results of Chapter Five illustrated, the eco-physical markers of performance are not always the same as eco-physical markers of flow. Nevertheless, initial studies could follow Mangalam et al.'s (2020) lead to determine how patterns in the spread of fractal fluctuations support performance during team coordination. For instance, just as Mangalam et al.'s (2020) results found critical relationships (e.g., between the elbow and hand) supporting body-level synergies, it may be possible that team-level synergies are also supported by certain patterns of promotion and inhibition of fractality between players with different positional roles or profiles. It is also unclear at this point why some players receive more directional influence while other players appear to exert more outward influence on other players. Further analysis of these network dynamics by practitioners (e.g., coaches and sports scientists) who are familiar with the players and competitive context may help establish the intuitive meaning of these rich networks of multiscale influence.

Beyond understanding the multiscale coordination that underpins team performance, the methods demonstrated here align with the theoretical approach to flow research proposed in the first three chapters of this thesis. Flow experiences are theorised to arise in the finely tuned metastable dynamics of performer-environment systems as the taut tensegrity structure of a performer's body supports anticipatory synchronisation between the multifractal structures of movement and stimulation. In such soft-assembled or interaction-dominant systems, performers' psychological experiences, such as flow,

may be fluidly contextualised by their role within unfolding synergies. Since ecological dynamics theorises performance as arising from processes that differ from those assumed in prevalent explanations of flow (see Chapters Two and Three), it is necessary to first establish some groundwork to support this novel approach to flow research. Chapter Four provided support for the possibility that these are, in fact, the processes and dynamics which underpin and characterise performance in a dyadic flow activity, while Chapter Five identified the fluid cascade-dynamical markers of flow in a competitive dyadic task. The present chapter provides a first step towards identifying similar markers of group flow in competitive and cooperative interpersonal coordination.

Utilising the method presented here to study flow experiences could entail modelling a self-reported measure of flow as a dependent variable with IRF responses as independent variables. It may be that players experience flow when they exert more influence on or are more sensitive to the fractality of other teammates or opponents. Given previous findings that increased flow of fractality across the body generally supported greater perceptual accuracy (Mangalam, Carver, et al., 2020a), it is possible that greater overall flow of fractality across teams may support group flow experiences corresponding to more effective team synergising. Alternatively, Chapter Five's discovery that flow experiences for both attackers and defenders were highly sensitive to the multiscale properties of their opponents could motivate the hypothesis that inter-team relationships crossing competitive boundaries will carry more information about flow experiences.

The present demonstration of this method analysed player movements in a football match to maintain a degree of continuity with the previous studies (i.e., from futsal 1v1s to 11v11 football) and due to the availability of football data. While the results demonstrate the feasibility of applying this method to the sport of football, sports with somewhat fewer players (e.g., ice hockey, basketball, volleyball, martial arts, net sports) would offer the advantage of lower-dimensional VAR models. Dyadic sports may also

support the possibility of exploring intra- and interpersonal spread of fractality simultaneously during competitive coordination. For instance, it may be that boxers' performance or experience could relate to the spread of fractality across the fluctuations in an individual's centre of pressure, sacrum, and head sway, or perhaps between the head sway or end effectors of the competing individuals. These are, of course, highly speculative hypotheses intended only to provide more precise examples of potential future research.

6.7 Conclusion and future directions for research and practice supported by this thesis

This chapter concluded the empirical portion of this thesis by testing the hypotheses that fractal fluctuations spread interpersonally during both cooperative and competitive coordination, with the results of the VAR model supporting both hypotheses. These results help contextualise the difficulties in flow research discussed in Chapter Two. If the coordination of both cooperating and competing performers rests on cross-scale interactions, the meaning of pre-defined componential markers of flow will likely shift, making traditional explanatory strategies difficult, if not untenable. Identifying flow within cascade dynamics clarifies how both dynamical laws and selected constraints jointly shape cascades and supports an understanding of how flow-inducing constraints may be selected.

The results of the three empirical chapters align with and add detail to the guidance for constraint-based facilitation of flow offered in section 3.12. An ecological dynamics rationale suggested that performers in flow must act on affordances, and that **attentional engagement would follow proximity to the boundaries of these affordances**. Rather than simple cut-off points which might be addressed by whole-integer Euclidean geometry, the ecological understanding that affordances are nested (Kelty-Stephen, 2024) led to the prediction that affordances and their boundaries would

display the jagged heterogeneity of multifractal geometry (Mandelbrot, 1999). This perspective suggested that forms of competitive coordination common to sport (e.g., antagonistic coupling) may be fertile ground for flow experiences because they force athletes to release and constrain movement system degrees of freedom as they navigate these affordances boundaries. Hypothesis One in Chapter Five tested and supported this prediction, finding that an activity constrained to keep participants in close proximity to affordance boundaries led to higher-than-average reports of flow. More generally, this result highlights the practical utility of the affordance concept for both researchers and practitioners in the domain of sport.

Practitioners and researchers interested in designing flow activities might consider how the constraints of a task (including the individual constraints of the specific athletes) distribute affordance boundaries across both space and time. For instance, the constraints of the activity analysed in Chapters Four and Five utilised a simple design which required participants to balance attacking/defending two targets separated by a distance of two meters. This somewhat "binary" setup led performance to unfold across an iteratively branching path (e.g., a cascade) as an initial movement toward the left target could nest further possibilities such as continuing toward the left target, or changing direction toward the right target, and so on. From the standpoint of visual observation typically available to practitioners, the "density" of these branchings might have been evident in the jittery fluctuations and sense of tension or tautness (implicating the concept of multifractal tensegrity) which characterised performance in the activity.

While constraining the 1v1 in the manner described above enabled more precise testing of the theoretically motivated hypotheses, practitioners interested in creating flow activities can explore a wide range of constraint manipulations. Manipulating the constraints of potential flow activities underscores what ecological theory uniquely provides to constraints-led practice. First, constraints obtain meaning by virtue of their

impact on lawful dynamic processes (e.g., performance behaviour realising affordances). Thus, when designing flow activities, it may be helpful to consider the pauses, contours, and tempos which constraint manipulations give to the temporal structure of the activity. Second, this dependence on dynamics means that constraints are not independent, but exist as nested structures (i.e., constraint ecologies) which are linked across a range of scales. Practically, this means that practitioners may need to observe the resulting dynamics of the activity rather than attempting to isolate the context-independent meaning of a specific constraint manipulation. With these considerations in mind, practitioners are well-positioned to interpolate between constraint manipulation, participant descriptions of experience, and visual observation of fluctuations around affordance boundaries.

Chapter 7:

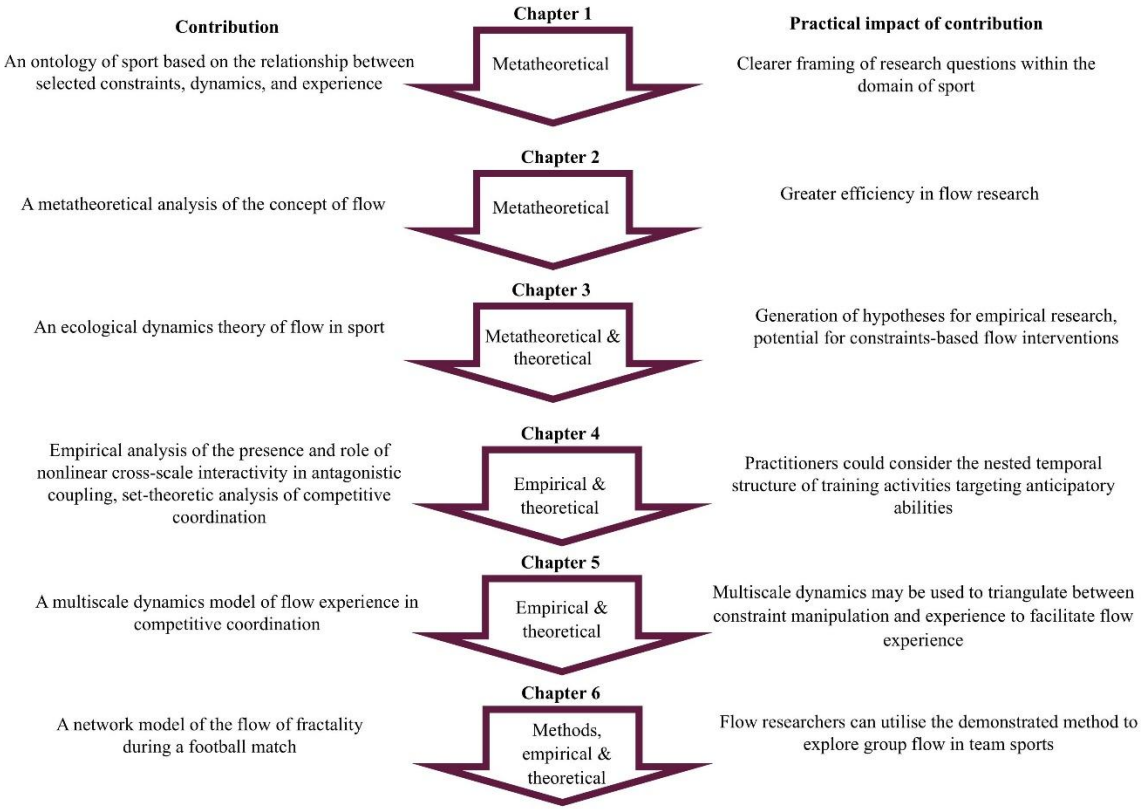
Epilogue

7.1 Summary and overview of the thesis

This thesis sought to investigate flow in sport. As the concept of flow was recognised to be in a state of crisis (see Chapter Two), supporting scientific progress in understanding and explanations of flow entailed both diagnosing metatheoretical, theoretical, and empirical issues, proposing viable solutions or alternatives, and implementing this paradigm (e.g., an integrated conceptual structure encompassing metatheory, theory, and empirical research) through empirical study to provide novel insights into flow in sport. More broadly, the exploration of flow in sport aimed to support more conscious shaping of the future of sport by illuminating the positive experiences they are capable of facilitating. This chapter reviews the contributions this thesis has made toward these aims (Figure 7.1).

Figure 7.1

Summary of the contributions of each chapter.



7.2 Situating flow in sport within the positive psychology movement

Biological organisms are largely united by the experience of avoiding pain, sickness, hunger, and, ultimately, death. There is little mystery or disagreement surrounding the worst experiences. As a survivor and refugee of the Second World War, Mihalyi Csikszentmihalyi was no stranger to these harsh realities of life. Nevertheless, Csikszentmihalyi spent his life helping found the field of positive psychology and attempting to understand life's most optimal experiences. The highlight of this positive psychology movement was the concept of flow (Csikszentmihalyi, 2000). Implicit in this work is a conviction that life should be lived not only in avoidance of pain or death, but in pursuit of what is good and meaningful. However, the identity of goodness and meaning are not characterised by the same degree of consensus as negative experiences, making the aims of positive psychology more elusive than pathology-focused psychology.

Rather than getting bogged down in philosophical discussion about the nature of optimality, Csikszentmihalyi took the pragmatic approach of observing which activities individuals *chose* to participate in without extrinsic reward, leading to the concept of flow. As discussed in Chapter Two, the concept of flow has been a victim of its early success. Though evocative, the qualitative descriptions of flow experiences failed to provide a causal understanding of flow sufficient to support interventions targeting flow experiences (Goddard et al., 2021; Schweickle et al., 2017; Swann et al., 2012), ultimately leading to proposals of a crisis for the concept of flow (Swann et al., 2018). Coincidentally or not, the crisis in understanding optimal experiences such as flow coincides with what some scholars have referred to as the "meaning crisis"; a time of social isolation, apathy, and lack of relevance (Vervaeke et al., 2017).

7.3 Finding a metatheoretical foundation for flow in sport

Given this backdrop, undertaking a programme of research on flow required in-depth consideration of the ontological and epistemological foundations of both flow and sport – the behavioural domain in which flow was considered. To support this aim, the background reading and preliminary research preceding the written thesis sought to retrace the bifurcating paths of scientific psychology in the nineteenth and twentieth centuries to identify the decisions which led to contrasting metatheories (for a comprehensive review of these issues, see Farrokh, 2025 and Chapter One). A sufficiently foundational common ground was identified in the work of Howard Pattee, a biophysicist interested in the origins of life and language, and the relationship between natural laws and constraints (Pattee, 2012b, 2012c, 2012a). Pattee held that dynamical and computational approaches to scientific psychology represented the two complementary languages of science – laws and constraints, respectively (Pattee & Rączaszek-Leonardi, 2012). Further analysis suggested that the relationship between these two languages was mediated by the scale of analysis imposed by the act of measurement (Kelty-Stephen, 2024; Von Neumann, 1955).

Considering the ontological nature of both flow and sport in terms of the laws-constraints relationship permitted metatheoretical analysis to more precisely inform empirical methodology. Rather than addressing the phenomenon of flow entirely in terms of rate-dependent dynamical laws or rate-independent constraints, a multiscale ecological dynamics approach suggested that taking multiple measurements at different scales would reveal the complex interplay between laws and constraints in the formation of cascades (Chapter One; Chapter Three; Chapter Four; Farrokh, 2025; Kelty-Stephen et al., 2025). The work of the ecological linguist Joanna Rączaszek-Leonardi, (2012), which suggested linguistic constraints are selected, based on their role in shaping dynamical contexts, provided a bridge between flow and sport. As argued in Chapter One, sports might be

ontologically framed as a process in which constraints are selected for the texture they give to the flow of experience by shaping the dynamics of sport performance behaviours, with flow perhaps relating to the need for intrinsically motivated participants. Thus, Chapter One contributed an explicit ontological account of sport, supporting clear framing of research questions within the domain of sports.

Chapters Two and Three explored how this multiscale, diachronic approach to the ontology of sport both clashed with the scale-bound and synchronic methods of traditional flow research and created novel possibilities for flow research. These chapters contributed a plausible explanation for the recognised crisis in flow research and solutions suggested by an ecological dynamics rationale. Two primary hypotheses arose from these three theoretical chapters. The common factor uniting many theories of flow was an assumption of vertical separation between scales and commitment to explanation in terms of independent component contributions (Simon, 1977). Demonstrating that this assumption may play a role in the crisis in flow research entailed testing the time series of performance in a potential flow activity to differentiate between component-dominant and interaction-dominant dynamics with surrogate analysis (Kelty-Stephen, Lane et al., 2023; Schreiber & Schmitz, 1996).

7.4 Applying metatheory and theory to empirical study

To start empirically testing these theoretical ideas, analysis identified the antagonistic coupling of 1v1 dyads as a common form of competitive coordination in sports which would provide a suitable task vehicle. Preliminary to any empirical findings, Chapter Four contributes an adaptable experimental paradigm for the empirical study of antagonistic coupling. Whereas the specification in this thesis utilised a futsal dyadic system format, the constraints of the experimental task might be adapted for a wide range of sports. A second consideration in this study was the lack of precedent for surrogate analysis in sports contexts. While several initial studies had documented multifractal

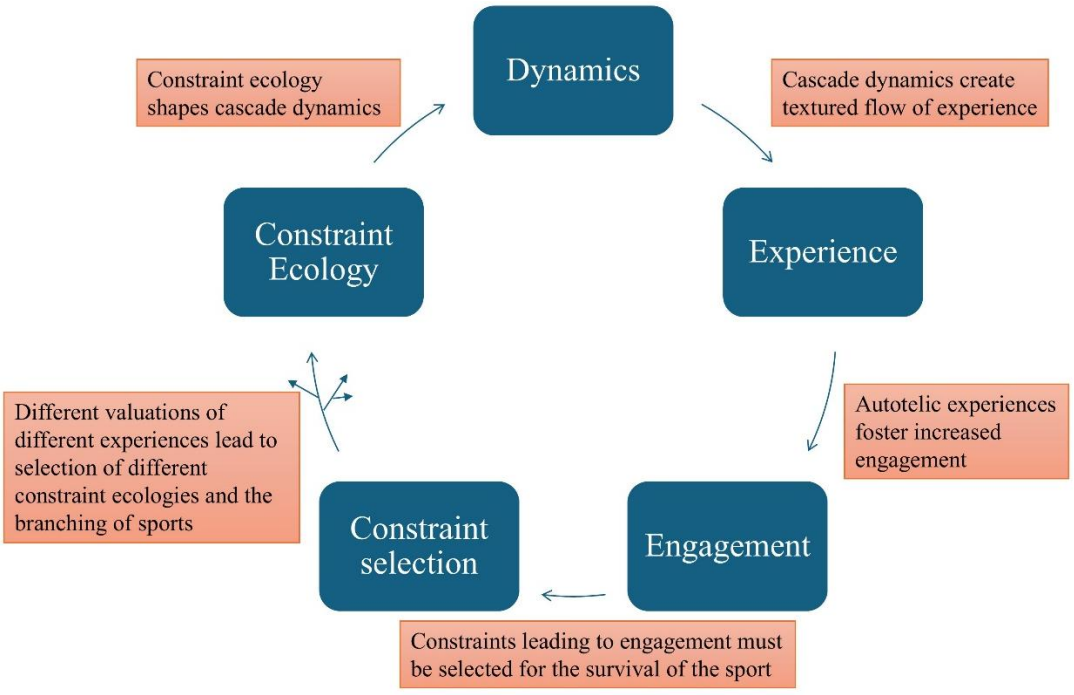
fluctuations in sports (Babault et al., 2024; Freitas Cruz & Sampaio, 2020), no studies which compared the widths of these multifractal spectra to linear surrogates were identified. Notably, the difference between the spectra width of the original time series and those of surrogate series preserving the mean, variance, and autocorrelation (i.e., the IAAFT surrogate analysis detailed in section 4.2.5.3) provides a conclusive test for nonlinear interactions between scales. Therefore, the introduction of this method into a new domain suggested careful initial exploration to support future research. The important role of multifractal nonlinearity in both performance and flow suggests further utilisation of this method in sport science and sports psychology. Chapter Four also brings a measure of anticipating synchronisation, which had been proposed in the physical sciences (Senthilkumar & Lakshmanan, 2007a), into the behavioural sciences for the first time, with the R code written to implement this method made available in the supplemental materials appended to this chapter. Thus, although data collection for Chapters Four and Five was concurrent, the preliminary nature of the research created two distinct phases of data analysis and warranted two separate chapters detailing these processes and results.

Because the results of Chapter Four's multifractal and surrogate analysis found that all trials in the study exhibited significant multifractal nonlinearity, Chapter Five was able to begin analysis of flow in an activity in which interaction-dominant dynamics had been established. More plainly, testing the first primary hypothesis generated by the three theoretical chapters supported the possibility that flow research had faltered when it attempted to apply the square peg of component-dominant explanations to the round hole of interaction-dominant performer-environment systems. The second key hypothesis arising from the theoretical work was the expectation that multifractal cascade dynamics could provide new ecological markers of flow. Returning to the proposal that flow factors

into the constraint selection process (see Figure 7.1), evidence that cascade dynamics can model self-reported flow experiences provides a mechanism for this selection process.

Figure 7.2

Constraint selection process from Figure 1.1. now filled in with theoretical and empirical insights from the thesis.



7.5 Cascade dynamics provide perceivable information for constraint selection

For a behaviour setting such as a sport to be shaped through a social process of constraint selection, there must be some *perceivable information* that enables multiple individuals to assess and discuss the impact of a constraint on experience via the dynamics of play (Heft et al., 2014). Although the popularity of some sets of constraints (e.g., common sports) indicates that a degree of consensus can be reached about what constraint selections facilitate experiences worth engaging in, the nature of the link between

constraint selection, dynamics, and experience had not been established. The unique suitability of multifractal geometry and cascade modelling for this task can be illustrated by comparison to approaches which address only lawful dynamics or formal, symbolic properties of constraints. Because natural laws are inexorable, they cannot be *selected*. Although dynamical laws can govern behaviour under a specified set of constraints, they have nothing to say about how those constraints are selected. By contrast, neglecting to identify constraints with their impact on dynamics creates a frozen or rate-independent analysis. For instance, the selection of flow activities has been framed as a form of "mimetic evolution" (Massimini et al., 1988) but the algorithmic nature of the meme concept cannot address rate-dependent dynamical processes (Swenson, 1997) and the selection process must be proposed to occur in a private realm of subjective consciousness. The multiscale dynamics approach here conserves the ecological emphasis on lawful dynamics while also permitting analysis of the nested constraints which shape these lawful flows.

Returning to the updated constraint selection model (Figure 7.1) allows a potential concern regarding the design of Chapter Five to be addressed: that is, Chapter Five models a *self-reported measure of flow* as a dependent variable. Given that self-reports in flow research have often been taken to reflect subjective experience, it is reasonable to ask how this methodology fits in with an ecological dynamics rationale. In response to this concern, the constraint selection model suggests consideration of the social process by which potential flow activities such as games and sports are shaped in natural environments. For example, children manipulating the constraints of a game often vocalise self-reports such as "this is/isn't fun" or "that's not fair" as they negotiate the constraint selection process. An ecological perspective acknowledges the important role of these verbal reports in the social coordination required to select constraints on flow activities. All that is suggested by an ecological perspective is that the experience which

these self-reports refer to are not exclusively internal or subjective (see section 3.6. and Seifert et al., 2022). Rather, the results of Chapter Five instead suggest that the multiscale dynamics of the dyadic activity provided a reference point to which self-reports and experiences can be linked.

Admittedly, the multiscale dynamics markers of flow in the 1v1 dyadic activity were complex and differed slightly between roles due to the different constraints associated with attacking and defending. Given the theoretical account of the process of attending to information for action in flow in section 3.9, this complexity should not be surprising. Because competitive coordination dovetails the affordances for one participant with the effectivities of the other, the information supporting action in these contexts is expected to be comprise complex, higher-order relational variables. However, the cascade model was able to reveal that greater precision navigating these jagged affordance boundaries (e.g., greater multifractal nonlinearity reflecting the effective release of degrees of freedom within these regions) accompanied deeper flow experiences. The multifractal tensegrity architecture implicated in these interactions (see section 5.5) also provides a unique window into the haptic element of "fingertip feel" in flow. These insights suggests that coaches and other practitioners should consider how the constraints of activities position affordance boundaries around which these critical interactions occur.

Building on Chapter Five's analysis of multifractality in flow during dyadic competitive coordination, Chapter Six advanced ecological dynamics research on flow with both empirical and methodological contributions by extending the investigation to larger group contexts. Chapter Five had suggested, but not confirmed, directional influences of multifractality between dyad members. Evidence of such directional flow in a related task would strengthen theoretical interpretations of cross-scale interactivity and strong anticipation while opening new lines of inquiry. Although multifractal fluctuations have been shown to flow across individual bodies (Mangalam, Carver, et al.,

2020a, 2020b) and cooperating individuals (Marmelat & Delignières, 2012), their directional flow during competitive coordination had not been previously investigated. Chapter Six thus provided initial evidence that multifractal fluctuations spread across competitive boundaries, providing new understanding of the competitive coordination which supports flow in sport. More broadly, the introduction of a network modelling approach represents a methodological contribution to research on both interpersonal and competitive coordination.

7.6 Conclusion

The theoretical developments of the first three chapters, and the empirical analyses of the next three chapters lay the groundwork for an ecological dynamics research programme on flow in sport. The empirical methods suggested by the metatheoretical analyses of the first three chapters demonstrated the ability to address research questions pertaining to flow in sport. Furthermore, the empirical findings of the thesis were consistent with the core hypotheses generated by the theory, indicating that that the ecological dynamics perspective presents a new direction for flow research. More broadly, these methods produce a different form of explanation for flow research, with the theorisation, development, and testing of this alternative explanatory format representing a key contribution of the thesis.

Most importantly, this thesis supports the mindful shaping of the future of sport. The constraint selection process reveals the values which shape sports as they evolve. While flow is proposed to occupy a position near the ontological core of every sport, due to the need for intrinsically motivated participation at early stages, established sports can be shaped by a broader range of potential values, some very distant from the original emphasis on the optimal experience of the participating athletes. Without a clear understanding of how flow experiences emerge in sports, it becomes difficult to tune the constraints of flow activities. Hopefully, the contributions this thesis has made to the

understanding of this process will empower athletes and sports practitioners to facilitate greater flow in sports participation at all levels.

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Appendix 5.1

The Flow Short Scale questionnaire

Participant name: _____

Date: _____

Role: Attacker __ Defender ___

Please read the prompt and fill in the circle that best describes your experience *during* the previous match.

	not at all			partly			very much
I feel just the right amount of challenge.	○	○	○	○	○	○	○
My thoughts/activities run fluidly and smoothly.	○	○	○	○	○	○	○
I don't notice time passing.	○	○	○	○	○	○	○
I have no difficulty concentrating.	○	○	○	○	○	○	○
My mind is completely clear.	○	○	○	○	○	○	○
I am totally absorbed in what I am doing.	○	○	○	○	○	○	○
The right thoughts/movements occur of their own accord.	○	○	○	○	○	○	○
I know what I have to do each step of the way.	○	○	○	○	○	○	○
I feel that I have everything under control.	○	○	○	○	○	○	○
I am completely lost in thought.	○	○	○	○	○	○	○

Compared to all other activities which I partake in, this one is …	easy	○	○	○	○	○	○	○	difficult ○
I think that my competence in this area is ...	low	○	○	○	○	○	○	○	high ○
For me personally, the current demands are ...	too low	○	○	○	just right ○	○	○	○	too high ○