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Analysing collective tactical behaviours in football using an experimental approach

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I further declare that I complied with the actual “guidelines of qualified scientific work” of the German Sport University Cologne.

Date, Signature

To Eileen

To my mum

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Publications

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Book chapter

Low, B. (2022). Collective tactical behaviours in football. In D. Memmert (Ed.), *Match Analysis, How to Use Data in Professional Sport* (1st ed., pp. 197-212). New York: Routledge.

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Abstract

In football, the scientific study of tactical movements is never an easy task. The many degrees of freedom afforded to players and ball poses a complex problem for researchers. Sports scientists have consequently turned to the science of complex systems to better understand footballers' tactical behaviours. In particular, many theories are drawn from the field of collective animal behaviours, where patterned behaviours at the collective level emerge from local interactions between members in a process of self-organisation. Accordingly, some principles of complex cooperative behaviours in animalia consequently became the paradigm for understanding collective tactical movements in footballers. This has been greatly facilitated by the introduction of player tracking systems, where players' dynamic movements are continuously recorded, allowing for the study of different configurations of play. The present dissertation first performed a systematic review of empirical studies (Study One), before focusing on two research gaps. First, much is still unknown about the underlying processes explaining tactical behaviours in 11 vs. 11; second, research is not sufficiently contextualised for practice. In view of these gaps, the present dissertation used an experimental approach, to analyse footballers' tactical behaviours in 11 vs. 11, based on their position data, and with the aim of seeking explanatory mechanisms underlying the observed tactical behaviours in different contexts. Two empirical studies were conducted, in which six youth football teams (under-17) participated in 11 vs. 11 field experiments, and performed 72 trials of attack vs. defence. Each study implemented a counterbalanced crossover design and examined the effects of an independent variable. Study Two examined the differences in players' collective tactical behaviours between two pressing strategies — deep-defending and high-press defending. Study Three compared the differences in collective tactical behaviours between two defending formations — 4-4-2 and 5-3-2. Measures of tactical behaviour were analysed at various levels of organisation: match level, team

level, group level, dyadic level, and individual level. These were supplemented with the notational analysis of players' passes. The findings from both studies offered some explanatory mechanisms about footballers' collective tactical behaviours as an effect of different strategies. In study two, the increased dispersion when performing the high-press can be explained longitudinally by further inter-line distances that consequently afforded more spaces to the opposing forward and attacking midfielder. In study three, the reduced dispersion when defending in a 5-3-2 formation compared to a 4-4-2, can be explained by forwards retreating closer to midfielders. Combining results from both empirical studies shows that deep-defending and midfield-pressing result in similar collective structures whereas high-press defending is characterised by greater longitudinal dispersion. Comparisons of various tactical variables with those of real matches reflect good representativeness of the experimental design. In addition, performing analyses at different systemic levels of organisation provide insights into tactical behaviours from micro to macro level perspectives. As practical implications, the high-press defending strategy could perhaps be used sparingly; choosing the 5-3-2 defending formation over the 4-4-2 may have the greatest impact on full-backs of the attacking team; and performing dyadic level analysis can provide more information on players' marking behaviour. In conclusion, the present dissertation proposed some explanatory models of collective tactical behaviours in response to different defending strategies, and methodologically proposed contextualised analyses that provide deeper insights to practitioners.

Zusammenfassung

Im Fußball ist die wissenschaftliche Untersuchung taktischer Bewegungsmuster eine generell schwierige Aufgabe. Die vielen Freiheitsgrade in den Bewegungen der Spieler und des Balles stellen die Forschung vor ein komplexes Problem. Sportwissenschaftler bedienen sich daher der Theorie der komplexen Systeme, um das taktische Verhalten der Fußballer besser zu verstehen. Hier wurden viele Ansätze aus dem Bereich der kollektiven Verhaltensweisen von Tieren verwendet, wo kollektive Muster aus lokalen Interaktionen zwischen sich selbst organisierenden Gruppenmitgliedern entstehen. Dementsprechend wurden einige Prinzipien komplexer kooperativer Verhaltensweisen in der Tierwelt zum Paradigma für das Verständnis kollektiver taktischer Bewegungen im Fußball. Diese Entwicklung wurde durch die Technologie der Spielertracking-Systeme verstärkt, welche die Bewegungen der Spieler kontinuierlich aufzeichnen, und die Untersuchung verschiedener Spielkonfigurationen ermöglichen. In der vorliegenden Dissertation wurde zunächst eine systematische Übersicht über empirische Studien erstellt (Studie Eins), bevor der Schwerpunkt auf zwei Forschungslücken gelegt wurde. Zum einen ist wenig über die zugrunde liegenden Prozesse bekannt, die das taktische Verhalten im 11-gegen-11-Spiel erklären. Zum anderen ist die Forschung für die Praxis nicht ausreichend kontextualisiert. Angesichts dieser beiden Lücken wurde in der vorliegenden Arbeit ein experimenteller Ansatz gewählt, um das taktische Verhalten von Fußballspielern im Spiel 11 gegen 11 auf der Grundlage ihrer Positionsdaten zu analysieren und nach Erklärungsmechanismen zu suchen, die den beobachteten taktischen Verhaltensweisen in verschiedenen Kontexten zugrunde liegen. Dementsprechend wurden zwei empirische Studien durchgeführt, bei denen sechs Jugendfußballmannschaften (unter 17 Jahren) an 11-gegen-11-Feldexperimenten teilnahmen und 72 Versuchsdurchgänge im Setting Angriff gegen Verteidigung durchführten. In jeder Studie wurde ein balanciertes Crossover-Design gewählt und die Auswirkungen einer unabhängigen Variablen untersucht. Studie Zwei untersuchte die Unterschiede im kollektiven taktischen Verhalten der Spieler zwischen zwei Pressing-Strategien: Angriffs- und Verteidigungspressing. Studie Drei verglich die Unterschiede im kollektiven taktischen Verhalten zwischen zwei Verteidigungsformationen: Der 4-4-2 und der 5-3-2 Formation. Das taktische Verhalten wurden auf verschiedenen Organisationsebenen analysiert: Spielebene, Mannschaftsebene, Gruppenebene,

dyadische Ebene und individuelle Ebene. Die Analysen wurden durch eine Notationsanalyse von Pässen erweitert. Die Ergebnisse beider Studien boten diverse Erklärungsmechanismen für das kollektive taktische Verhalten der Fußballer als Resultat verschiedener Strategien. In Studie Zwei lässt sich die erhöhte Längsstreuung in den Spielerpositionen beim Angriffspressing durch größere Abstände zwischen den Linien erklären, welche den gegnerischen Stürmern und offensiven Mittelfeldspielern mehr Raum bieten. In Studie Drei lässt sich die geringere Streuung beim Verteidigen in einer 5-3-2-Formation im Vergleich zu einer 4-4-2 Formation dadurch erklären, dass sich die Stürmer näher zu den Mittelfeldspielern zurückziehen. Die Kombination der Ergebnisse aus den beiden empirischen Studien zeigt, dass Verteidigungs- und Mittelfeldpressing zu ähnlichen kollektiven Strukturen führen, wobei das Angriffspressing durch eine größere Längsstreuung gekennzeichnet ist. Vergleiche diverser taktischer Variablen mit denen realer Spiele zeigen eine gute Repräsentativität des Versuchsaufbaus. Darüber hinaus bietet die Untersuchung von verschiedenen systemischen Organisationsebenen Einblicke in taktischen Verhaltensweisen von der Mikro- bis zur Makroebene. In der Praxis könnte der vereinzelt Einsatz von Angriffspressing wertvoll sein; die Wahl der 5-3-2-Verteidigungsformation gegenüber der 4-4-2 könnte die größten Auswirkungen auf die Außenverteidiger der angreifenden Mannschaft haben; und die Analysen auf dyadischer Ebene könnten tiefere Einblicke in das Deckungsverhalten der Spieler liefern. Insgesamt bietet diese Dissertation verschiedene Erklärungsmodelle für kollektives taktisches Verhalten als Reaktion auf diverse Verteidigungsstrategien, sowie eine methodische Erarbeitung kontextbezogener Analysen, die den Praktikern im Sport tiefere Einblicke gewähren.

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Chapter 1: Introduction

Data analytics in association football has been receiving considerable attention. In large parts, this is due to the exponential increase in position data, brought about by the proliferated use of player tracking systems (Rein & Memmert, 2016). Consequently, the discipline of performance analysis has also seen growing interest in the study of players' dynamic movements (Sarmiento et al., 2018), due to its potential in gleaning tactical insights into performance.

However, analysing tactics, particularly through objective methods of scientific inquiry, is by no means easy. The freedom of movement available to teammates, opponents, and the ball, and the many interactions that ensue, make such an endeavour highly complex. Hence, studies in this discipline analysing tactical behaviours have increasingly adopted theoretical paradigms in system complexity, conceiving football games as complex systems (Balague et al., 2013; Lord et al., 2020). Envisaged as such, players' collective movements are believed to emerge from local interactions in a process of self-organisation. And these collective behaviours can be examined at multiple levels of organisation. Since tactics have been defined as the actions performed by players in adaptation to the dynamically changing match situations (Gréhaigne & Godbout, 1995), its epistemological study in this body of research, involves the examination of variables representing the collective spatiotemporal properties of footballers, and often, their responses to strategy. The latter being defined as actions planned in advance, over longer timescales, after considering as much information as possible (Gréhaigne & Godbout, 1995). In sum, compared to the traditional notating of discrete events, this research paradigm gives us a more complete understanding of performance, as it can better link players' underlying behavioural mechanisms to performance outcomes (Glazier, 2010).

Today, more than a decade has passed, since the first original studies analysed footballers' collective tactical behaviours through paradigms of system complexity (Frencken et al., 2011; Yokoyama & Yamamoto, 2011). But a review of related literature, as performed in the present dissertation, showed that research is still under-theorised at the 11 vs. 11 level. This is largely attributed to a lack of experimental research, as studies predominantly utilised the more convenient observational design. While the latter approach brings the benefit of analysing real-world elite performance, it is difficult to confidently determine cause and effect, elements necessary for establishing theories, especially in relatively new bodies of research as this. Therefore, more experimental methods of investigation are needed to help progress this discipline of sports science.

The present dissertation aims to analyse footballers' tactical behaviours in 11 vs. 11 based on their position data, using an experimental approach. Specifically, two original studies were performed to examine players' tactical behaviours as an effect of two defending strategies — pressing and formation. The research questions that these studies sought to answer were:

- How do footballers' tactical behaviours differ when using a high-press defending strategy and a deep-defending strategy? (Study Two)
- How do footballers' tactical behaviours differ when defending in a 4-4-2 and a 5-3-2 formation? (Study Three)

The structure of the dissertation is as follows. Chapter 2 presents a review of related literature, and encompasses an overview of: theoretical backgrounds underpinning research in this field; a systematic review of empirical research (Study One), focusing on their methods and key findings; and the justifications for the current thesis. Chapters 3 and 4 present the two empirical studies pertaining to the respective topics of pressing (Study Two) and formation (Study Three). Chapter 5 presents a synthesised discussion and conclusion.

Chapter 2: Literature review and Study One

2.1 Theoretical paradigms

Tactical analysis is frequently performed by coaches and analysts in most football teams. But despite its wide use in applied practice, analysing tactics in research, particularly through objective methods of scientific inquiry, poses a challenge. The freedom of movement afforded to teammates, opponents, and the ball, and the many interactions therefrom, make such an endeavour highly complex. Consequently, researchers have increasingly underpinned studies on tactical analysis with theoretical paradigms from the field of system complexity (Lord et al., 2020).

Although scientists have yet to agree on a formal definition of a complex system, it can be generally described as a system comprising many components that display emergent behaviours resulting from their interactions with each other or with the environment (Bar-Yam, 1997). The word ‘emergent’ means that the behaviour of a system cannot be simply inferred by studying those of its components in isolation (Corning, 2002; Funtowicz & Ravetz, 1994; Gibb et al., 2019). A summary of some main characteristics of complex systems show that: (1) they contain large numbers of elements; (2) the elements interact interdependently; (3) the interactions are physical or informational; (4) the interactions are dynamic and nonlinear; (5) complex systems are open systems, and interact with their environment; (6) complex systems have a history; and (7) each element is ignorant of the behaviour of the system as a whole (Cilliers, 1998). Arguably, these characteristics similarly manifest in a game of football. Just like elements of a complex system, (1) the twenty-two players^a in a game

^a Scientists have not explicitly stated what number of elements constitutes ‘large’ for a system to be complex, or even what constitutes an ‘element’ of a system. But since one measure of complexity is the number of possibilities (Ashby, 1957; Bar-Yam, 1997), this dissertation maintains the proposition that complexity in team sports, in general, arises from the numerous possibilities of interaction between teammates and opponents (Davids et al., 2013; Salmon & McLean, 2020).

interact with one another. (2) Players' instantaneous movements depend on those of teammates, opponents, and the ball (Folgado et al., 2014; Marcelino et al., 2020; Travassos et al., 2011), and therefore can be described as dynamic and interdependent. (3) Being a contact sport with lots of running (Aquino et al., 2020; Bradley et al., 2009; Di Salvo et al., 2009), players' interactions can be easily described as physical; however, they are also informational, since players perform actions based on their perceptions of the continuously changing match situations (Araújo et al., 2006; Silva et al., 2013). (4) These exchanges can also be considered nonlinear, as they do not mathematically adhere to a superposition principle (Saat et al., 2017), thus a change in an input does not proportionally change the output. (5) The proven influences of external factors like match location (Bialkowski et al., 2014; Fernandez-Navarro et al., 2018; Santos et al., 2017a), turf (Andersson et al., 2008; López-Fernández et al., 2019), weather (Brocherie et al., 2015), crowd support (Wunderlich et al., 2021), and altitude (Buchheit et al., 2015) indicate that football games are open systems that interact with their environment. (6) Penultimately, players' behaviours change according to their history; for instance teams were observed to maintain the same formation after a win, but change formations after a loss (Tamura & Masuda, 2015), and teams with a losing match status tend to recover the ball in more advanced pitch positions (Santos et al., 2017a), have more ball possession (Lago & Martin, 2007), or reduce their movement synchronisation (Folgado et al., 2018), compared to when the scores were level; hence the past is co-responsible for their present behaviour. (7) Finally, in a football game, the amount of information that each player can instantaneously perceive and process from their respective viewpoint is limited (Jordet, 2005; McGuckian et al., 2020); thus, in performing their individual roles, it is hard for a single player to concurrently possess complete information about the behaviour of the team as a whole. Due to these similarities, the complex systems paradigm presents itself as a viable framework for investigating tactical behaviours in football (Bar-Yam, 2003; Gréhaigne et al., 1997; Lames & McGarry, 2007; Low, 2022; McGarry et al., 2002; Salmon & McLean, 2020).

The emergent behaviours in a complex system typically arise from the processes of self-organisation amongst its elements (Corning, 2002). Accordingly, self-organisation, refers to the processes wherein patterns at a global level of a system spontaneously emerge from the interactions of lower-level components (Camazine et al., 2003; Coveney, 2003; Skår, 2003). These descriptions of emergence and self-organisation that involve the interactions of elements at different system levels, bring us to the next point of hierarchy. Hierarchical organisation is characteristic of many complex systems (Corominas-Murtra et al., 2013; Oltvai & Barabási, 2002; Sales-Pardo et al., 2007; Trusina et al., 2004). This means that a complex system comprises sub-systems, and at each level, an entity exists as three things at the same time: it is made up of parts from sub-systems at a lower level; it exists as a complex system in itself; and it is a part of another complex system on the next level above. These perspectives on different levels of organisation have been used in the study of football. One of the earliest publications was by Gréhaigne and Godbout (1995), who proposed that the systemic nature of football can be studied at the match level and the team level. The match level is viewed as a complex system comprising two interacting teams, while at the team level, each of those teams is in itself a complex system, comprising eleven players as elements of the system. Other studies have extended these levels of organisation to the group and dyadic levels. The group level views a subset of players as a complex system, and could encompass groups of defenders, midfielders, and forwards (Goes et al., 2020; Gonçalves et al., 2014). Group level analysis could also constitute subsets of players that are dynamically changing (Ribeiro et al., 2019; Ribeiro et al., 2020a; Ribeiro et al., 2020b), since in a match, for instance, players could work together with different teammates in different situations. The dyadic level of organisation represents a complex system formed by pairs of players either in the same team (Folgado et al., 2014; Folgado et al., 2015) or opposing teams (Siegle & Lames, 2013; Vilar et al., 2014). Taken together, these principles of emergent self-organised complex systems, existing in various levels of organisation, provide a framework for the study of collective behaviours, not just in football, but nature in general.

Although the study of complex systems originated from the basic sciences of physics and chemistry (Katchalsky & Curran, 1965; Nicolis & Prigogine, 1977), it is from the biological sciences, and in particular, the complex collective behaviours in animalia (Anderson & McShea, 2001; Couzin & Krause, 2003; Hölldobler & Wilson, 2009; Sumpter, 2006), whereon the complexities in team sports are modelled (Duarte et al., 2012a; Passos et al., 2013; Silva et al., 2016b). Due to the importance of survival, complex ecosystems in the animal kingdom, exhibit features of competition and cooperation usually not considered in physical and chemical systems (Bonabeau et al., 1997). Competition could occur between or within animal groups over scarce resources as food, water, territory, or mates (Couzin & Krause, 2003; Hölldobler & Wilson, 2009; Sumpter, 2010), and is thought to be a driving force in the process of natural selection (Bonner, 1988). In a similar way, competition could also be observed in football, as teams compete to win matches in the conventional way that we know, and players in the same team compete for limited starting places (Passos et al., 2016) or elite youth progression (Gil et al., 2007a; Gullich, 2014). Accordingly, one example of an evolutionary change in professional football is its increasing physical demands over time as the sport becomes more competitive (Barnes et al., 2014; Bradley et al., 2016; Bush et al., 2015). Yet, while competition drives evolution, it is in features of cooperation—the capacity for concerted action, as individual parts act as a unit to achieve a larger collective benefit (Park, 1927)—that complex emergent patterns and structures are observed in collective animal groups. Pelicans flying in V-shape formation show reduced heart rates and wingbeat frequency (Weimerskirch et al., 2001), while achieving 70% increase in range (Lissaman & Shollenberger, 1970) compared to a solo bird. Army ants on the move self-organise to form distinct lanes to minimise congestion despite numbering in the thousands (Couzin & Franks, 2003); they also form living bridges to overcome gaps on a foraging trail (Reid et al., 2015). Fire ants link their bodies to form waterproof rafts to survive floods (Mlot et al., 2011). Fish group together when exposed to the threat of predators (O'Connor et al., 2015; Partridge, 1982), increasing their shoal size and cohesion (Hoare et al., 2004), therewith producing more tightly clustered shoals, with shorter distances to

their neighbours (Schaerf et al., 2017). Coordination is important, as fish that are attracted toward, and align their direction of travel with, their nearest neighbours are rarely attacked (Ioannou et al., 2012). Conversely, increased fragmentation and irregularities in the spatial structure of prey groups tend to result in more predatory attacks (Handegard et al., 2012). Cooperative emergent behaviour is also seen when animal groups hunt as a collective (Bailey et al., 2013; Macdonald, 1983). Wolves have been known to hunt by fanning out and encircling their prey (Escobedo et al., 2014; Mech & Boitani, 2003; Muro et al., 2011). Worker ants (*Eciton burchellii*), numbering hundreds of thousands, form fan-shaped swarms that spread over the ground, gathering large quantities of prey (Hölldobler & Wilson, 2009). Bluefin tuna hunting in large schools (>10 members), similarly adopt a parabolic shape, perpendicular to the direction of travel, funnelling or encircling their prey; these structures also offer hydrodynamic benefits to one another (Partridge, 1982; Partridge et al., 1983) (some examples are shown in Figure 1). Thus, across different taxa, two trends in cooperative behaviour can be observed, particularly relating to predator-prey interactions. (1) Grouping together is a common defence mechanism against predators. (2) Encircling prey is a common characteristic of collective hunting. These group structures bear similar resemblances to the collective behaviours in competing football teams, particularly in regard to their attacking-defending roles. Teams in defence tend to group together to reduce goalscoring opportunities for their opponents, while teams in attack tend to spread out and occupy larger spaces to create more goalscoring opportunities (Castellano et al., 2013; Fonseca et al., 2012; Moura et al., 2012) (Figure 1d). Hence, these emergent group structures arising from the attacking-defending nature of football share similar principles of group behaviour drawn from the competition and cooperation of collective animal groups in complex biological systems.

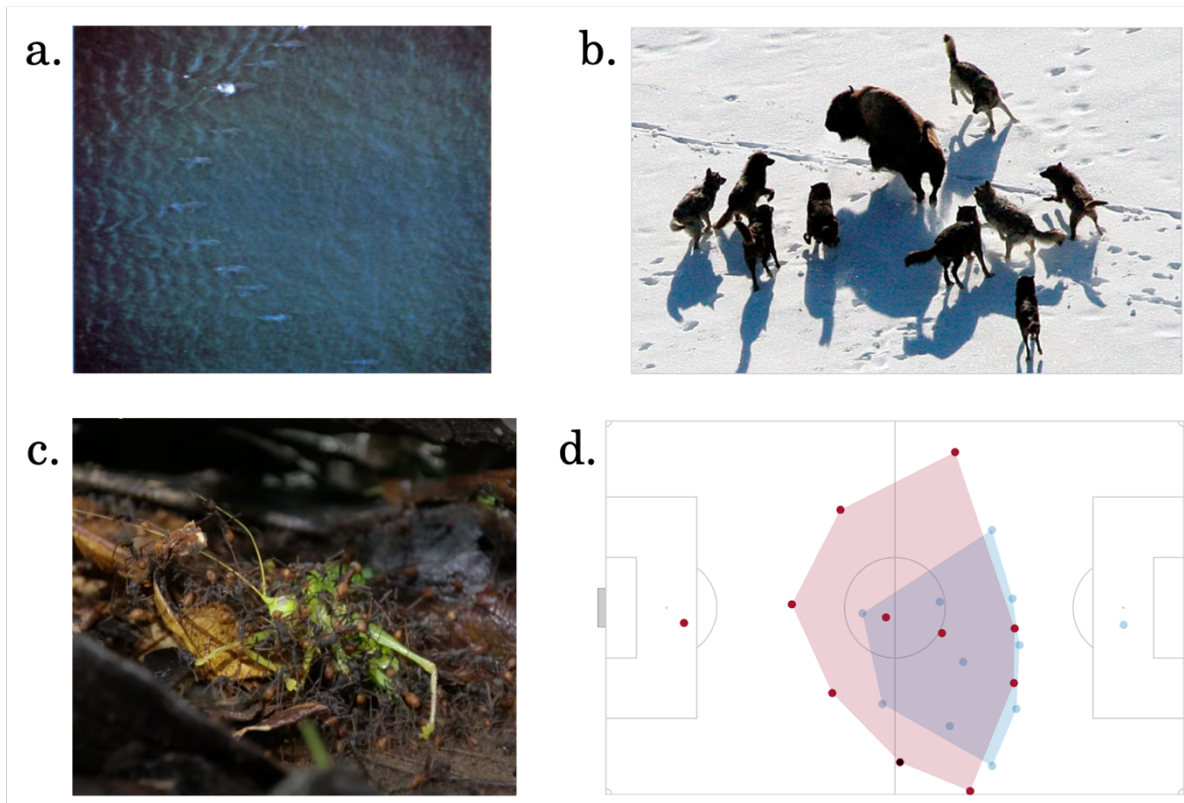


Figure 1: Complex cooperative behaviours in animalia and football. (a) Giant bluefin tuna collectively hunting in a parabolic formation. This highly cooperative behaviour forces schools of prey between the extreme ends of the parabola; bluefin tuna then surround and hunt them. Aerial photographs have shown that tuna achieve this parabolic formation, and inter-individual spacing, with remarkable regularity (Partridge, 1982). (b.) Grey wolves encircling a bison. (c.) Army ants swarming their prey (d.) Attacking teams in football occupying larger areas than defending teams. Pictures taken from (a.) Partridge (1982); (b.) Wu et al. (2019); and (c.) Fothergill (2015)

While members of an animal collective appear homogeneous, non-random inter-individual differences have been found to exist within each group structure. Amongst members, differences in factors like age, sex, hunger, speed, and size can influence the spatial position adopted by an individual within the group (Bolnick et al., 2003; Couzin & Krause, 2003; Herbert-Read, 2016; Krause, 1994). Fish that were starved tend to occupy positions at the front of the group, to increase their chances of food consumption (Hoare et al., 1998; Krause, 1993; Krause et al., 2000); a consequent trade-off is that these fish are potentially the first to encounter predators. Hungrier caterpillars are also found at the front of the group, and tend to lead group movement (McClure et al., 2011). Hungry

whirlgig beetles on the other hand, take up peripheral positions in the group while satiated beetles occupy central positions, but when the threat of a predator arises, males move to the periphery while females move to the centre (Romey & Wallace, 2007). In bird flocks, faster individuals tend to occupy leading positions at the front of moving groups (Couzin et al., 2002; Pettit et al., 2015; Pettit et al., 2013), and further away from the group centre; individuals with higher error and higher rates of turning tend to be at the rear, and closer to the group centre (Couzin et al., 2002). In primates, juveniles are more centrally located, whereas dominant males tend to be at the front of the pack (Farine et al., 2017; Janson, 1990a, 1990b; Rhine et al., 1985; Rhine et al., 1981). Sociability traits also explained within-group position, as more sociable members were more centrally located and closer to conspecifics, while less sociable members were found on the periphery or at the front (Bode et al., 2011; Jolles et al., 2017). Scientists have also found that inter-individual variability can be critical to group success. Bee colonies with high diversity in characteristics like genes (Jones et al., 2004), foraging profiles (Burns & Dyer, 2008; Muller & Chittka, 2008), and decision strategies (Dyer et al., 2014), perform better in tasks like nest thermoregulation and nectar collection. In contrast, colonies with lower inter-individual variability have reduced performances in tasks like comb building, storage of honey and pollen, and brood rearing (Fuchs & Schade, 1994); they were also more susceptible to parasites (Baer & Schmid-Hempel, 1999). Colonies of *Thermothorax* ants are more productive when there is high variability in the aggressiveness of their workers (Modlmeier & Foitzik, 2011). In one breed of a social spider (*Anelosimus studiosus*), colonies with a mix of aggressive (asocial) and docile (social) individuals capture more prey than homogeneous colonies (Pruitt & Riechert, 2011). These studies show that characteristic non-random patterns do exist in the spatial position an individual adopts in a complex collective group structure, and inter-individual differences in seemingly homogeneous groups play an important role in group success.

Similarly, the spatial structures of football teams also comprise non-random inter-individual differences in footballers' inherent characteristics like

anthropometry and physiology. Goalkeepers are frequently the tallest and heaviest players (Bernal-Orozco et al., 2020; Deprez et al., 2015; Gil et al., 2007b; Hazir, 2010; Rebelo et al., 2013; Reilly et al., 2000; Sporis et al., 2009), with the highest percentage body fat (Boone et al., 2012; Gil et al., 2007b; Rebelo et al., 2013). In outfield players, the tallest and heaviest tend to be defenders (Deprez et al., 2015; Vescovi et al., 2006), in particular, centre-backs (Lago-Peñas et al., 2011; Rebelo et al., 2013; Wong et al., 2009). Forwards tend to have the highest variability in anthropometry, with different studies finding them to be among the shortest (Franks et al., 1999; Malina et al., 2000) and lightest (Wong et al., 2009), or tallest (Marques et al., 2016), leanest, and highest muscle mass / percentage (Bernal-Orozco et al., 2020; Gil et al., 2007b). Together, goalkeepers (Sporis et al., 2009), centre-backs (Boone et al., 2012), and forwards (Gil et al., 2007b; Marques et al., 2016) tend to have the highest jump heights. In relation to running, midfielders tend to have the best endurance (Deprez et al., 2015; Rebelo et al., 2013; Sporis et al., 2009; Tonnessen et al., 2013), while forwards tend to be the fastest players (as obtained from sprint tests) (Boone et al., 2012; Deprez et al., 2015; Gil et al., 2007b; Haugen et al., 2020; Haugen et al., 2012, 2013; Marques et al., 2016; Sporis et al., 2009; Vescovi et al., 2006). The effects of age also show that goalkeepers and defenders tend to be older (Bloomfield et al., 2005). Thus, inter-individual variability within a collective group structure exists in the complex biological systems of both animal groups and football teams. This stands in contrast to complex systems in the basic sciences, like the field of thermodynamics for instance, where particles are identical and move randomly.

Off the pitch, complex collective behaviours have also been studied in humans. Spectators in a stadium spontaneously form a Mexican wave (Farkas et al., 2002). Women synchronise their menstrual cycles when living or working closely together (Stern & McClintock, 1998). The collective movement of marathon participants, particularly at the start line, can be modelled using hydrodynamic theory (Bain & Bartolo, 2019). Audience clapping can synchronise, despite beginning asynchronously, but this is not possible with fast clapping (Neda et al., 2000); this is an applied manifestation of the experiment in coupled

oscillators, when pendulums beginning at different frequencies converge to an average frequency if the initial frequencies do not differ too greatly (Kuramoto, 1975, 1984). Beyond a certain car density, vehicular traffic transits into a highly correlated state where vehicles move with approximately the same speed, resembling the motion of a solid block; this traffic state, although slower, is safer due to higher predictability and reduced lane-changing; such modelling helps authorities design traffic controls to maximise throughput (Helbing & Huberman, 1998; Helbing & Treiber, 1998). Sometimes, collective human behaviours are studied to prevent negative events such as panic situations in crowds (Helbing et al., 2000; Low, 2000). On opening day, the oscillation of London's Millennium Bridge, arising from the synchronisation of pedestrians' gait, caused great concern; as the bridge swayed side-to-side, pedestrians spontaneously aligned their swing and stance phases, further amplifying the oscillations before authorities closed the footbridge (Strogatz et al., 2005). At a micro level, complex coordinative behaviours can also be seen in individuals, such as cardiac resynchronisation with pacemakers (Young et al., 2003), and the self-organised synchronisation of circadian rhythms to environmental factors like light and temperature (Aton & Herzog, 2005; Pavlidis, 1973). Taken together, these studies show that, similar to animal groups, humans also exhibit non-random patterns of complex coordinative behaviour, from macro to micro levels.

But what are the underlying mechanisms taking place at local level interactions amid global level patterns (in humans and animalia)? Research shows that at local levels of interaction, information transfer tends to take place between nearest neighbours (Couzin, 2007; Herbert-Read et al., 2011; Inada & Kawachi, 2002; Rio et al., 2018). Couzin (2007) explained that during group movement, although an individual's sensory capabilities are restricted due to crowding, the close behavioural coupling allows a localised change in direction to be amplified, as information propagates towards the wider group population, resulting in a group level change in direction. This also means that during collective movement, individuals position themselves relative to group members

(or relative to the group centre) rather than their absolute positions (Berdahl et al., 2013; Couzin & Krause, 2003; Couzin et al., 2002). Spontaneous information transfer within a group confers some benefits. Firstly, the collective sensory capabilities of the group are much larger than for any individual, such as the collective sensitivity to risk (Sosna et al., 2019), and allows for the averaging of individual errors (Grünbaum, 1998). In humans, group members with approximately average intelligence can form groups with high collective intelligence scores; this was correlated with high social sensitivity of group members and conversational turn-taking (Woolley et al., 2010). Second, uninformed individuals do not jeopardise group cohesion. In fact, only a small minority of individuals are needed to guide a group toward a target location (food source, or along a migration route) (Couzin et al., 2005), a result that was extended to humans, even without the need for verbal communication (Dyer et al., 2009; Dyer et al., 2008). In football, information transfer also takes place between nearest individuals. Players tend to be more synchronised with teammates in neighbouring positions, reflecting that the movement of one player closely affects that of a neighbouring teammate (Folgado et al., 2014; Folgado et al., 2015). Silva et al. (2016a) further showed that with practice (and increased tactical expertise), the time delay between synchronised individuals decreases. Nearest neighbour synchronisation was also found in directly competing opponents (Narizuka & Yamazaki, 2016; Siegle & Lames, 2013), characterising defensive marking when a player moves in relation to the opposing player he is tasked to mark. Although players' positions relative to their team centroid show more stability than their absolute x - and y -coordinates (Sampaio & Maças, 2012), they are more synchronised to their group centroid (i.e. defenders, midfielders, forwards) compared to the team centroid (Gonçalves et al., 2014). This could indicate a hierarchical order of reference positioning: players position themselves relative to the team centre rather than the static pitch; but within the team, they position themselves in relation to yet nearer neighbours. Therefore, the principle of information transfer via nearest neighbours manifests in the collective group movements of animals, humans, and even football teams.

A large contributing factor to these collective behaviours is the environment. Animals and humans appropriately adjust their behavioural movements according to different environmental contexts. This can be seen in the self-organised lane-forming of pedestrians in narrow walkways, where Helbing and Molnar (1995) showed that the number of lanes formed scales linearly with the width of the walkway. Often, however, the interaction between system and environment is bidirectional. In the basic sciences, this is akin to a dissipative system — an open system operating far from equilibrium, exchanging energy with the environment (Prigogine, 1978; Prigogine & Lefever, 1968). In the sociobiological sciences, Couzin and Krause (2003) explain that individuals change the local properties of their environment, which subsequently influences the movements of others; this further alters the environment and the process is repeated. This was exemplified in some studies. Ants deposit pheromones between nest and foraging areas, so as to lay trails for conspecifics (Beckers et al., 1992, 1993; Bossert & Wilson, 1963). Pedestrians walking on grass initially take the most direct route to their destinations, but over time, they change to existing trails (Helbing et al., 1997a; Helbing et al., 1997b). Hence, the environment can shape individuals, just as individuals can shape the environment, which goes on to shape future behaviour.

This notion of the environment shaping action (and vice-versa) bears similarities to the field of ecological psychology, wherein early pioneers like James Gibson believe that the environment plays an important role in shaping perception and action (Gibson, 1966, 1979). This stands in contrast to cognitive psychology, where only the internal mental processes of a participant are studied (often in a laboratory) (Mace, 1977). Gibson (1966) believed that since perception is related to the senses, and the senses only work when they are stimulated, the starting point in understanding an individual's perception is the environment, because it is the source of all stimulation, and therefrom, information. The environment then, in the form of its various elements like medium (e.g. air), substances (e.g. water), surfaces (e.g. grass), objects (e.g. trees, ball, goal), and even other individuals (e.g. conspecifics, predators, teammates, opponents),

offers an individual perceivable opportunities for action known as affordances (Gibson, 1979). The information provided by these affordances drives perception and action, and subsequently, their continuous and reciprocal interdependency (Turvey & Carello, 1986; Warren, 2006). It is also worthy to note that this perception is of a direct nature, where actions are subsequently performed without any intermediate stage of mental depiction (Gibson, 1966). The ecological psychology approach to understanding perception and behaviours has also found its way into sports science, mainly in the form of ecological dynamics (Araújo & Davids, 2019; Araújo et al., 2006; Araújo et al., 2019; Vilar et al., 2012). In this paradigm, the athlete-environment system is the relevant unit of analysis; actions are the direct realisation of affordances, and are self-organised under constraints (described later), rather than an internal representation of the mind or external instructions from a coach (Araújo & Davids, 2019; Araújo et al., 2019). In team sports, affordances can also be collectively perceived by a team, leading to subsequent group behaviours (Silva et al., 2013). Some empirical studies using an ecological dynamics framework have led to useful findings in improving our understanding of sports behaviours. In one vs. one, defenders tend to be closer to the ball when they are far away from the goal they are defending; but at closer proximities, this distance increased (Headrick et al., 2012). In the game of rondo, a defender's movement is tightly coupled with those of surrounding passers, and the coupling increases at higher intensities, and in older age groups (Menuchi et al., 2018). Taken together, incorporating the role of the environment is an important factor in understanding an individual's decision-making and action.

As system complexity permeates sports science literature, another paradigm emerged in the discipline of motor control — constraints. One of the famous problems of motor control was that presented by Nikolai Bernstein (1967), who stated that a movement task can be achieved with a multitude of possible movement patterns (e.g. muscle activation patterns, joint movement patterns); this begets the problem of how the central nervous system determines redundant and relevant degrees of freedom in executing such a movement. In

addressing this question, which became popularly known as “Bernstein’s problem”, Peter Kugler et al. (1980) presented his theory of coordinative structures and proposed that when a group of muscles are constrained to act as a unit, such a structure can be considered dissipative, hence providing a principled understanding of coordination and control. Thus, constraints limit the possibilities for action of a movement system (Kugler et al., 1980; Newell, 1986), and its usage in understanding the development of coordination became an alternative to more traditional prescriptive approaches (Gesell, 1929). Karl Newell (1986) went on to categorise three types of constraints, whose interactions optimise movement coordination and control: organismic constraints are those internal to the system being analysed (e.g. height or weight of the analysed individual); environmental constraints are those external to the analysed system (e.g. ambient light and temperature); and task constraints relate to the goal of the activity and specific constraints imposed (e.g. rules limiting response dynamics of movements, implements or machines limiting response dynamics)^b. While identifying organismic constraints may be obvious, the distinction in the latter two is not always so, as Newell (1986) explained that environmental and task constraints are not mutually exclusive, and their definitions depend on the nature of the task. Over the years, this framework of constraints has been used in various fields of sports science such as skill acquisition (Chow et al., 2015; Davids et al., 2007; Renshaw et al., 2010), sports coaching (Renshaw et al., 2019), and sports performance (Glazier, 2010). This includes many studies in football (Ometto et al., 2018), as researchers manipulate organismic, environmental, and task constraints as independent variables, to consequently observe their effects on dependent variables. Organismic constraints could include comparing players in different age groups (Figueira et al., 2018; Olthof et al., 2015), players of different skill levels (Silva et al., 2014a; Silva et al., 2014b; Silva et al., 2014c), or changing the number of

^b This categorisation of constraints differs slightly from those of ecological dynamics described previously (Araújo & Davids, 2019; Araújo et al., 2019), where constraints are described as physical (e.g. properties of a field) or informational (e.g. movements of other individuals). Nevertheless, their broader definitions are consistent in that they both limit the degrees of freedom of a system.

players in a team (Aguiar et al., 2015; Gonçalves et al., 2016; Sampaio et al., 2014). Since Newell (1986) wrote that constraints reside at each level of analysis in the organism, extending this to football implies that the analysed system can include any of the levels of organisation described earlier — individual, dyadic, group, team, or match level. Environmental constraints could include different pitch dimensions (Frencken et al., 2013; Olthof et al., 2018; Vilar et al., 2014), pitch orientations (Coutinho et al., 2018a), or pitch lines (Coutinho et al., 2018b; Coutinho et al., 2020). Task constraints could include different formations priorly instructed (Baptista et al., 2020; Memmert et al., 2019), the effects of a training programme (Coutinho et al., 2018c; Sampaio & Maçãs, 2012; Santos et al., 2018; Santos et al., 2017b; Silva et al., 2016a), or the allowed number of ball touches (Coutinho et al., 2021). In overview, this framework is used extensively in different fields of sports science, and guides researchers and practitioners in better understanding sports behaviours amid the many degrees of freedom associated with complexity.

Another important feature of complex systems that needs further elaboration is timescale. While earlier paragraphs have described complexity at various spatial scales (macro to micro levels), analysing systems at the appropriate timescale is also important, because it tells us how long complex emergent processes take (Kuehn, 2015). In motor systems, synaptic transmissions occur in the scale of milliseconds (Greengard, 2001; Sabatini & Regehr, 1999), while evolutionary biology takes place over a scale of thousands of years (Darwin, 1859). A study on avian flocks showed that a change in manoeuvre propagates along a timescale of milliseconds, beginning slowly, before increasing the speed of propagation (Potts, 1984). In a football match, Silva et al. (2016a) showed that the mean delay in time for a player to adjust his movements with respect to those of his teammates ranges from less than one second (with the most coupled teammate) to about four seconds (with the least coupled teammate); this time delay also decreased after a fifteen-week training programme, suggesting that the speed of information transfer in teammates improves with weekly practice. In the drill of Rondo (characterised by four

players keeping ball possession and one player in the middle attempting to win the ball), time delay in footballers' movements relative to one another can occur at a scale of less than one second; this time delay is shorter in experienced players or when performed in smaller spaces (Menuchi et al., 2018). Over longer timescales, scientists have also found various patterns in players' collective behaviours. Teams' dispersion and collective movement up and down the pitch are more predictable and more pronounced in the second half of a match, compared to the first half (Duarte et al., 2013b). The oscillating patterns in dispersion resulting from the attacking-defending nature of the game also showed lower frequencies in the second half (Moura et al., 2013). Players' synchronisation patterns were also more regular in the second half (Duarte et al., 2013a). Over the course of periodised training, team dispersion showed an increasing trend throughout a 22-week programme (Aquino et al., 2016). These findings show that complex collective behaviours in nature and football can emerge at different timescales, and researchers should select the appropriate timescale to observe the appropriate behaviours of a system.

Further complexity emerges when timescales are considered together with decision-making and actions. Animal groups are known to exhibit a speed-accuracy trade-off in decision-making and actions. When searching for a nest-site under harsh conditions, ant colonies make decisions quickly, but with reduced accuracy, as decisions are more individual than collective (Franks et al., 2003); this was also seen in honeybees who adopt careful selection procedures in their collective decision-making, rather than quick, and potentially bad, judgements (Franks et al., 2002). In the competitive sport of football, however, good performance entails making the right decisions and actions as quick as possible, leading us to the concepts of tactics and strategy. Tactics have long been regarded as the spontaneous actions that players perform in adaptation to the dynamically changing match situations, while strategy refers to the elements of play made in advance, so that players can organise themselves after considering as much information as possible (Gréhaigne & Godbout, 1995; Gréhaigne et al., 1999). In the ecological dynamics approach, one distinction between the two is

that strategy could involve a stage of mental representation (Araújo et al., 2009), since it is commonplace for coaches to use visual representations in the form of videos, slides, tactical boards and the like in preparing their teams for upcoming games (Carling et al., 2007); conversely, tactical actions emerge from players' continuous and *direct* perceptions of the dynamically-changing environment, where *direct* means without an intermediate stage of mental representation (Araújo et al., 2009; Araújo et al., 2019). This distinction in direct and indirect perception was also made in Gibson's 1966 text, where an individual's direct response to stimulus information in the environment is known as *knowledge of* the environment, while indirect responses are based on stimulus sources provided by another individual, and is known as *knowledge about* the environment. A second, and more immediately apparent, difference between tactics and strategy is their respective timescales in which they occur. Tactical actions are performed under strong time constraints whereas strategic plans can be contrived with the relative luxury of time (Gréhaigne et al., 1999). While it may seem that tactics occur near-instantaneously, studies have shown that the duration of emergent tactical patterns can occur over a variety of timescales. Ric et al. (2017) found that each possession of the ball for an individual player occurred on average over a timescale of 2.71 seconds. Team ball possession, however, occurs over a timescale of approximately thirty seconds (Gonçalves et al., 2019; Ric et al., 2016), whereas the expansion and contraction speeds when teams change their dispersion (transiting between attacking-defending roles) occur over timescales of approximately three seconds (Ric et al., 2016). This also means that tactics and strategy can scale spatially, as decision-making (Gréhaigne et al., 2001) and affordances (Silva et al., 2013) occur from individual to collective levels. Therefore, this can be surmised that good team performance not only involves having the right strategies, but also being trained, individually and collectively, to intuitively perform the right tactical actions throughout the course of the match.

Up to this point, much of the evidence in the preceding pages linking the game of football to complex systems have been largely phenomenological, but

some studies have attempted to quantitatively demonstrate proof of concept. Many of them have shown that, similar to the field of motor control (Kelso, 1984; Kugler et al., 1980), the movements of two opposing units can be modelled as coupled oscillators, particularly in the longitudinal direction, due to the attacking-defending nature of the game; this was shown in 11 vs. 11 (Duarte et al., 2013a; Duarte et al., 2013b; Frencken et al., 2012), small-sided games (Duarte et al., 2012c; Frencken et al., 2011; Olthof et al., 2015; Silva et al., 2014b), and 1 vs. 1 (Duarte et al., 2012b; Headrick et al., 2012; Laakso et al., 2017). These studies strengthen earlier papers that provide mainly descriptive recommendations of modelling football as a dynamical system (Gréhaigne et al., 1997; McGarry et al., 2002). Kijima et al. (2014) also quantitatively showed that the coupled oscillations in the attacking-defending behaviours of football follow the rules of fractional Brownian motion, and exhibit a Hurst exponent of ~ 0.7 , indicating a memory effect. In overview, despite numerous studies adopting an approach of system complexity, few have attempted to characterise definitive system states in the game of football. In 1 vs. 1, the point when an attacker passes a defender has been descriptively proposed as symmetry-breaking between stable and unstable behaviour (Vilar et al., 2012). However, this did not scale to small-sided games or 11 vs. 11, as various order parameters showed stability even in the occurrence of critical events like shots or goals (Bartlett et al., 2012; Frencken et al., 2011; Frencken et al., 2012). Narizuka and Yamazaki (2016) showed that by analysing the directional alignment of players' velocity vectors, football games can be divided into an order and disorder phase, where the former is characterised by players of one team chasing players of the other. A recent publication by Welch et al. (2021) analysed collective variables in three phases of play, attacking, defending, and out-of-play. They subsequently showed that defending phases of play are characterised by highly ordered team movement, and could be quantitatively modelled upon the polar state seen in fish schools that exhibit high directional alignment; out-of-play phases could be modelled on the swarm pattern in fish schools (characterised by relatively dense grouping but little alignment); while attacking phases of play had the widest distribution between polar and transitional states. This is corroborated by other

studies showing defensive behaviours as stable patterns (Ric et al., 2016), characterised by highly synchronised movements (Marcelino et al., 2020), while attacking behaviours have less synchrony, but also a wider distribution of behaviours depending on team strength (Marcelino et al., 2020). In summary, there are different perspectives on how system states can be characterised in the complex system of football; one similar trend however is that the attacking and defending behaviours can be conceived as collective system states that teams in a football match alternate between; additionally, order parameters are better at distinguishing defensive phases of play compared to attacking phases.

2.2 Position data from player-tracking technology

Remarkable as they are, early models of self-organisation in collective behaviours (Ashby, 1947; Wiener, 1948) were not experimentally validated because of limitations in tracking technology then. Much has changed today however, as technology has allowed the possibility of animal tracking, across continents (Kays et al., 2015) and even under water (Hussey et al., 2015), enabling scientists to validate theories and models (Sumpter et al., 2012).

Position-tracking has also proliferated the field of sports science, being frequently used in universities and professional clubs. Such player-tracking systems provide the instantaneous positions of players (and sometimes the ball) at various frequencies, and typically express them in the form of geodetic or cartesian coordinates. These systems also provide timestamps, allowing for their analysis at appropriate timescales. Based on their methods of capturing data, the systems can be broadly classified into: global positioning systems (GPS), optical tracking systems, and radio-frequency systems — an overview of all three systems can be found in the works of Buchheit et al. (2014); Carling et al. (2008); Randers et al. (2010); Rico-González et al. (2019). In 1947, William Ashby wrote that the configuration of a system, at any given moment, is defined as the set of numbers which are the values of the variables describing the system. And the behaviour of the system is determined by the successive configurations

interspersed with regular time intervals. In football, Gréhaigne et al. (2001) called them configurations of play — a snapshot in a particular instance of time depicting the positions of players and the ball. Thus, the very nature of player-tracking systems make them perfectly suitable tools to study collective movement complexity in football, in a way that is vastly superior to qualitative observation.

2.3 A systematic review of empirical research (Study One)

Since the beginning of the last decade, a large number of studies have examined players' tactical behaviours based on their complex collective movements (Lord et al., 2020; Sarmiento et al., 2018). Study One of this dissertation (Low et al., 2020) therefore comprises a systematic review about empirical research in this field to understand its state of the art, and identify possible gaps that this dissertation could address.

Abstract

Background

Performance analysis research in association football has recently cusped a paradigmatic shift in the way tactical behaviours are studied. Based on insights from system complexity research, a growing number of studies now analyse tactical behaviours in football based on the collective movements of team players.

Objective

The aim of this systematic review is to provide a summary of empirical research on collective tactical behaviours in football, with a particular focus on organising the methods used and their key findings.

Methods

A systematic search of relevant English-language articles was performed on one database (Web of Science Core Collection) and one search engine (PubMed), based on PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-

analyses) guidelines. The keywords ‘football’ and ‘soccer’ were each paired with all possible combinations of the following keywords: ‘collective movement behaviour’, ‘collective behaviour’, ‘tactical behaviour’, ‘interpersonal coordination’, ‘space’, ‘Voronoi’, ‘synchronisation’, ‘tactical analysis’, ‘constraints’, ‘ecological dynamics’, and ‘dynamic positioning’. Empirical studies that were related to tactical analyses of footballers’ positional data were sought for inclusion and analysis.

Results

Full-text articles of 77 studies were reviewed. A total of 27 tactical variables were identified, which were subsequently organised into 6 categories. In addition to conventional methods of linear analysis, 11 methods of nonlinear analysis were also used, which can be organised into measures of predictability (4 methods) and synchronisation (7 methods). The key findings of the reviewed studies were organised into two themes: levels of analysis, and levels of expertise.

Conclusions

Some trends in key findings revealed the following collective behaviours as possible indicators of better tactical expertise: higher movement regularity; wider dispersion in youth players and shorter readjustment delay between teammates and opponents. Characteristic behaviours were also observed as an effect of playing position, numerical inequality, and task constraints. Future research should focus on contextualising positional data, incorporating the needs of coaching staff, to better bridge the research-practice gap.

2.4 Research problem and aims of the thesis

Based on the findings of the systematic review, two gaps in this body of research were identified which the present dissertation attempts to address: (1) much is still unknown about the underlying processes explaining tactical behaviours in 11 vs. 11; (2) research is not sufficiently contextualised for practice.

Underlying processes in 11 vs. 11

More than a decade ago, tactical analysis in football was viewed as an under-theorised field of study (Garganta, 2009); this made it difficult to understand the explanatory mechanisms behind observed tactical behaviours. This could be understandable, as it was around the same time that player-tracking systems became available (Di Salvo et al., 2006). Since then, some common findings in collective tactical behaviours have emerged that improved our general understanding of tactical behaviours. For instance, as found in Study One, (1) better tactical expertise was characterised by higher movement regularity, wider dispersion in youth players, and shorter time delay between the movements of teammates and opponents; (2) increasing player numbers in small-sided games increases dispersion and movement regularity; (3) increasing the pitch size in small-sided games increases the inter-team distance, distance to nearest opponent, movement regularity, and reduces pitch movement variability; (4) changing conventional goals to multiple mini goals increases inter-team distance, distance to nearest opponent, and increases usage of the lateral pitch areas; and (5) in numerical inequality, lower dispersion, increased movement regularity, higher synchronisation, and less advanced pitch positions, characterised the conservative team behaviour of the numerically inferior team. Such knowledge helps coaches in practice design, because they can predict the consequent collective tactical behaviours when manipulating various constraints in training. However, many of these relationships were established from research in small-sided games, whereas explanatory models of tactical behaviour responses in 11 vs. 11 remain lacking.

One reason for this could be due to peculiar differences in their study designs. Studies on small-sided games, unsurprisingly, adopted mainly experimental designs ($n = 36$ in Study One), whereas studies on 11 vs. 11 disproportionately adopted observational ($n = 34$) rather than experimental designs ($n = 7$) (Figure 2). In this field, observational studies typically examine the tactical behaviours of professional football teams during official matches,

through the retrospective analysis of their position data, while experimental research typically comprises controlled field experiments, where scientists overtly manipulate independent variables (or constraints) to examine their effects on the tactical behaviours of footballers. The large disparity in observational vs. experimental study designs in 11 vs. 11 could be due to the advantages of the former over the latter (O'Donoghue, 2010; Thomas et al., 2015). (1) Observational research does not require any intervention from scientists, whereas experimental research requires considerable effort in its setup; (2) observational research has higher external validity than experimental research, since footballers are studied based on their actual performances in their natural competition environments; and (3) entire seasons of data can be easily obtained in observational research, since position data can be simply procured from third-party providers, whereas experimental research requires huge logistical rigour to achieve similarly large samples. Despite these differences, one main benefit experimental study designs have over observational designs is the ability to determine cause and effect. This is due to their trade-offs in internal and external validity (Campbell, 1957; Campbell et al., 1963). Experimental research has higher internal validity, because its controlled nature gives scientists greater confidence that changes in the dependent variable indeed arose from manipulations of the independent variable (McDermott, 2011). This is juxtaposed to observational research where the influence of many unknown variables limits the ability of explaining cause and effect, rendering findings to be typically associational (Carlson & Morrison, 2009). Experimental research may be difficult to conduct in some fields of science because of ethical concerns to do no harm; in epidemiology, for instance, it is unethical to expose an experimental group to a disease and compare them against a control group of healthy participants. The field of tactical behaviours in football, however, faces no such concerns, and therefore stands to benefit from more experimental research. Furthermore, since scientists have advocated the importance of understanding the underlying mechanisms leading to performance (Glazier, 2010; McGarry, 2009), experimental studies, then, hold explanatory potential in linking the collective team behaviours to performance outcomes. Thus, the

present dissertation adopts an experimental approach in an attempt to understand the underlying processes contributing to players' collective tactical behaviours in 11 vs. 11 football.

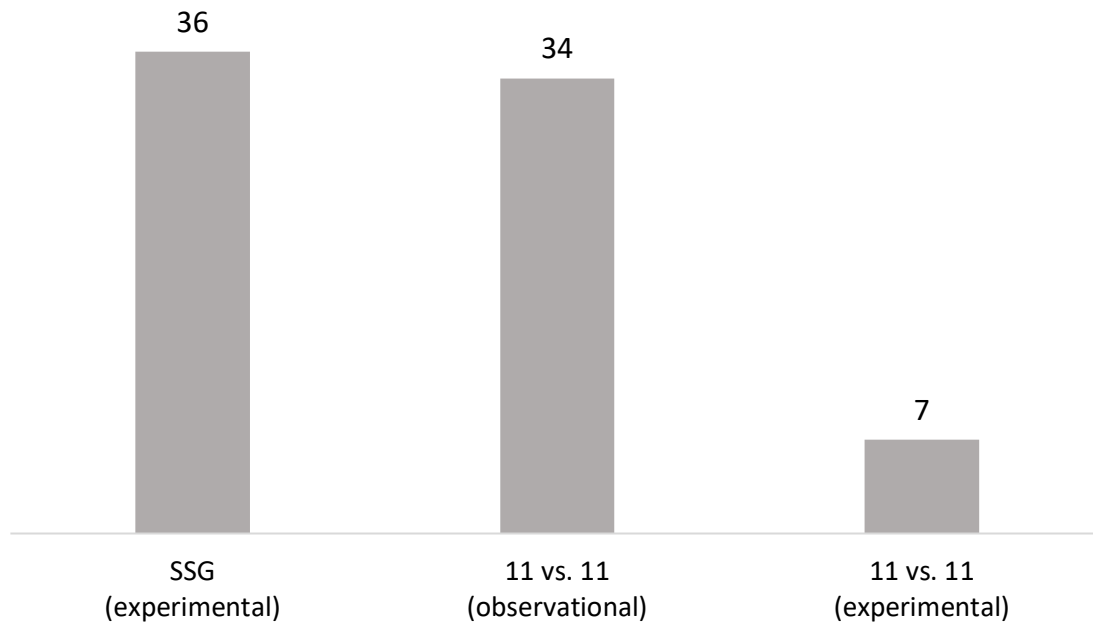


Figure 2: Number of studies adopting experimental and observational study designs in small-sided games and 11 vs. 11. As counted from the systematic review of Low et al. (2020).

This is attempted through the conduct of field experiments, so that findings can be extended to players' natural competition environments. As features of good experimental design, Egon Brunswik (1956) advocated for representativeness in the tasks that experimenters required participants to perform if findings are to be generalised to their natural environments. Thus, in addition to the conventional representative sampling of participants (Kruskal & Mosteller, 1979, 1980), the representative sampling of experimental conditions is also important. This is contrasted to the artificially created environments of traditional laboratory experiments, which Brunswik termed as *systematic* design rather than *representative* design. In the absence of the latter, behaviours emerging from the former are only specific to the task performed in the laboratory, and lack the representative degrees of freedom that characterise

complexity in football tactical behaviours for instance. This paradigm of representative design has found its way into sports performance research in the form of ecological dynamics (Araújo et al., 2019; Davids et al., 2006); when applied to the present dissertation, the conditions of an experiment should also represent those of footballers' natural competition environment toward which generalisation is intended. Hence, the empirical studies that follow are conducted via 11 vs. 11 field experiments.

Insufficiently contextualised research for practice

Last but not least, another gap identified in this body of research is the lack of context for effective translation to practitioners. Although position-tracking technology is used in many professional football clubs, practitioners mostly use it to monitor training loads (Impellizzeri et al., 2019), rather than analyse tactical behaviours. This dissertation proposes two contributing factors, which it subsequently attempts to address: (1) lack of distinction in phases of play and (2) scale of analysis.

In 2009, a perspective paper by Tim McGarry (2009) encouraged the study of players' behaviours with and without possession of the ball, to gain a more complete assessment of performance. This is relevant because published books on coaching frequently prescribe different playing principles in distinct phases of attack and defence (Daniel, 2003; *FIFA Youth Football Training Manual*; Jankowski, 2015; Zauli, 2003). Despite this, the following years showed that only 26 of the 77 published studies distinguished between phases of ball possession (with five of them being 1 vs. 1) (Low et al., 2020). Since players' collective tactical behaviours have been shown to be characteristically different in attack and defence (Castellano et al., 2016; Gonçalves et al., 2019; Marcelino et al., 2020), the field experiments used in the present dissertation will distinguish between attacking and defending phases of play to help bridge the gap between theory and practice.

Secondly, a majority of studies analysed tactical behaviours at the match and team levels of organisation, whereas analyses at lower levels of organisation are small in numbers. Figure 3 shows, based on Study One, the distribution of analyses performed at each of these levels. Part of providing contextualised research for practitioners entails analyses at lower levels of organisation like the group and dyadic levels. For example, group level analysis can show us the behaviours of defenders, midfielders, or forwards as part of the broader team effort (Gonçalves et al., 2014), while dyadic level analysis can inform us about marking behaviour between directly competing opponents (Siegle & Lames, 2013). The empirical studies of this dissertation therefore perform analyses at each level of organisation to strive for a more holistic understanding of collective tactical behaviours.

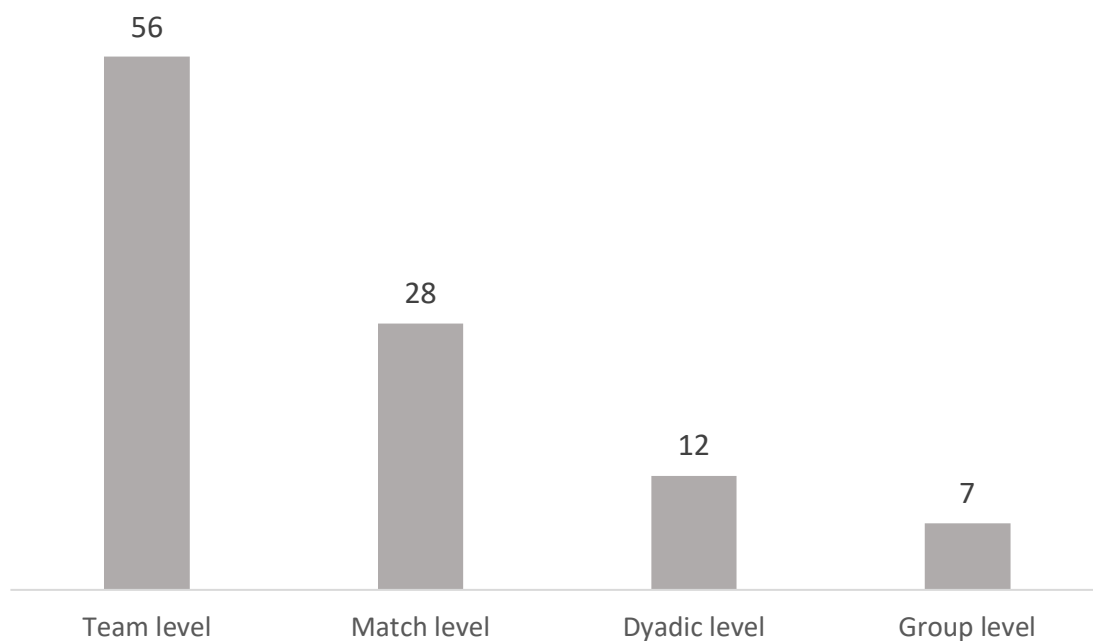


Figure 3: Number of studies analysing tactical behaviour at various levels of organisation. As counted from Study One.

In view of these considerations, the aim of the present dissertation is to understand how the underlying mechanisms at different levels of organisation contribute to the observed collective tactical behaviours in 11 vs. 11 football as an effect of different strategies. In so doing, explanatory models of tactical

behaviour can potentially provide more contextualised knowledge for practitioners. Two empirical studies are conducted that examine the consequent tactical behaviours in footballers as an effect of two defending strategies: pressing (Study Two) and formation (Study Three). The justifications for these studies are provided in their respective chapters, and their aims are as follows:

- Study Two: to analyse footballers' collective tactical behaviours from their position data, as an effect of two contrasting pressing strategies, high-press defending and deep-defending
- Study Three: to analyse footballers' collective tactical behaviours, based on their position data, as an effect of two defending formations, 4-4-2 and 5-3-

2

Chapter 3: Study Two

The porous high-press? An experimental approach investigating tactical behaviours from two pressing strategies in football (Low et al., 2021)

Abstract: The aim of this study was to analyse footballers' tactical behaviours from their position data, as an effect of two contrasting pressing strategies, high-press defending and deep-defending, using a trial-based experimental approach. Sixty-nine youth footballers participated in this 11 versus 11 study, performing 72 trials of attack versus defence, in a counterbalanced crossover study design. Players' position data were captured using a local positioning system, and processed to calculate measures of inter-team distance, trial duration, distance to nearest opponent, dispersion, team length, team width, team shape, space control gain, inter-line distance, and individual area. This was augmented by the notational analyses of passes. The findings showed that using a high-press defending strategy leads to: closer inter- team distance; larger dispersion, due to a longer team length; and larger inter-line distances between defenders, midfielders, and forwards. The resulting effects on the attacking team include reduced ball possession time; larger individual areas for attacking midfielders and forwards; longer team length; and more penetrative passes performed. Some differences in marking behaviour were also observed. Consequently, the study recommends that high-press defending be used sparingly due to these trade-offs.

Chapter 4: Study Three

Defending in 4-4-2 or 5-3-2 formation? Small differences in footballers' collective tactical behaviours (Low et al., 2022)

Abstract: This study explored footballers' tactical behaviours, based on their position data, as an effect of two defending formations, 4-4-2 and 5-3-2, using an experimental approach. Sixty-nine youth footballers participated in this 11-versus-11 study, performing 72 trials of attack versus defence. Players' position data were tracked using a local positioning system, and processed to calculate measures of collective movement. This was supplemented by the analysis of passing networks. The results showed small differences between the two conditions. Compared to a 4-4-2 formation, defending in 5-3-2 reduced dispersion (-0.69 m, $p = 0.012$), midfield-forward distance (-0.81 m, $p = 0.047$), and defence-forward distance (-1.29 m, $p = 0.038$); the consequent effects on attacking teams included reduced team widths (-1.78 m, $p = 0.034$), reduced necessity for back-passes to the goalkeeper, and less connectivity in the passing network. The effects of the two defending formations seem to have the greatest impact on fullbacks of the attacking teams, since they were main contributors of the reduced team widths, received more passes, and had higher betweenness centrality in the right-back position during 5-3-2 defending. In summary, the present study potentially demonstrates how the underlying mechanisms in players' collective movements and passing behaviours show that the 5-3-2 is more conservatively defensive than the 4-4-2.

Chapter 5: Discussion and Conclusion

The present dissertation aimed to understand the underlying processes in footballers' collective tactical behaviours in 11 vs. 11 at various levels of organisation as an effect of two prior strategies, defensive pressing (Study Two) and defending formation (Study Three). Each study was performed through a field experiment consisting repeated measures of attack vs. defence. Players' tactical behaviours were analysed based on their position data, obtained from player-tracking units, and this was further supplemented by the analysis of their passes. In overview, more differences were found in Study Two (pressing) than Study Three (formation), yet both studies demonstrated how collective tactical patterns at higher levels of organisation (e.g., match and team) can be linked to interactions at lower levels (i.e., group, dyadic, and individual). Study Two showed that the increased dispersion when performing high-press defending (team level) is related to further inter-line distances (group level) and affords more individual space to opponent forwards and attacking midfielders (individual level) while marking behaviours changed (dyadic level). Study Three explained how the 5-3-2 is more conservatively defensive than the 4-4-2 by showing that reduced dispersion in the former (team level) was contributed by forwards retreating closer to midfielders (group level), and therewith changing marking opponents (dyadic level). Thus, both studies provided explanatory models of footballers' consequent tactical behaviours at various levels of organisation, as an effect of different strategies.

Combining the results of both studies can provide further insights into players' tactical behaviours. Since the participants in both studies were the same, and the 4-4-2 formation in Study Three used a midfield-press, we can gain a more holistic overview of collective tactical behaviours across three different types of pressing — deep-defending, midfield-press, and high-press — where two different patterns were observed. Firstly, defensive structures are inherently

different when performing the high-press, whereas deep-defending and midfield-pressing have similar collective structures. This can be seen in Figure 4, in the values of mean dyadic distance, team length, LpW ratio, and the three inter-line distances. Measures of dispersion tend to be similar during deep-defending and midfield-pressing but greater during high-press defending. Trial length has the reverse effect — similar during deep-defending and midfield-pressing but lower during high-press defending. This is also illustrated in Figure 5, wherein a principal component analysis (PCA) performed on these variables showed that deep-defending and midfield-pressing have similar characteristics — as seen by the overlap between red and blue ellipses — while high-press defending is more differentiated (as seen in the green ellipse). The region in the middle of the graph, where the green dots lie within the blue or red ellipses, represent high-press trials with characteristics similar to midfield-pressing and deep-defending ($n = 14$). These trials were visually reinspected (via video and GUI animation), and majority of them ($n = 10$) were found to be occurrences wherein the high-press was overcome, and defending teams consequently retreated to a midfield-press or deep-defence. The second pattern of collective behaviour identified is the progressive trend observed in several variables across the three different pressing strategies (shown in Figure 6). In particular, LpW ratio (attacking teams) and individual areas of attacking midfielders and forwards showed a progressively increasing trend when confronted with deep-defending, midfield-press, and high-press; conversely, inter-team distance showed a reverse trend — being highest when confronted with deep-defending, and lowest in high-press defending. This means that progressively changing the defending strategy from deep-defending to high-press defending: progressively affords more spaces to opponent forwards and attacking midfielders; progressively elongates opponents' playing shape; and progressively reduces the inter-team distance. Taken together, these findings can be broadly organised into defending and attacking behaviours; defensively, collective behaviours are similar in deep-defending and midfield-pressing, but distinctly different in high-press defending; offensively, collective behaviours show more progressive trends.

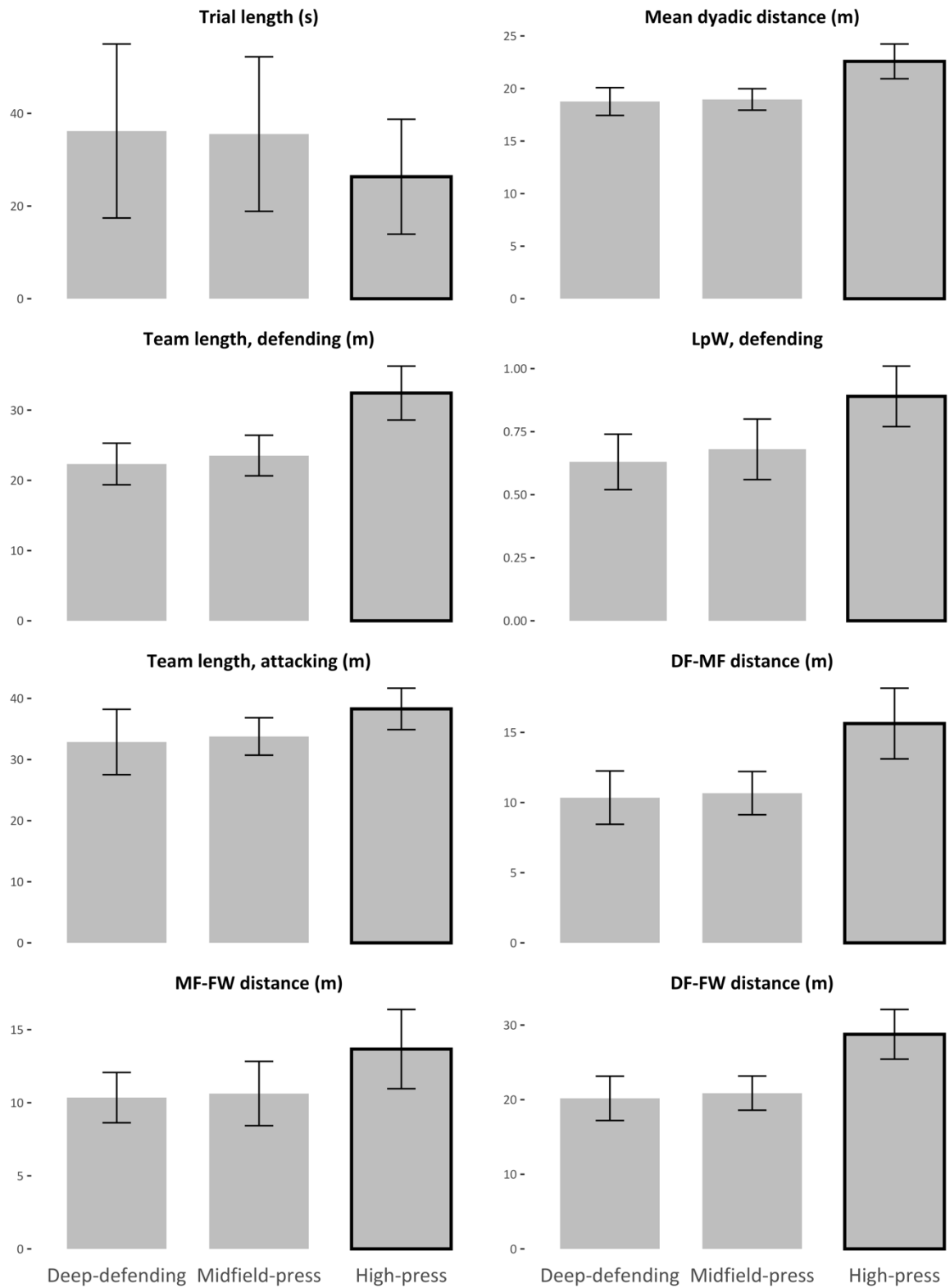


Figure 4: Tactical variables showing that high-press defending is distinctly different, while deep-defending and midfield-press are similar.

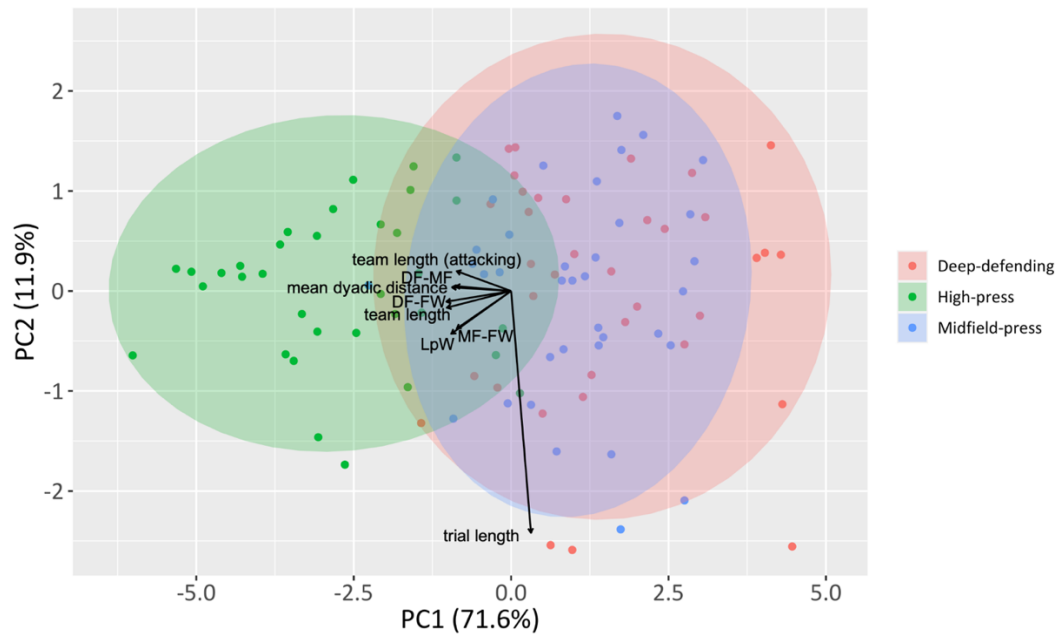


Figure 5: Principal component analysis on trial length, mean dyadic distance, team length, LpW ratio, and the three inter-line distances. Ellipses represent the 95% confidence interval of trials using each defending strategy. The arrows represent PCA loadings, and are multiplied by 2.5

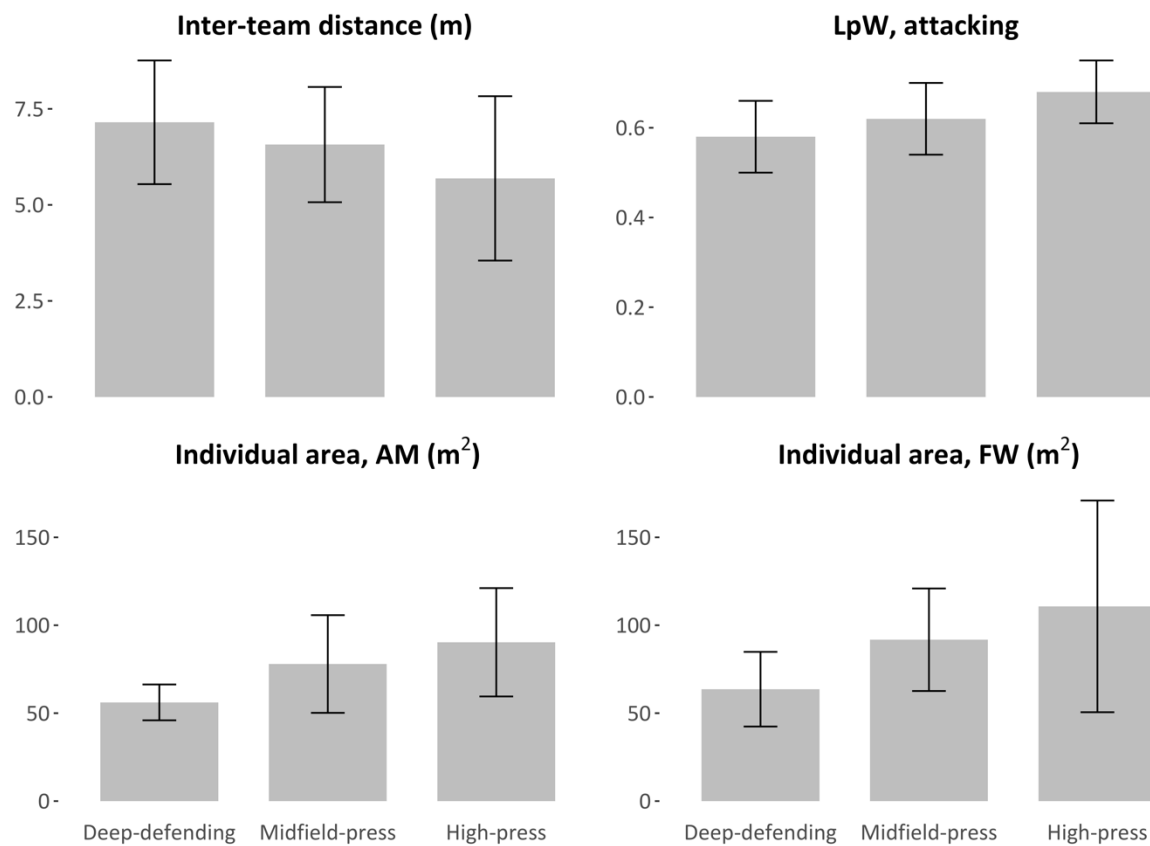


Figure 6: Tactical variables showing progressive trends across different pressing strategies

These patterned observations in response to different defending strategies indicate that collective behaviours in football teams are adaptive, just like complex group behaviours in other fields of science. As written in chapter one, social insects like army ants (*Eciton hamatum*) not only form living bridges to shorten a foraging trail, but dynamically lengthen, widen, and change bridge positions according to traffic conditions and features of the environment, demonstrating a collective knowledge of cost-benefit trade-off, where the benefits of having more workers foraging meant less of them forming the structure (Reid et al., 2015). A similar breed of army ants have also been known to form shelters using their massed bodies, and regulate temperature and humidity within by dynamically adjusting their positions and shape (Hölldobler & Wilson, 2009). In flocks of starlings, complex group patterns are formed, and continuously modified, when defending against peregrine falcons (Storms et al., 2019). These examples are just a few among many, showing that, across many animal taxa, group structures are highly sensitive to members' perceptions of predatory risk and resources (Caraco et al., 1980; Creel et al., 2014; Schaerf et al., 2017). For a long time, researchers have stated that systems can internally reorganise to result in changes in behaviour (Ashby, 1947), and that part of what constitutes complexity is to have structure with variations (Goldenfeld & Kadanoff, 1999). Empirical results in the present dissertation thus demonstrate the variations in footballers' collective structures according to different defending strategies (pressing and formation), just as collective animal groups vary their group structure according to their continuously-changing circumstances.

One of the strengths of this dissertation comes from the experimental design of the two empirical studies. This has allowed for more contextualised analyses in attacking and defending situations, and different levels of organisation. Moreover, in an experimental study, determining prior task constraints like formation, pressing strategy, and playing position removes the ambiguity that frequently accompanies observational research. For example, certain formations (e.g. 4-3-3 and 4-5-1) may be too similar to distinguish, even with position data (Carling, 2011); determining if a player is a defender,

midfielder, or forward may not always be so clear-cut, rendering group level analysis difficult; and it is hard to know if any changes in formation, playing position or playing style took place in the middle of the match (and attempting to find out could be a tedious process). Methodologically, one may argue that constraining the experimental conduct to organised phases of ball possession (beginning from a goal-kick) reduces its representativeness of real-life matches. Furthermore, the nature of emergence, as described in chapter one, also implies that the behaviour of a system cannot be simply inferred from the behaviour of its components, or from a smaller subset of timescale (Corning, 2002; Funtowicz & Ravetz, 1994; Gibb et al., 2019). However, scientists have also written that the collective behaviour is contained in the behaviour of the parts *if they are studied in the context in which they are found* (Bar-Yam, 1997). Thus, context is important in understanding the explanatory mechanisms underlying performance (Glazier, 2010; Lames & McGarry, 2007; McGarry, 2009), in which case the present dissertation showed that: the increased dispersion during high-pressure defending can be explained by longer team length and further inter-line distances, therewith resulting in larger individual areas for the opposing attacking midfielder and forward (study two); and the reduced dispersion when defending in 5-3-2 compared to 4-4-2 can be explained by forwards retreating closer to midfielders (study three). The values of some dependent variables in this dissertation show consistency with those of real matches; this was the case for inter-team distance (Frencken et al., 2012; Olthof et al., 2019), mean dyadic distance (Figueira et al., 2018; Palucci Vieira et al., 2018), and team length (Castellano et al., 2013; Castellano & Casamichana, 2015; Olthof et al., 2019). In contrast, team width during attack was distinctly higher than those of real matches (Castellano et al., 2013; Castellano & Casamichana, 2015; Olthof et al., 2019), consequently leading to lower LpW ratios. This disparity could be presumed to be a consequence of the trial-based design; when the ball was lost, wide players maintained their lateral positions for the restart of the next trial, but in a real match, they would need to reduce their dispersion, especially in the immediate seconds after a transition (Moura et al., 2013; Moura et al., 2016). Therefore, although the experimental study design trades off some external

validity (Campbell, 1957; Campbell et al., 1963), comparisons with literature showed good representativeness in extending the findings to real matches, and more importantly, allowed us to establish some explanatory mechanisms related to pressing and defending formations.

The empirical studies present some practical implications that coaches could consider. In adopting a high-press defending strategy, coaches should be cognisant of some trade-offs: players are further apart, opposing forward and attacking midfielder are given more spaces, and more penetrative passes are conceded. The high-press is therefore advised to be used sparingly, perhaps when time is running out. When choosing between the 4-4-2 or 5-3-2 defending formations, the latter formation is more compact because forwards retreat closer to midfielders; this reduces opponents' passes but more passes are made to their full-backs. A practical application for data analysts could be in classifying the pressing behaviours of opponents, if their position data from previous matches is known. This is presented in greater detail in the Appendix, where a linear discriminant analysis using select tactical variables (inter-team distance, distance to nearest opponent [defending], centroid x-coordinate [defending], team length [defending], team width [defending], distance to nearest opponent [attacking], team length [attacking], team width [attacking]) can classify a team's pressing behaviour, and reflect any tendency for a particular pressing style. In summary, these recommendations can help predict collective behaviours when using a defending strategy, or predict the defending strategy based on players' collective behaviours.

The empirical studies also present some limitations. Firstly, only under-17 footballers from a convenience sample were tested, making it unclear if these behaviours extend to professional players or other youth players. Secondly, the limited number of formations tested also needs to be considered. Study two examined pressing using a 4-4-2 formation, and study three confined comparisons to only 4-4-2 and 5-3-2. Furthermore, the attacking teams in both studies always used 4-2-3-1. As there are many different formations that teams

can adopt (see supplementary Table A of Study Three for an overview), and even more permutations between those of two competing teams, much is still unknown if these findings generalise to other formations. A third limitation is that the controlled nature of the trial-based study design restricts the study of tactical behaviours to only organised phases of attack and defence. This leaves knowledge gaps about collective tactical behaviours in other phases of play like transitions (defence to attack and attack to defence), wherein probabilities of scoring are higher (Tenga et al., 2010a; Tenga et al., 2010b; Tenga et al., 2010c). For these reasons, readers should exercise caution before generalising their findings.

In conclusion, analysing tactics in football has been known to be complex, but the present dissertation has shown that, using an experimental approach underpinned by principles from complex collective behaviours, some underlying mechanisms can help explain players' tactical behaviours related to pressing and formations. In high-press defending, the larger dispersion exhibited can be explained longitudinally by further inter-line distances that consequently afford more spaces to the opposing forward and attacking midfielder. The reduced dispersion when defending in a 5-3-2 formation compared to a 4-4-2, can be explained by forwards retreating closer to midfielders. Methodologically, adopting an experimental approach trades off external validity, but with well-constrained and representative task designs, can help provide more contextualised findings for both researchers and practitioners. Performing analyses at different systemic levels of organisation provide insights into tactical behaviours from micro to macro level perspectives. Future research could extend similar investigations to other participant demographics (e.g. professionals, women, youth players), other formations, or seek confirmation in real-life matches.

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Appendix

Linear discriminant analysis

A linear discriminant analysis was performed, to establish a model for predicting the type of pressing a team performed — high-press, midfield-press, or deep-defending. This was computed using the statistical software R (version 3.6.1), with the *lda()* function in the “MASS” package.

First, the dependent variables at match, team, group, and individual levels were considered. In addition, the *x*-coordinate of the defending team’s centroid was added, because it logically reflects how far up the pitch a team is collectively positioned. Next, a correlation analysis was performed to check for highly correlated variables. This was performed using the *pairs.panels()* function from the “psych” package and is presented in Figure 7. In defending teams, the team length was found to be highly correlated with: mean dyadic distance ($r = 0.90$), LpW ratio ($r = 0.90$), defence-midfield distance ($r = 0.81$), midfield-forward distance ($r = 0.81$), and defence-forward distance ($r = 0.96$); therefore, team length was retained, while the latter five variables were dropped. Similarly, in attacking teams, team length was correlated with mean dyadic distance ($r = 0.78$) and LpW ratio ($r = 0.85$); thus, the team length was again retained while the latter two variables were dropped. The first discriminant analysis model was then performed on the remaining variables using the *lda()* function. The first discriminant function (LD1) achieved 94.8% separation while the second discriminant function (LD2) achieved 5.2% separation. The scaled coefficients are as follows (given to two significant figures):

$$\begin{aligned} LD1 = & 0.22(InterTeamDist) - 0.010(TrialLength) + 0.081(DistNearestOpp, def) \\ & - 0.32(Centroid, x, def) + 0.070(Length, def) - 0.082(Width, def) \\ & - 0.29(DistNearestOpp, att) + 0.11(Length, att) - 0.20(Width, att) \\ & - 0.00020(Voronoi, CM, left) + 0.0026(Voronoi, CM, right) \\ & - 0.0099(Voronoi, AM) - 0.0052(Voronoi, FW) \end{aligned}$$

$$\begin{aligned}
LD2 = & -0.061(InterTeamDist) - 0.014(TrialLength) - 0.83(DistNearestOpp, def) \\
& - 0.088(Centroid, x, def) - 0.15(Length, def) - 0.039(Width, def) \\
& + 1.1(DistNearestOpp, att) - 0.13(Length, att) - 0.23(Width, att) \\
& - 0.0023(Voronoi, CM, left) + 0.00086(Voronoi, CM, right) \\
& + 0.027(Voronoi, AM) + 0.0030(Voronoi, FW)
\end{aligned}$$

This initial model achieved 97.7% and 93.1% accuracy on training (60% of data) and testing datasets (40%) respectively. However, several coefficients (Trial length, Voronoi, CM, left; Voronoi, CM, right; Voronoi, AM; Voronoi, FW) contributed very low values, particularly for LD1, and therefore were deemed to be contributing to noise rather than signal. These variables were then dropped and a new discriminant analysis was performed (but same seed retained).

The second model achieved 96.2% separation for LD1 and 3.8% separation for LD2 (also shown in Figure 8). The scaled coefficients are as follows:

$$\begin{aligned}
LD1 = & 0.30(InterTeamDist) - 0.32(DistNearestOpp, def) - 0.29(Centroid, x, def) \\
& + 0.11(Length, def) - 0.065(Width, def) - 0.13(DistNearestOpp, att) \\
& + 0.085(Length, att) - 0.21(Width, att)
\end{aligned}$$

$$\begin{aligned}
LD2 = & 0.027(InterTeamDist) - 0.86(DistNearestOpp, def) - 0.13(Centroid, x, def) \\
& - 0.22(Length, def) - 0.058(Width, def) + 0.78(DistNearestOpp, att) \\
& + 0.032(Length, att) - 0.19(Width, att)
\end{aligned}$$

The biplot for this model, and its coefficients are shown in Figure 9. The model achieved 93.8% and 97.5% accuracy on the same training and testing datasets respectively.

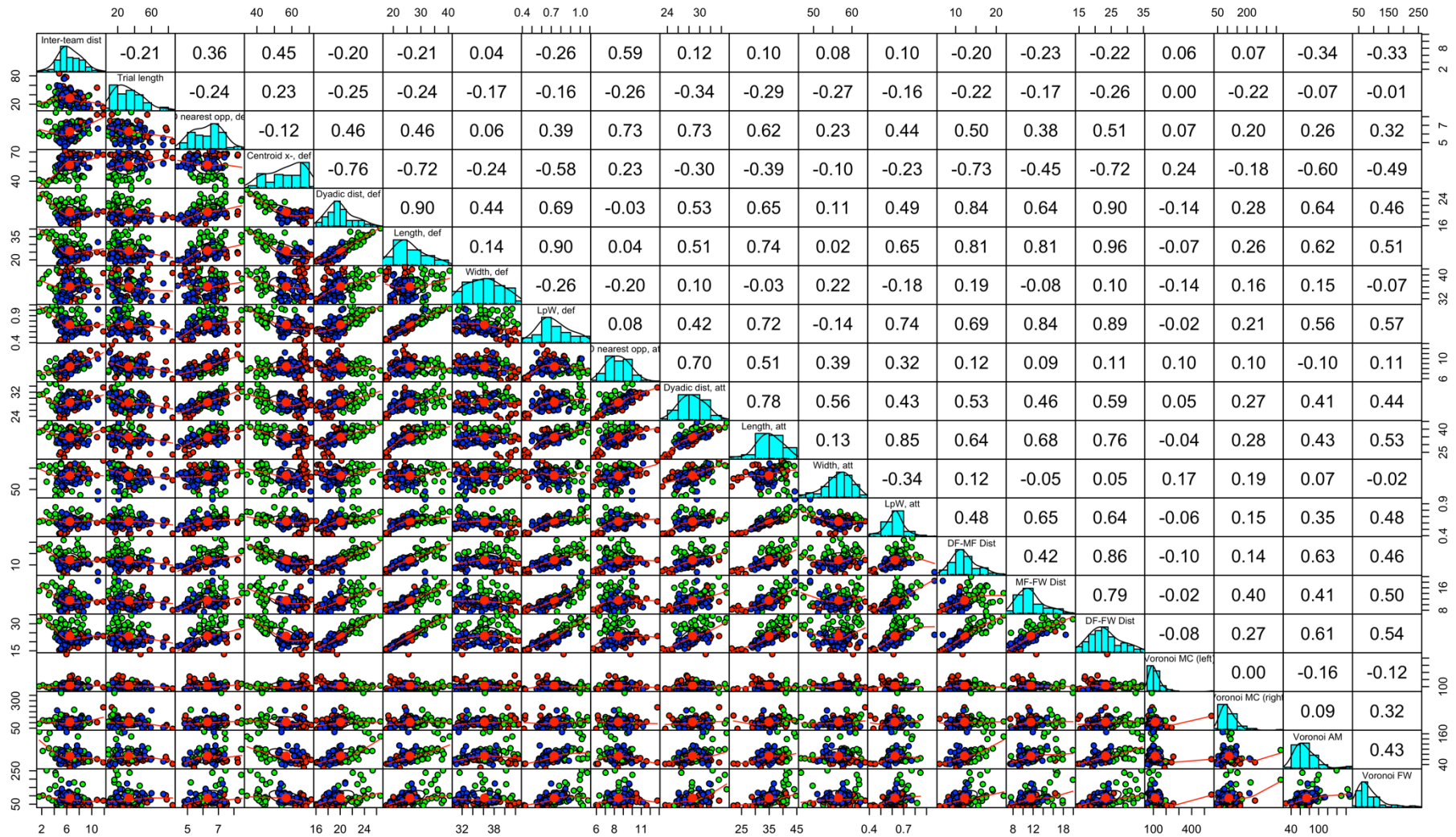


Figure 7: Correlation coefficients between dependent variables

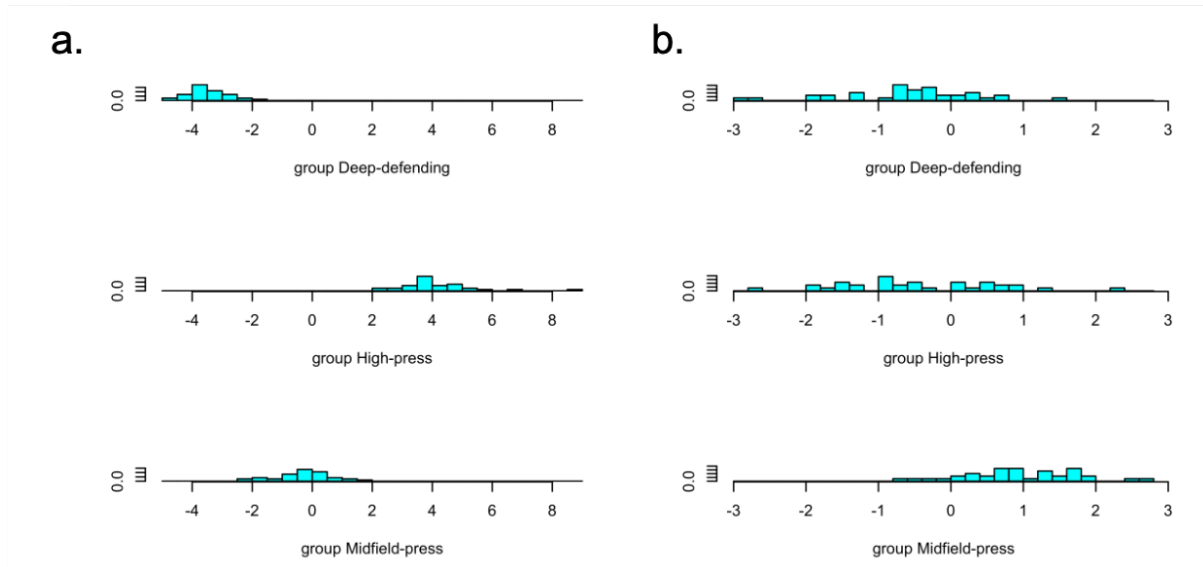


Figure 8: Histograms for (a.) discriminant function 1 and (b.) discriminant function 2

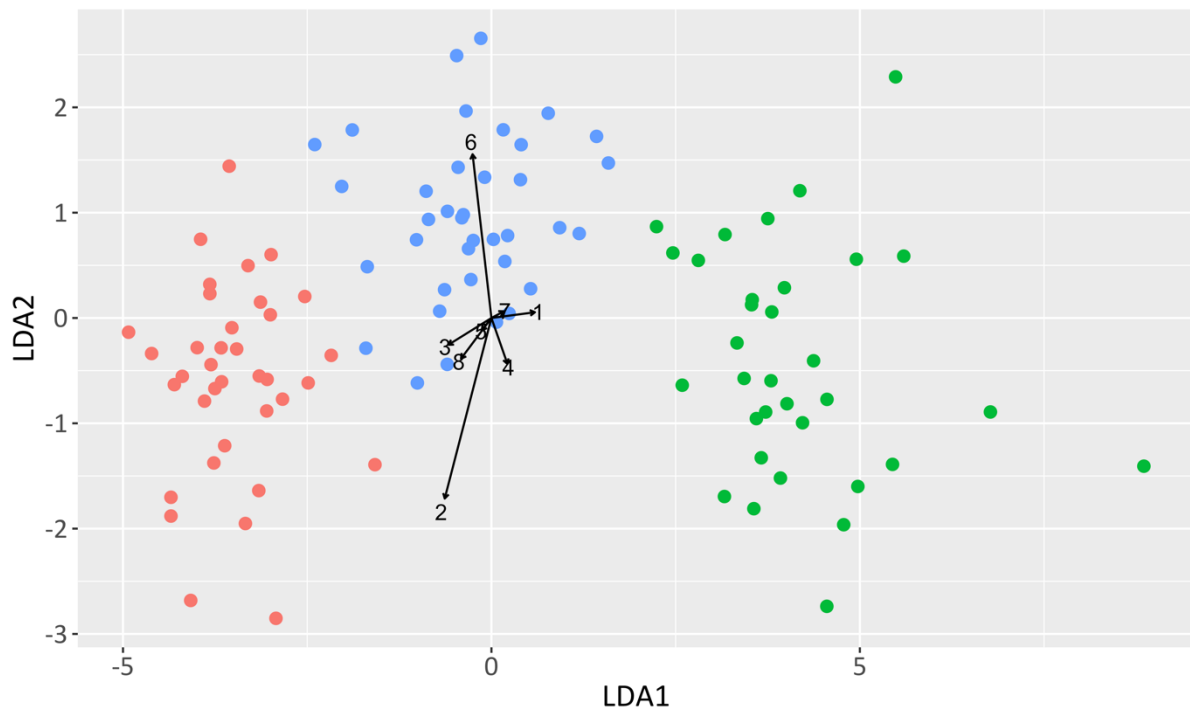


Figure 9: Biplot of linear discriminant analysis showing deep-defending (red), midfield-press (blue), and high-press (green) trials. Coefficients are shown as arrows (multiplied by two) and are so labelled: 1 = inter-team distance, 2 = distance to nearest opponent (defending), 3 = centroid x-coordinate (defending), 4 = team length (defending), 5 = team width (defending), 6 = distance to nearest opponent (attacking), 7 = team length (attacking), 8 = team width (attacking)