Understanding the Decision Making Process in Elite Athletes: Using a Psychophysiological Approach to Measure Intuitive Decisions

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Abstract

Sport decision making is highly complex, time pressured, often using incomplete or misleading information. With the additional need to plan motor movements, expert athletes have been described as relying on intuitive decision-making strategies. Using such strategies can explain how individuals make effective decisions under these extreme constraints.

Our understanding of intuition is hampered by the challenge of measuring it. One strategy is to use proxy measures based on the characteristics of intuition. Specifically, it is suggested that intuitive decisions are those that are made with little cognitive effort. Pupillometry has been used to measure cognitive load, and thus provides a potential measure of intuition and its underlying processes.

The body of work presented in this thesis aimed to examine the use of intuitive decision-making strategies in elite athletes. It begins with a systematic review of the literature that examined cognitive load in athletes from a perceptual-cognitive perspective. The systematic reviewed highlights a gap in the literature that uses pupillometry in sport, despite its extensive use in other fields. Aiming to fill that gap, the thesis presents two experimental studies that examined the use of intuitive decision-making strategies in both domain-generic and domain-specific tasks. The collective results of these studies suggest that measurement of cognitive load in perceptual-cognitive tasks is possible using pupillometry. The studies further demonstrate that the order in which cognitive tasks are completed can influence the cognitive load experienced. These findings provide insight into the nature of decision making in sport and considerations for measurement and training, particularly in video-based decision-making tasks like those used as part of larger training programs. Alongside these considerations, the thesis highlights methodological concerns and suggestions for future research. By tackling a difficult area to measure and proposing a way forward this thesis provides insights in to expert perceptual-cognitive processing and its training.

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List of Abbreviations

DSR – Decision-specific reinvestment

DSRS – Decision-specific Reinvestment Scale

ECG – Electrocardiograph/Electrocardiography

EEG – Electroencephalogram/Electroencephalography

EMG – Electromyograph/Electromyography

ERD – Event-related desynchronisation

ERP – Event-related potential

ERS – Event-related synchronisation

FMRI – Functional magnetic resonance imaging

HRV – Heart rate variability

MOT – Multiple object tracking

PET – Positron emission tomography

RH – Recognition heuristic

ToL – Tower of London

TTF – Take the first

Statement of Original Authorship

Except where reference is made in the text of the thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis accepted for the award of any other degree or diploma. No other person's work has been used without due acknowledgment in the main text of the thesis. This thesis has not been submitted for the award of any degree or diploma in any other tertiary institution.

All research procedures reported in the thesis received the approval of the relevant Ethics/Safety Committees (where required).

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Chapter 1: General Introduction

The programme of works presented in this thesis examines the intuitive decision-making process of elite athletes utilising a psychophysiological measurement technique, pupillometry. Decision making is highly complex and involves the ability to rapidly and accurately select the correct response from a range of presented alternatives (Raab & Farrow, 2013). Central to this thesis is understanding how individuals can make effective decisions under the extreme time pressures inherent to sporting scenarios. Given the nature of sporting decisions, the perspective adopted is the intuitive decision-making approach, whereby decisions are reached more automatically and without extensive conscious processing.

This first chapter provides a brief background of judgement and decision-making research and why the understanding of intuitive decision-making strategies is important (section 1.1). It then explains the context (section 1.2) of the research undertaken and follows on to highlight the specific aims, objectives, and purpose of the current body of work (section 1.3). Section 1.4 discusses the significance and scope of the research programme. Finally, section 1.5 provides an outline of the remaining chapters of this thesis.

1.1 BACKGROUND

Decision making has been identified as a key component that demonstrates the perceptual-cognitive advantage that expert athletes possess over their lesser skilled counterparts (Broadbent et al., 2015). In a sporting context, decision making is highly complex, is often performed under extreme time pressures, and in many situations made additionally difficult by athletes making judgements on incomplete or (deliberately) misleading information (Pizzera & Raab, 2012), meaning sport provides an ideal vehicle to study decision making behaviour (Hodges et al., 2006). The perceptual-cognitive advantage of experts is typically assessed using video simulation tests that investigate decision-making skills. It is worth noting, however, that research has shown that the motor system is important and highly engaged in perceptual skills leading some researchers to refer to the skills as perceptual-cognitive-motor (Piggott et al., 2019).

Often the difference between winning and losing a sporting match is related to key decisions (either good or bad) made by individuals or teams. This attention has driven researchers to examine this ability in elite sport athletes. Despite this interest, however, Raab et al. (2019) highlight a concern that the theories adopted more broadly in cognition and action research have been adopted much slower in the field of sport. Raab et al. (2019) summarised publications from a search conducted using the Web of Science database and found 168 papers that examined judgement or decision making in sport. From these papers, and reflecting on the past 50 years of research, they identify four independent research streams: economic, social judgement, ecological, and cognitive approaches. In a recent systematic review, Ashford et al. (2021a) expanded on this approach found a total of 53 articles that had examined the decision making process specifically within a team sport context. Given the interest in this line of research, it seems there is still very limited research that has examined the decision-making process in sport.

Research has suggested that the characteristics of specific domains (e.g., time pressure, level of uncertainty etc.,) influence the "default" cognitive mode that decision makers adopt (Okoli et al., 2016). Given the similarities to other time pressured, complex decision-making domains, and the limited number of studies in sport, research has made use of the research from areas such as firefighting. Indeed, some of the earliest work that has developed our understanding of human decision making behaviour examined the decision making of firefighting personnel (Klein et al., 1986). Within emergency situations (such as firefighting) it is generally accepted that overall performance, and particularly decision making, is likely to be better if the conditions allow for sufficient time to consider the range of possible alternatives. However, firefighters are required to make critical decisions in often highly uncertain situations and immense time pressures that do not allow the luxury of generating and assessing a number of possible suitable choices (Okoli & Watt, 2018). Instead experts, when faced with complex environments that are time-pressured and highly stressful, appear to adopt approaches that better manage in these circumstances (Okoli et al., 2016). In these types of high-pressured decisions, experienced individuals still appear to perform well, despite the constraints imposed on them.

Much like in firefighting (and other emergency services situations) decisions in sport are also made under time constraints, however athletes are still able to function at a high level i.e., they make good decisions. To explain this, researchers have sought approaches that explain how experts are able to make effective decisions under these conditions. The approach of interest in this thesis is intuitive decision making and more specifically the view taken by Daniel Kahneman of two decision making systems. Kahneman (2011, p. 20) describes the systems as such:

> "System 1 operates automatically and quickly, with little or no effort and no sense of voluntary control".
>
> "System 2 allocates attention to the effortful mental activities that demand it, including complex computations. The operations of System 2 are often associated with the subjective experience of agency, choice, and concentration."

Within this context, therefore, intuitive decisions are popularly referred to as "thinking fast" while decisions that arise from System 2 which are more deliberative in nature, are commonly known as "thinking slow".

1.2 CONTEXT

Whilst the study of intuitive decision making has gained recent interest in empirical research (e.g., Betsch & Glöckner, 2010; S. Porter et al., 2008), the body of work that has examined this within sport (a domain which poses unique challenges) is still emerging (e.g., see Johnson & Raab (2003) and Raab & Laborde (2011) as examples of emerging research examining intuitive decision making in sport/athletes). The novelty of examining the use of intuition or System 1 decisions in sport presents a challenge for researchers, in particular to understanding exactly *how* to measure intuitive decision making. A particular focus within this thesis is a key central characteristic that distinguishes intuitive from deliberative decision making, cognitive load.

1.3 PURPOSES

The research strategy adopted in this thesis is to first identify suitable approaches to measure cognitive load in sport with the purpose of developing and testing a method to test intuitive decision-making strategies in athletes. To that end, the primary focus of this thesis is to enhance our understanding of how intuitive decisions in sport are utilised and how they can be measured objectively. Intuitive decisions, by their very nature, are difficult to measure as they are made by individuals quickly and subconsciously. One of the cornerstones of intuition is cognitive effort/load, which is the specific area of interest in this thesis. While this thesis focusses on intuitive decisions in athletes, the body of work presented has implications for theories of cognition more broadly. That is because sport is an excellent vehicle for studying these types of decisions, as they are made under time pressure and using often incomplete information. The research also has important implications for designing decision making tests and training programs.

This thesis has two specific aims:

1. To determine and test a measurement tool that is sensitive to detect cognitive load differences between intuitive and deliberative decisions.
2. To compare the difference in cognitive load of athletes and non-athletes in a sport-based decision-making task.

1.4 SIGNIFICANCE, SCOPE AND DEFINITIONS

This thesis provides a valuable contribution to understanding the nature of decision making and particularly in relation to intuition. This research tackles a difficult area to measure and presents a way forward that can lead to insights into perceptual-cognitive expertise in complex domains such as sport, but also for measurement and training of other tasks that require complex decision making. It addresses a gap in the extant literature that has examined cognitive load as a proxy for intuition. Within this thesis, cognitive load is defined as the amount of mental resources that an individual exerts while performing any given task (Paas et al., 2003). Given the broad scope intuitive decision making can cover and the complications surrounding measurement, this thesis narrows its focus on cognitive load as a key cornerstone of intuitive decisions within field hockey athletes. In that context, the definition of intuitive decision making adopted in this thesis is decisions that are reached quickly and with limited amount of cognitive effort.

While the scope of the current investigations is narrowed, the findings presented will be useful for athletes of a variety of sports, particularly team invasion sports, in understanding how expertise is developed and how researchers can measure this complex ability. The programme of research presented in this thesis adds to the literature on intuitive decision making in sport and will be useful to other researchers, sport scientists, and coaches by providing insight into the underlying mechanisms that can assist designing training programs.

1.5 THESIS OUTLINE

Chapter 2 provides an introduction to the thesis and describes the theoretical background of intuitive decision making, setting the scene for the chapters that follow.

Chapter 3 provides a systematic review of the extant literature that has measured cognitive load from a perceptual-cognitive perspective within athletes. The purpose of this chapter is to understand measurement of cognitive load in athletes with a focus on i) the technologies and tools that have been used, and ii) the specific measurement techniques utilised.

Chapter 4 builds upon the gaps identified in Chapter 3 and tests the cognitive load experienced by individuals during two different tasks that aimed to elicit either intuitive- or deliberative-based decisions. In addition to investigating how the task demands influence the cognitive load experienced by individuals, this chapter also describes the use of pupillometry as a method to measure cognitive load.

Chapter 5's purpose is to extend on the findings presented in Chapter 4 by adopting the same pupillometry methodology to examine intuitive decisions within elite field hockey athletes. Chapter 5 presents a study, that utilises a domain-specific video-based decision-making task to compare the cognitive load experienced in athletes and non-athlete participants.

Chapter 6 provides a general discussion of the thesis and a summary of the key findings. It also provides an overview of the major contributions to theory and methodology, presents the practical applications, and discusses the strengths and limitations of the programme of research. Chapter 6 concludes with an outline of recommendations for future directions of this body of work.

Chapter 2: Literature Review

2.1 EXPERTISE

For many years, researchers have been interested in gaining a richer understanding of the underlying psychological factors that discriminate high achieving individuals from less successful ones in sport (D. T. Mann et al., 2007). Researchers have reported that experts are generally more proficient decision makers and their ability to predict future events is evidence of this (D. L. Mann & Savelsbergh, 2015; Starkes & Allard, 1993; Williams & Jackson, 2019a, 2019b). From a historical perspective, our understanding of expertise can be traced back to early work from De Groot and colleagues (1965) who studied the mechanisms that explained how expert chess players selected their moves. This line of work identified that world-class chess players could rapidly perceive chess moves. Specifically, De Groot found that expert chess players were superior in recalling, almost perfectly, the positions of chess pieces after viewing them for only five seconds. As the expertise level of these chess players dropped, so too did this ability to recall the locations of chess pieces accurately. De Groot linked this ability to the players' expertise, rather than their general memory ability. This was supported by illustrating that memory of structured formations was superior, however, when presented with unstructured and meaningless configurations of chess pieces, experts' recall was no better than that of novices. De Groot linked this ability to the extensive knowledge players had of meaningful configurations, which developed as a function of expertise (Williams & Ericsson, 2005) rather than possessing an overall larger short-term memory capacity.

De Groot's findings that experts have superior recall of domain-specific information was further developed and formalised by the work of Chase and Simon (1973). Chase and Simon proposed a theory that suggested what differentiated world-class chess players from lesser skilled players was their larger knowledge of complex patterns (or chunks) accumulated over their years of experience, rather than possessing overall greater mental abilities (often referred to as "hardware" skills). This is a finding that has been replicated in several studies within sport showing that expert athletes are better able to recall positions of players when presented with situations that reflect matches, however, are no better than novices for unstructured positions of players.

Building on the foundational work of de Groot (1965) and Chase and Simon (1973), the expert performance approach proposed by Ericsson and Smith (1991) is one of the most well-known frameworks used to study expertise. As Figure 2.1 illustrates, the expert performance approach identifies three important stages for empirically testing and understanding the nature of expertise. The first stage seeks to capture the performance of experts in situ through laboratory or field-based testing aiming to first identify expert performers but also critically, to elicit differences between experts and novices. The second stage seeks to identify the underlying mechanisms of expertise through process-tracing measures (e.g., eye movements, video occlusion, verbal reports). The main goal of this stage is to go beyond description of differences to understand exactly *how* experts perform better than novices. The final stage of the expert performance approach seeks to examine how this expertise is developed and often uses retrospective practice history profiling, think aloud protocols, and interviews (Williams & Ericsson, 2005).

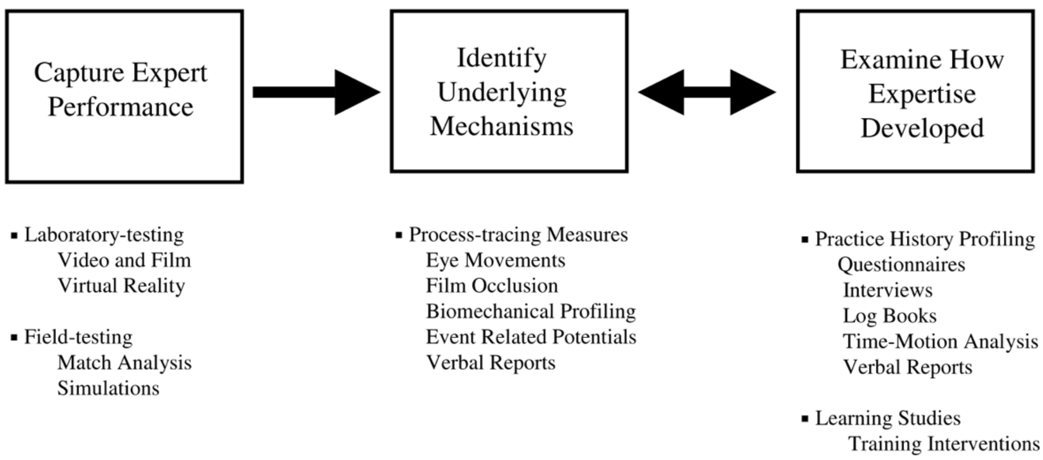

Figure 2.1 An illustration of the expert performance approach and some of the methods and measures that may be used at each stage. *Note*. From "Perceptual-cognitive expertise in sport: Some considerations when applying the expert performance approach", by M. A. Williams et al., 2005, *Human Movement Science,* 24(3), p. 286.

From the perspective of the expert performance approach, researchers can use the framework to understand the development of expertise. Namely, i) identify *what* differentiates experts (stage 1), ii) determine *why* experts differ from novices (stage 2), and iii) examine *how* their expertise is developed (stage 3). In other words, this area of research seeks to understand the determinants of elite performance and to inform training and development.

Advances in the methods and technologies used to train elite athletes have led to significant improvements in the levels of performance seen in benchmark events. These advances allow expertise researchers to examine how performers progress from beginner to highly skilled (stage 3 of the expert performance approach). While there can be little doubt that experts demonstrate superiority when compared to their lesser skilled counterparts (Vaeyens et al., 2007), detailed understanding of the perceptual-cognitive mechanisms which underlie their decision-making expertise is still missing (D. T. Mann et al., 2007; Williams, Ward, et al., 2004).

2.2 DECISION MAKING IN SPORT

Through the expert performance approach to understanding sporting expertise, the ability to anticipate an opponent's actions has been identified as a key perceptual-cognitive skill that elite athletes possess (Broadbent et al., 2015). Research has found that elite athletes possess the ability to extract anticipatory information from advance kinematic cues of opponents. These perceptual cues that are available prior to key moments (e.g., prior to ball release in cricket bowling (Müller et al., 2006) or serving in racquet sports (Farrow et al., 2005)) provide experts with an abundance of information about the upcoming opponent actions and allow them to anticipate key elements (e.g., direction, type, force) that provide them with a distinctive advantage. This advantage provides athletes with a richer source of information which they utilise to make better quality decisions and can be observed through athletes making decisions much earlier than their lesser skilled counterparts.

From a historical perspective, one of the earliest works that examined anticipation in athletes was a study by Abernethy and Russell (1987). This study sought to understand the temporal and spatial characteristics that underpinned successful anticipation, as a component of expertise in decision making, within racquet sport players through occlusion. Occlusion techniques are commonly used to study anticipation and involve the removal of information, either temporally (e.g., pausing or stopping a video at certain time periods prior to the key action) or spatially (e.g., selectively removing specific parts of an opponent's body during the action). Fifty-five participants (20 expert badminton players and 35 novices) completed a video-based anticipation task. Participants watched a recording of a badminton player performing a variety of shots (32 in total) in five separate conditions, giving a total of 160 trials presented in a randomised order. The five conditions were:

- t1: occlusion of the display four frames (167 ms) prior to racquet-shuttle contact
- t2: occlusion of the display two frames (83 ms) prior to racquet-shuttle contact
- t3: occlusion of the display occurred at the point of racquet-shuttle contact
- t4: occlusion of the display occurred two frames (83 ms) after racquet-shuttle contact
- t5: no occlusion of the display occurred (i.e., the full flight path of the shuttle was visible)

The authors reported that experts were able to predict the landing location of the shots more accurately at the t2 occlusion point. They interpret this as the experts being able to extract vital information between the period from t1 to t2, which enhanced their anticipation ability. This work has since been expanded on in work beyond racquet sports. For example, Müller et al. (2006) examined the ability for cricket batsmen to detect advance information and anticipate the type and length of cricket deliveries. The information available to the batsman was manipulated using a combination of temporal and spatial occlusion techniques. Müller et al. (2006) suggested based upon their findings that expert batsmen were able to pick up advance information from specific early cues (especially the bowling hand and arm) while lesser skilled players could not.

Anticipation ability is only one example, however, of an underlying skill that experts (athletes) demonstrate their perceptual-cognitive advantage. Another ability identified by Broadbent et al. (2015), decision making, is defined as the ability for an athlete to rapidly and accurately select the correct option from a range of presented alternatives (Raab & Farrow, 2013). Decision making in sport is a complex process, which is often time pressured, and in many situations made additionally difficult by athletes making judgements on incomplete or (deliberately) misleading information (Pizzera & Raab, 2012). Further complicating decision making as a key skill, is that it often involves sport-based action choice movements (i.e., actions to pass, shoot etc.) and requires an assessment of one's own action capabilities (Bruce et al., 2012).

The time pressures imposed on decision making in sport as well as the presentation of misleading cues by opponents can create "gaps" in the information that an athlete can access. The presence of these information gaps complicates the task of detecting appropriate information (the ability to perceive relevant information accurately) and ultimately the ability to pick and execute appropriate decisions. Athletes with a high level of decision-making ability are typically those that are better at filling in these information gaps or even dealing with the incomplete information, allowing them to make better decisions.

In fast-paced team sports such as hockey and football, making accurate and effective decisions is particularly challenging. This is because, in addition to elements of time pressure and action choices, these sports also emphasise strategy and tactics (Baker, Côté, et al., 2003). So, decisions made by athletes must also consider global tactics of their team and strategies that can vary from week-to-week and even within matches (e.g., first half vs. second half). Thus, understanding how athletes make effective decisions under such extreme conditions while also performing physical skills (e.g., kicking, catching) is a key component in understanding overall performance. Moreover, understanding how athletes manage to perform complex components of performance can help us to develop effective training programs to enhance these abilities, and move beyond the second stage of the expert performance approach for areas like sport.

Research to date has tended to examine the underlying perceptual-cognitive skills that feed into an overall decision making process, such as anticipation (Chalkley et al., 2013; Müller et al., 2006; Williams, Ward, et al., 2004), pattern recall (Abernethy et al., 2005; Gilis et al., 2008), practice histories (Baker, Coté, et al., 2003; Baker, Côté, et al., 2003), perception (Abernethy et al., 2001) and knowledge base (MacMahon & McPherson, 2009) using a range of methodologies. Across these perceptual-cognitive abilities there are several paradigms that have been utilised to understanding decision making in sport (see Table 2.1 for a summary).

While these underlying abilities provide experts with their perceptual advantage, they can be seen as secondary skills that contribute to decision making as the primary skill (MacMahon & McPherson, 2009). There has been limited work that has examined decision making or action selection itself as a primary skill in which athletes are asked to indicate their choice of action, rather than what they anticipate will happen next (as is the case with anticipation studies). Moreover, much of this published work has been descriptive in nature, comparing experts and novices. While there has been research that has examined other key skills that underlie successful decision making such as anticipatory recall (Chalkley et al., 2013; Müller et al., 2006) and pattern recognition there has been little research examining the mechanisms that explain the differences in decision-making performance from a psychophysiological perspective i.e., moving into stages two and three of the expert performance approach.

Table 2.1 Common paradigms that have been used to measure components of decision-making performance in sport

Component	**Tests/approaches and example references**
Perception	General perceptual ability tests (Raab & Farrow, 2013)
	Eye tracking (Williams, Janelle, et al., 2004)
	Temporal and spatial occlusion technique (Davids et al., 2005)
	Point-light (Abernethy et al., 2001)
	Psychophysiological methods (Janelle et al., 2004)
Knowledge	General knowledge and memory tests (Ericsson & Simon, 1984)
	Recall tests (McPherson & Kernodle, 2003)
	Recognition tests (Raab, 2003)
	Verbal reports (McPherson, 1999)
Decision	Option-selection (Abernethy, 1990)
	Option-generation (Johnson & Raab, 2003)

Note. Adapted from *Judgement, decision making and success in sport* (p. 44), by Bar-Eli et al., (2011).

One of the key arguments within the sport expertise research (as with the foundational work in chess by de Groot and Chase and Simon) is that the remarkable abilities of athletes are not necessarily general abilities. That is, these superior processing abilities are primarily domain-specific (Abernethy et al., 2005). For example, Abernethy et al. (1994) tested seven expert, seven intermediate, and 15 novice snooker players on a range of general visual tests and sport-specific perceptual tests. The general visual tests included measures of; static acuity (both monocular and binocular) at far (6.1 m) and near (35 cm) distances; phoria (horizontally and vertically at far and near distances) as an indication of symmetry of extraocular muscles; and colour vision (tested at the far viewing distance). In addition, depth perception at a distance of 3.66m and ocular dominance was assessed. The authors found no group differences on any of the general optometric measures, which demonstrated that experts do not possess “superior overall vision” compared to novices. When the same participants were required to recognise and recall slides that depicted typical game situations, however, they found that experts did demonstrate superior performance. A particularly notable finding from this study was that when slides were presented that depicted snooker balls placed randomly, the experts showed no superior ability to recall the positions of the snooker balls. The authors conclude that this is evidence that expert snooker players differ from novices in their ability to rapidly encode, recall, and recognise perceptual information that is structured and do not possess generally better visual skills, reflecting the same pattern as in the classic chess work i.e., Chase & Simon (1973). More recent work also supports the finding that more sport-specific visual skills, rather than general skills differentiate experts from novices. In a recent scoping review by Hodges et al. (2021), the authors found for interceptive sports, high evidence for several sport-specific cognitive skills (e.g., anticipation, eye movement control), while also reporting equivocal or low evidence supporting general skills (such as visual acuity) to distinguish across skill groups. Taken together this provides strong evidence to support the notion that in sport, as in other areas investigated, perceptual-cognitive skills are highly specific to a given domain.

2.3 INTUITION

One theoretical framework that has received some significant attention in judgement and decision making literature more recently is that of intuitive decision making strategies (Harteis & Billett, 2013; Kahneman & Klein, 2009). While there is an emerging body of work in sport and exercise science that has begun investigating intuitive decision making approaches e.g., Raab & Gigerenzer (2015), there is a richer existing literature in fields such as economics, management science, psychology, and social sciences (Plessner et al., 2011). One of the main challenges in understanding intuition is exactly “what” intuition actually is. Intuition has multiple definitions, and the definitions differ slightly between certain domains. For example, from a psychology perspective, intuition has been defined as a decision or “judgement (1) that appears quickly in consciousness, (2) whose underlying reasons we are not fully aware of, and (3) is strong enough to act upon” (Gigerenzer, 2007, p. 16). However, in other fields, intuition is defined as “an involuntary, difficult to articulate, affect-laden recognition or judgement that is based on prior learning and experiences and is formed without deliberative or conscious rational choice" (Raab & Laborde, 2011, p. 89). Abernathy and Hamm (1995, as cited in Epstein, 2010) identified 20 different definitions for intuition (see Table 2.2 for examples of definitions presented in the literature).

Table 2.2 Definitions of intuition used within the literature

Definition/characteristics	**Reference**
"The intellectual technique of arriving at plausible but tentative formulations without going through the analytics steps by which such formulations would be found to be valid or invalid conclusions"	(Bruner, 1960, p. 13)
"A cognitive process that somehow produces an answer, solution, or idea without the use of a conscious, logically defensible, step-by-step process"	(Hammond, 1996, p. 60)
"The essence of intuition or intuitive responses is that they are reached with little apparent effort, and typically without conscious awareness. They involve little or no conscious deliberation"	(Hogarth, 2001, p. 14)
"Intuition is our capacity for direct knowledge, for immediate insight without observation or reason"	(Myers, 2002, p. 1)
"Intuition is a process of thinking. The input to this process is mostly provided by knowledge stored in long-term memory that has been primarily acquired via associative learning. The input is processed automatically and without conscious awareness. The output of the process is a feeling that can serve as a basis for judgements and decisions"	(Plessner et al., 2011, p. 4)

Despite these different definitions, what is generally accepted about intuitive decisions, however, is that they are fast, automatic, and require minimal (cognitive) effort. A popular view that is useful for examining intuitive decisions, as mentioned in Chapter 1, is the System 1 and System 2 approach (Kahneman, 2011; Stanovich & West, 2000). Kahneman (2011) describes System 1 as fast, automatic, and effortless (i.e., intuitive) whereas System 2 is slow, contemplative, and effortful (i.e., deliberative). Kahneman suggests individuals use of each system is fit to the situation, specifically, that the brain defaults to using System 1 as a more resource-effective system, but, when required, System 2 can interrupt the automatic processing to actively search for alternative solutions.

This view of two distinct systems, however, has been criticised in the literature in recent years which raises doubts about the suitability of such a dichotomous viewpoint (Keren & Schul, 2009; Kruglanski & Gigerenzer, 2011). In particular Keren and Schul (2009) note that the dimensions (e.g., decision speed, cognitive ease) used to separate the two systems are continuous variables rather than dichotomous. They conclude their critique of the two-system theories by stating "the bottom line of our investigation is that the theoretical structure of two-system theories is ill-defined, and consequently, we wonder whether two-system models are testable with currently existing methods" (Keren & Schul, 2009, p. 546).

One of the challenges, therefore, of a simplistic dual-systems perspective is deciding on the *boundaries* of these systems to know when a decision is intuitive (System 1) or when it is deliberative (System 2) (Raab & Johnson, 2007b). While the labelling of these 'systems' differs in the literature (for a summary see Evans, 2008), the central tenet of intuitive decisions is they occur automatically and with limited conscious control or cognitive effort. Glöckner and Witteman (2010) argue that in order to advance the field of intuitive decision making beyond simplistic dual-process models, researchers should first concentrate on investigating processes underlying intuition.

In a similar way, Ashford et al. (2021b) identified three classifications of decisions made by rugby athletes. The classifications were No-thought, Fast-thought, and Slow-thought. Ashford et al. (2021b) defined No-thought decisions as decisions that involved no conscious thought prior to taking an action, Fast-thought decisions whereby a rapid conscious thought lead to an action, and Slow-thought as decisions which involved a slow and deliberate conscious decision, weighing up many options before taking action.

The idea that some decisions can be classified as "No-thought" suggests that there are decisions that experts make that involve no (or very little) cognitive control. A view that Christensen et al. (2016) labelled 'Automatic'. The main tenet of the 'Automatic' view of skill learning is that over the course of learning a skill, automation occurs through an overall reduction in cognitive control and for advanced skills cognitive control makes no positive contribution to performance. Christensen et al. (2016) identifies several key features of skilled performers that fit with the ‘Automatic’ perspective. For example: (i) once a skill has been acquired, attention to the performance can be reduced (reduced attention), (ii) additional tasks can be performed with minimal impact on well-learned skills (dual-task tolerance), and (iii) performer’s memory of a highly learned skill can be reduced or absent (reduced memory). They also identify, however, some features of skilled performance that would suggest cognitive control is required. As an example, if a performer does not provide enough attention to a given task, the performer may execute an incorrect action. To combat this, Christensen et al. (2016) propose a hybrid view (termed ‘Mesh’) that allows a more integrated explanation of how cognitive and automatic processes function together in an intricately meshed manner. This view further highlights the challenges of dual-process systems.

2.4 INTUITION IN SPORT

As noted earlier, due to gaps and misinformation presented to athletes, decisions are often made in uncertain circumstances where all the possible alternative choices and their consequences are not known. It is for this reason that athletes may often rely on and utilise decision making approaches that are capable of dealing with uncertainty. It is with this in mind, that here it is appropriate to examine sport decision making and specifically action choice through the lens of intuitive decision making, given its fit to the demands of the situation, particularly time and resource pressure.

One perspective of how experts make decisions under these constraints, and one of the more widely accepted frameworks for studying intuitive decision making in domains like sport and medicine, is the fast-and-frugal heuristics approach (Raab & Gigerenzer, 2015). Heuristics are defined as basic “rules of thumb” that allow an individual to take a “shortcut” to knowledge (Volz et al., 2006). They are strategies that ignore available information or focus on just a few key points of data to make decisions, rather than more complex strategies that compare many sources of information and weigh them up to make decisions (Raab, 2012). As highlighted above, intuitive decisions are typically faster, relatively unconscious, difficult to articulate or explain processes of, and are formed without deliberation of a conscious choice, yet strong enough to act upon (Raab & Laborde, 2011). In comparison, deliberation can be defined as the process of consciously analysing all of the available options, weighing them up, and deciding on an appropriate (and rational) choice (Kruglanski & Gigerenzer, 2011). Kruglanski and Gigerenzer (2011) highlight that it is commonplace for these two processes to be identified as dichotomous which has resulted in a dual-process approach (intuitive vs. deliberative, for a review see Evans (2008)), however they present an alternative view that unifies these processes. Kruglanski and Gigerenzer (2011) suggest a theoretical approach that views intuitive and deliberative judgements as being rule-based as opposed to distinct systems that are qualitatively different processes. Within this view, they provide evidence (using example heuristic rules) to support their position that, not only are intuition and deliberation both rule-based, but they can also be explained by the same rules. For example, they argue that the recognition heuristic (RH) can be used both intuitively and deliberatively.

The RH is described by Goldstein and Gigerenzer (2002, p. 76) as "If one of two objects is recognized and the other is not, then the recognized object has higher value with respect to the criterion". As an illustration of how powerful the recognition heuristic can be, consider the question of which of the following athletes has won more Olympic gold medals, Louis Smith or Usain Bolt? Even individuals with no specific knowledge of the Olympic Games are likely to correctly answer. This is possibly the case because only one of these names (Usain Bolt) is recognised so the individual is able to rely on the "go with what you know" approach (Raab & Gigerenzer, 2015). However, if both names are recognised e.g., Usain Bolt and Michael Phelps this heuristic is no longer effective (Raab, 2012).

It has been suggested that in situations where individuals do not have the time or information available to utilise complex decision making strategies (for example in sport), heuristics provide an alternative and equally effective approach (Johnson & Raab, 2003). Research has suggested that heuristics consist of three common building blocks that give rise to several distinct heuristics (Gigerenzer & Gaissmaier, 2011). The three elements proposed include: a search rule, a stopping rule, and a decision rule (Gigerenzer & Gaissmaier, 2011; Johnson & Raab, 2003). A search rule specifies where to look for information, a stopping rule determines when to cease searching for information, and a decision rule specifies how to make the final decision (Raab & Gigerenzer, 2015). A fast-and-frugal heuristic is one such strategy that individuals can utilise to make effective decisions with incomplete information (as in the case of athletes). That is, it is an intuitive strategy that can ignore parts of the available information yet still yield effective decisions (Raab, 2012).

Illustrating the use of heuristics in sport, Johnson and Raab (2003) examined the "take the first" heuristic as an intuitive decision making approach in handball. German and

Brazilian male handball players viewed 31 video scenes of attacking situations during which the video froze on a particular frame for 45 seconds. Once the freeze frame occurred, participants were required to name as quickly as possible their first decision that intuitively came to mind. Following this decision, they were asked to name as many additional options as they could, before finally deciding out of all the options identified prior, which was the best for the specific presented scenario. The results of this study showed that the sooner an option was generated, the greater the likelihood of it being appropriate. The authors suggested that this demonstrates utilising a "take the first" heuristic (i.e., intuitive) produced effective decisions. However, Johnson and Raab (2003) identified that although the use of this heuristic was supported by the finding that participants chose their first option in around 60% of instances, it does not *prove* that individuals actually used this heuristic within the experimental task. They suggest that future work should seek to further explain their results.

In a study by Hepler and Feltz (2012), the authors sought to replicate the findings of the Johnson and Raab (2003) study while also examining additional facets that had been theorised but not yet experimentally tested. Hepler and Feltz (2012) included 70 participants (34 male, 36 female) who were students (undergraduate or graduate) that all had at least one year competitive basketball playing experience. Participants completed two different tasks: an option generation (OG) task and a decision-making performance (DMP) task. The OG task generally followed the same procedure described by Johnson and Raab (2003). Participants viewed 13 video clips of attacking situations taken from footage of a high school basketball match. Similar to previous studies, participants were instructed to watch the presented video scenarios and verbally state the first option that came to their mind as quickly as possible. Their initial response was recorded and then they were then given 45 seconds to write down any additional options they perceived. Following this, the participants selected the option they perceived to be the best and finally they rated their confidence level of that decision. In the DMP task, participants viewed recorded scenarios (13 different videos) and were asked to make a decision on the next move and then rate their confidence in that decision. Scoring of correct choices was calculated by the average ratings from experienced coaches on the appropriateness of each possible option, ranging from 0 (inappropriate) to 4 (best possible).

Hepler and Feltz (2012) found that participants chose the first option they generated as the best decision 72.3% of the time. This was in line with previous studies (Johnson &

Raab, 2003; Raab & Johnson, 2007a) and provides support that experts often utilise the "take the first" heuristic in dynamic scenarios that are under extreme time pressures such as decisions made in fast-paced sporting situations. The evidence presented in these studies suggests that athletes utilise approaches that appear to align with heuristics such as "take the first". As discussed above, heuristics are approaches that allow individuals to make decisions that focus on just a few key pieces of information, rather than more complex strategies that compare all the available options. A key question that Hepler and Feltz (2012) propose for future research is why do people only adopt the take the first heuristic 60% of the time? It is possible this is linked to how this is measured, in that more sophisticated measures are needed to understand the situations when/when not are intuitive decision-making strategies (like heuristics) used.

2.5 MEASURES OF INTUITIVE DECISION MAKING

A complication to understanding intuition (beyond the varied definitions of the term) is the issue of measurement. In order to gain a deeper understanding of whether experts utilise intuitive decision-making strategies (such as the "take the first" heuristic), we must be able to measure their underpinning mechanisms. Because intuitive decisions are generally faster than deliberative decisions, it is important to measure speed of responses. However, it is necessary to distinguish between the decision-making process and the actions associated with the decision (e.g., passing or shooting). This is particularly relevant within the domain of sport.

Of the identified characteristics of intuitive decisions, the degree of cognitive effort exerted is a particular challenge for measurement. It is hypothesised that intuitive decisions are those that are made with little cognitive effort and therefore appear easier. That is, intuition demands lower levels of mental resources. Kahneman (2011, p. 59) describes cognitive ease as situations when things are going well and there is no need to redirect attention. For example, individuals experience cognitive ease when reading words printed in a clear font whereas reading words that are in a poor font or worded in complicated language would require engaging in more cognitive effort.

Research examining intuitive decision making, therefore, should seek methods to measure cognitive load to provide an understanding of intuitive decision making. Early work from Daniel Kahneman (1973) suggested that any physiological marker of cognitive processing effort should: i) be sensitive to detect within-task variations in load produced by task parameters; ii) reflect differences between tasks with qualitatively different cognitive operations; and iii) be sensitive enough to detect differences between individuals with different abilities on the same cognitive operations. Recent research into cognition and decision making in sport has begun to utilise various neuroimaging and psychophysiological technologies such as functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), and electroencephalography (EEG) to understand the underpinning cognitive demand of decision making.

2.5.1 Functional magnetic resonance imaging

There are two commonly used technologies within the neuroimaging field that are used to measure brain activation to understand cognitive processing. These are Functional Magnetic Resonance Imaging (fMRI) and Magnetoencephalography (MEG). fMRI is a specific type of magnetic resonance imaging that uses a strong magnetic field and radio frequency energy to capture highly detailed representations of the brain's structure (Andreassi, 2013). Advances in technology have allowed researchers to observe changes in metabolic processes in different brain structures through measurement of hemodynamic changes such as blood oxygen concentration, blood flow, and blood volume (Andreassi, 2013; Latash, 2008) as individuals engage in cognitive tasks, such as decision making. Among the advantages of using fMRI over other neuroimaging techniques is its higher spatial resolution when compared to other neuroimaging techniques such as Positron Emission Tomography (PET).

Volz et al. (2006) utilised fMRI to measure the neural correlates of an intuitive decision making strategy, the recognition heuristic (RH). In the study by Volz et al. (2006), 18 participants were concurrently presented the names of two cities and asked to select which had a greater population. They found that when participants were required to rank two alternatives and only one of the alternatives was recognised, participants more often selected the recognised alternative. The authors suggested that this finding demonstrates the recognition heuristic was adopted as a decision-making approach in this task. Of particular interest in this study, was that participants completed this task while simultaneously having their brain activity recorded using fMRI. The authors reported that not only did participants select the recognised alternative, but this was also associated with an increased activation within the anterior frontomedial cortex (brain region associated with producing social-cognitive judgements and adaptive emotional responses) and the retrosplenial cortex (area of the brain linked with processing of declarative memory). The increased activation in these regions was suggested to demonstrate differences in neural activation between decisions that were based on the recognition heuristic and those that were not.

A limitation of fMRI is its relatively lower temporal accuracy. For observable differences in brain activity to be detected using fMRI, the actions (or decisions in this case) performed require time to produce the metabolic changes that the MRI signal reflects. This timescale can sometimes be in the tens of seconds or even minutes (Latash, 2008). To combat this limitation, researchers have begun to utilise electroencephalography (EEG) measurement. The major advantage of EEG over fMRI is its higher temporal resolution, which can be between 500 and 1,000 msec (Andreassi, 2013). Given one of the key elements of intuitive decisions is speed, in order to accurately link processing with neural activation, a higher temporal accuracy is needed.

2.5.2 Electroencephalography

EEG is a method of recording the electrical activity of neurons in the brain through the use of non-invasive electrodes placed on specific positions of the scalp (Park et al., 2015). Due to the fact that electrical activity must travel through the skull before it reaches the scalp electrodes, the EEG signal is very small and requires amplification by specialised EEG recording equipment (Thompson et al., 2008). Although EEG provides a lower spatial resolution when compared to some neuroimaging techniques (like fMRI), its major advantage is the ability to measure cortical activity with an extremely high temporal resolution. Given that human processing speeds are very rapid, it has been suggested that EEG may be a well-suited method to accurately capture the underlying cognitive processes that occur (Park et al., 2015).

Research utilising EEG in the sporting domain has largely focused on two main analyses: spectral analysis (frequency) or event-related potentials (ERPs). ERPs highlight changes that occur in brain activity related to a specific event of interest (e.g., perceiving a stimulus or responding to one). ERPs have been used as a technique for studying complex human behaviour (Hill & Raab, 2005).

Event-related potentials

As an example of the use of ERPs derived from EEG for analysis of cognitive function in sport, a study by Taliep et al. (2008) compared one of the commonly studied ERPs, the P300, in skilled and less-skilled cricket batsman. The P300 ERP refers to a positive polarity in the EEG signal that peaks around 300ms after the stimulus is presented. In their study, the P300 latency, P300 amplitude, response selection, and reaction time were investigated. The participants' task was to view a series of cricket deliveries from the perspective of a batsman and identify the delivery by responding with a finger press that corresponded to either an in-swing or an out-swing delivery (or no response for a slow delivery). This was completed while connected to an EEG recording device. The authors found that the skilled batsman had a significantly shorter median P300 latency when compared to lesser skilled batsman for both in-swing and out-swing deliveries. It was suggested that the short P300 latency of the skilled batsman was likely associated with a faster evaluation and discrimination of the delivery type, and thus was able to discriminate the participants based on expertise. Furthermore, they suggested that, because the more skilled batsmen possess the ability to detect the delivery type earlier, they could therefore make an earlier (i.e., faster) decision more automatically and with less attention. This was further supported by the smaller P300 amplitude measured on the skilled players.

Spectral analysis

The other common analysis technique utilised by EEG researchers in sport is spectral analysis, also known as frequency analysis. Spectral analysis decomposes the EEG signal into the frequency components of the overall signal, typically referred to as frequency bands (Thompson et al., 2008). The most commonly investigated frequency band in sport expertise research is the alpha band because it has been demonstrated to be sensitive to cognitive functions e.g., decision making (Yordanova et al., 2001). Alpha waves are rhythmic oscillations that occur in the range of 8-13Hz (cycles per second). They are typically related to being in a "relaxed state" e.g., sitting quietly with eyes closed, but once an individual engages in any cognitive activity (such as mental arithmetic) the amplitude of this signal reduces or may even disappear (Andreassi, 2013). Alpha rhythms are more easily distinguishable from other rhythms in the raw EEG signal and can be clearly seen as a distinct set of oscillations (Park et al., 2015). Changes in the alpha band are commonly analysed using a method called event-related desynchronization (ERD). ERD measures the increase or decrease in alpha band power relative to a reference period, expressed as a percentage. It is hypothesised that cognitive processing is linked to great suppression of alpha power, and therefore desynchronization (Klimesch, 1999).

The use of electroencephalography (EEG) in studies of human cognition has provided great insight into how individuals perceive and process information. EEG has been utilised in a range of research areas including sleep (I. Campbell, 2009), medical diagnosis (Ibrahim et al., 2018; Ribas et al., 2013), and of course sport (Babiloni et al., 2009; Babiloni, Marzano, Iacoboni, et al., 2010; Del Percio et al., 2008).

An example that has used this method is a study by Babiloni (2009) where they compared elite gymnasts' and non-athletes' cortical activation during judgement of observed actions in gymnastics routines. Participants viewed 120 rhythmic gymnastics videos that showed elite gymnasts executing real exercises on different apparatuses during competition. At the conclusion of each video, the participant's task was to judge the level of performer on a scale ranging from 0 to 10. The authors found that alpha ERD in the occipital and temporal cortex demonstrated lower amplitude in the elite gymnast group compared to non-gymnasts. The lower alpha ERD (i.e., less desynchronisation) found in elite athletes compared to non-athletes was suggested as a possible index of neural efficiency.

2.5.3 Eye tracking and Pupillometry

For more than thirty years, sport science research has utilised eye tracking technologies to help understand the visual search strategies adopted by highly skilled athletes. Eye tracking technology provides an excellent method to investigate the underpinnings of perceptual processing of experts (Discombe & Cotterill, 2015). Consistently and in line with the expert performance approach, research has found differences in various visual search parameters between experts and novices (Carnegie et al., 2020). These differences have been demonstrated across a range of sports including baseball (Kato & Fukuda, 2002; Toole & Fogt, 2021), ice hockey (Panchuk et al., 2017), football (Aksum et al., 2020), golf putting (M. Campbell & Moran, 2014; Vickers, 1992), tennis (Singer et al., 1996), and even in officiating (Hancock & Ste-Marie, 2013). Eye tracking technology has come a long way since the 1980's and is now more affordable, more accurate, more reliable, and more portable which has seen a surge in the number of eye tracking studies in sport (Discombe & Cotterill, 2015).

Modern day eye tracking devices typically use miniature cameras attached to frames that resemble eyeglasses. One of these cameras illuminates the eye (either monocularly or binocularly), normally using infrared reflections, to track the position of the pupil. The other camera (often termed the 'scene camera') is pointed in front of the individual to record their first-person perspective. Using specialised software, these two cameras are then synchronised and calibrated to known points in the real-world giving rise to the ability to track where the participant is looking i.e., their gaze direction (Kredel et al., 2017). This setup provides researchers with the previously mentioned gaze metrics such as fixations, but in most cases, also provides an additional metric of interest – the size of an individual's pupil.

The pupil is the transparent opening in the centre of the eye, that normally appears black, which can vary somewhere between 2mm and 8mm in diameter. This variation in size occurs in response to three kinds of stimuli: it constricts due to brightness of light (the pupil light response, PLR); near fixation (the pupil near response, PNR); and it will dilate in response to an increase in cognitive effort e.g., (mental effort or arousal level) (the psychosensory pupil response, PPR) (Mathôt, 2018). Research using pupillometry has demonstrated that the pupil size changes in response to mental effort (Piquado et al., 2010). This evidence is in line with research that demonstrates pupil size changes with increasing demands of allocating attention (Verney et al., 2004) and greater task difficulty (G. Porter et al., 2007), as these are more cognitively demanding. In fact, this evidence is so compelling that the psychologist Eckhard Hess described the pupil as a window to the soul (as cited in (Kahneman, 2011).

In a seminal study by Hess and Polt (1964), they investigated the pupil size changes resulting from increases in mental activity. In their experiment, participants were presented with mathematical problems to solve of increasing difficulty while simultaneously recording their pupil size. They found that pupil size gradually increased in diameter until it reached a maximum dilation immediately before the participants provided an answer, and then subsequently returned to baseline control size. Since this early work, pupillometry has continued to be a methodology adopted by researchers to measure changes in cognitive load in fields that include speech (Govender & King, 2018), driving (Čegovnik et al., 2018; Palinko et al., 2010; Palinko & Kun, 2012), medicine (Szulewski, Kelton, et al., 2017), and sport (M. Campbell et al., 2019; Cardoso et al., 2019; Tapper et al., 2021).

However, despite this strong evidence and the abundant research base that has utilised eye tracking technology in sport, few studies have utilised pupil dilation in understanding the decision-making process. Instead, research has typically focused on visual search metrics such as the number, duration, and location of fixations and saccades or the concept of the Quiet Eye (QE) (Carnegie et al., 2020).

One exception is a study by Cardoso et al. (2019) who examined the amount of cognitive load exhibited by football (soccer) players in relation to the amount of procedural tactical knowledge (PTK) and declarative tactical knowledge (DTK). They hypothesised that players with higher levels of PTK and DTK would exhibit lower levels of cognitive load compared to those with lower levels of PTK and DTK. The study included 36 male academy players from a Brazilian first-division team, all of which had been involved in regular soccer-specific training. Players PTK was measured using a system that evaluates tactical performance with and without the ball called the FUT-SAT (I. Costa et al., 2011). To assess players level of DTK, a video-based occlusion task was performed. Players were presented with 11 video clips which paused at a key moment where they were asked to verbally respond indicating what the player with the ball should do next, as quickly as possible. To measure cognitive load, participants pupil size was recorded using an Applied Science Laboratories Mobile Eye Tracking-XG device during the DTK task.

For analysis, Cardoso et al. (2019) defined four distinct moments to allow a more precise measurement of cognitive load experienced during the experimental task. The first moment utilised (M0) which was used to determine the baseline value for pupil diameter. The lowest value of the pupillary diameter between the end of the calibration and the end of the experiment was set as the baseline for pupil diameter.

The three remaining moments were defined based on the actions required by the participant during the stimuli videos and with a hypothesised difference in information processing load. The phases were defined as:

i. M1 (Video): the phase while the participant was watching the video
ii. M2 (Verbalisation): the phase in which the participant responded verbally to indicate their game play decision
iii. M3 (Rest): the phase between when the participant had provided their verbal response until the start of the next video stimuli.

The results of this study revealed a link between tactical knowledge and cognitive load. Specifically, players with higher levels of DTK and PTK demonstrated lower cognitive load (as evidenced through smaller pupillary diameters) in the video-based task. Cardoso et al. (2019) also found that the highest level of cognitive load occurred during the moment M1 (Video), regardless of the form of tactical knowledge (i.e., PTK or DTK). Given that the video phase (M1) of these trials required players to consider a range of possible options and perceptual cues (e.g., players, ball position etc.,) before ultimately selecting an appropriate choice, the authors suggest this moment is higher in task difficulty so an increase in cognitive load is expected.

Interestingly, the authors also found that the players with a higher DTK displayed lower cognitive loads during the verbalisation moment (M2), that is the phase where participants verbalise their response. It was suggested that this could be explained by the specific structure of DTK. As the players were required to provide a verbal response, it is possible that players with higher levels of DTK found the task of verbalising their decisions easier and therefore linked to a lower cognitive load.

The study by Cardoso et al. (2019) is certainly novel and presents a strong case that pupillometry can measure cognitive load and that a reduction in cognitive load is linked to expertise (players with greater levels of tactical knowledge). What isn't clear from this study, however, is if the observed difference in cognitive load is also found in truly novice players. The authors importantly suggest there could be a neural basis for these findings and propose that players with greater levels of tactical knowledge better utilise their cognitive resources. This would manifest as less neural activation and consequently lower cognitive loads, a phenomenon commonly referred to in the literature as neural efficiency.

2.6 ADDITIONAL CONSIDERATIONS FOR INTUITION IN SPORT

The nature of sport as time-pressured and requiring planning and execution of physical movements means that there are considerations within intuition related to the physical and cognitive demands, the resources required, and the pacing of decisions.

2.6.1 Neural efficiency

Neural efficiency theories propose that when cognitive functions are performed at their optimal, they can be performed quickly, allocation of cognitive resources is minimised and performance is maximised (Rypma et al., 2006). This finding has been supported in a number of neuroscientific studies in a broad range of cognitively demanding tasks (Neubauer & Fink, 2009). For example, research has demonstrated that a more localised cortical activation resulted in an overall lower cortical activation. This has been interpreted as an efficiency model (Haier et al., 1992).

The neural efficiency hypothesis is further supported by a study by Babiloni et al. (2010) which examined the neural efficiency of expert karate athletes. In this study, elite and amateur karate athletes, as well as non-athletes, viewed 120 karate videos which depicted karate athletes performing choreographed actions against imagined opponents. The participants' task was to judge the technical/athletic ability of the karate exercise on a scale of 0 to 10. The authors report that the elite karate athletes when compared to non-athletes demonstrated a lower alpha ERD (as measured through EEG) during the entire video. It was again suggested that this was evidence for a possible neural efficiency.

In addition to studies that have demonstrated differences in brain activity between experts and novices in a variety of sports, there is evidence to suggest that differences exist within expert populations between good and poor performances. For example, Loze et al. (2001) investigated the pre-shot alpha power using EEG of elite air-pistol shooters, examining differences between the best and worse shots. The scoring to determine the best shots used multiple methods including the actual shot score, as well as ratings of shooting performance and post-hoc technique analysis. The authors found that occipital alpha power increased during the pre-shot epochs before the best shots but decreased before the worst shots. Loze et al. (2001) suggest this result is due to a reduction of attention to external visual stimuli during the pre-shot period of good shots.

The use of neurophysiological technologies in sport is still in its infancy and as highlighted by Park et al. (2015) has had limited impact on sports practitioners thus far. This could be in part due to the expense, need for specialist analysis techniques, or simply that the current technology has limitations (although developments are making mobile EEG more easily accessible).

2.6.2 Decision reinvestment

Of relevance for an understanding of intuitive decision making in sport is work that has examined individual differences in conscious control of actions and decision processes. For example, Taliep and John (2014) link the neural efficiency report in their study of cricket batsmen to the hypothesis of reinvestment. The reinvestment hypothesis broadly suggests that if a performer attempts to consciously control their movements with explicit knowledge (or "how it works") the movements themselves are affected negatively or breakdown (Masters & Maxwell, 2008). Further, the tendency to reinvest is proposed as a trait, measurable through the reinvestment scale, which classifies respondents as high or low reinvestors, and consequently more or less likely to break down under pressure, respectively. The effects of reinvestment have been demonstrated in a number of studies across many domains including handball (Laborde et al., 2014), stroke rehabilitation (Orrell et al., 2009), and during walking in older adults (Uiga et al., 2020), however typically in relation to motor skills. Subsequent work extended on the body of literature to examine investment in relation to decision making under pressure (Kinrade et al., 2010).

Kinrade et al., (2010) describe the development of the Decision-Specific Reinvestment Scale, which adapts items from the Reinvestment Scale (Masters et al., 1993) to apply to decision-making components of performance. The Decision-Specific Reinvestment Scale (DSRS) measures an individual's tendency to engage in conscious decision-making. The DSRS utilises two factors to understand an individuals' predisposition for engaging in conscious control of decision making. These factors are labelled 'decision reinvestment' and 'decision rumination'. A high score of the decision reinvestment factor reflects an individuals' propensity to consciously monitor the processes that lead up to a decision. The decision rumination factor assesses whether the respondent tends to reflect upon previous poor decisions. In developing this 13-item two-factor tool Kinrade et al., (2010) found that the Decision-Specific Reinvestment Scale were moderately related to the propensity for team sport athletes to choke, as judged by their respective coaches.

Kinrade et al., (2010) provide preliminary evidence that the Decision-Specific Reinvestment Scale can be used to understand an individual's propensity to choke but also highlight the need for future work to extend on these findings. One such study that has expanded on this line of work by Laborde et al. (2014), found a difference in the underlying neurophysiological activity between high reinvesters and low reinvesters in novice handball players. However, one of the limitations of this study was that the participants were all novice athletes with no experience in handball competitions. Furthermore, the authors highlight that adopting alternative techniques such as EEG might help to gain a deeper understanding of the involvement of the prefrontal cortex with respect to decision reinvestment.

2.6.3 Types of sports

As can been seen from the literature reviewed here, intuitive decision-making strategies are those that can be classified as requiring less cognitive effort. It is also highly possible that these strategies can be seen as more efficient from a psychophysiological perspective. To date, most of the studies that have utilised psychophysiological measurement techniques have focused on sports that involve closed motor skills. Closed motor skills are those that are performed in a stable environment where the performer determines when to execute their movement i.e., internally paced (Magill & Anderson, 2010). While this covers a great number of sporting situations such as archery (Chen & Hung, 2010), golf (Baumeister et al., 2008), basketball free throw (Chuang et al., 2013), and pistol shooting (Loze et al., 2001), there are many other sports where the timing is influenced by opponents' actions or sport-specific rules e.g., the shot clock in basketball. These more dynamic and open type environments provide ideal scenarios for sport expertise researchers to examine the underlying cognitive processes used by athletes. However, currently few studies have examined more dynamic and open types of sporting situations using psychophysiological measures. One example that has utilised EEG is a study by Taliep and John (2014). This study examined the role of verbal-analytical engagement and an athlete's ability to detect visual cues. In this study, 8 skilled and 10 less-skilled cricket batsmen viewed video footage of a bowler delivering a number of balls that were projected onto a screen. The participant's task was to identify the type of delivery by responding as quickly and accurately as possible. This task was completed while participants were connected to an EEG recording machine to record the underlying cortical activation of the left (T2) and right (T4) temporal regions of the brain. The authors found that T3 event-related synchronisation (ERS) was significantly greater for skilled batsmen from approximately 1500ms prior to ball release, but decreased as the ball approached release, reaching non-significance by 250ms. It was suggested that this increase in amplitude of alpha activity in the left temporal cortex for skilled batsmen may be a result of a suppression of the verbal and analytical centres which has been linked to promoting implicit motor learning (Zhu et al., 2015). This suppression allowed the skilled batsman to "block out" task irrelevant processing, resulting in an overall more efficient neural activation. With respect to the right temporal area (T4), there were no significant differences of alpha power between skilled and less-skilled batsman.

Chapter 3: Measurement of Cognitive Workload in Athletes: A Systematic Review

3.1 ABSTRACT

Research suggests that expert athletes extract key perceptual information much earlier than lesser skilled athletes, helping them to respond earlier to an opponent's actions and make better quality decisions. In addition to providing an earlier response to opponents' actions, it has been suggested that this advantage might also reduce the cognitive load experienced by expert athletes. Given the high-pressured performance environments athletes face, understanding how key decisions are made is an important step towards making performance improvements. Measurement of cognitive load can help verify this advantage, and influence training to improve decision making performance. Recent advances in technology have made it possible to capture elements of expert performance in a more portable, less intrusive way, however, to date, the specific tools and technologies used to measure cognitive load within perceptual-cognitive tasks has not been systematically reviewed. This systematic review aimed to synthesise and discuss the literature that has measured cognitive load in sport within perceptual-cognitive tasks. A systematic search for papers that included keywords related to cognitive load and cognitive effort within athletes was conducted. A total of 17 papers were included in the final review. The most frequently used technology was electroencephalography (EEG). Despite being regularly used, the specific EEG analysis technique and method of reporting findings varied between papers, providing mixed evidence. Additionally, the review found that only one paper has utilised pupillometry to measure cognitive load, despite its extensive use in other domains, ease of application, and the large volume of eye movement registration use within sport more broadly. For these reasons, and barriers to the use of EEG, it is recommended that future research test and validate the use of pupillometry as a technology potentially capable of providing useful insight into the cognitive load experienced by athletes in decision making situations.

3.2 INTRODUCTION

A key feature of expert performers is the apparent ease with which they perform complex tasks. This is no different in the sporting domain and has often led to speculation that experts are better at preserving and efficiently allocating their mental resources to task-relevant stimuli (Furley & Memmert, 2012). Classic research by Abernethy and Russell (1987), for example, showed that expert athletes can extract key perceptual information much earlier than lesser skilled athletes, helping them to respond earlier to an opponent's actions. Of particular note is the suggestion by Abernethy and Russell (1987) that, in addition to allowing expert badminton players to respond earlier, expert perceptual processing may also reduce the information-processing load experienced. It has been suggested that expertise in perceptual processing may be linked to a reduced information-processing load - also termed cognitive workload or cognitive load - which may allow experts to make more rapid responses in sport-specific decision-making tasks. To help inform future research into the effects of cognitive load on decision making, understanding how researchers can measure this aspect of an athlete's decision-making ability is important. The aim of the systematic review presented in this chapter, therefore, was to synthesise and discuss the literature that has measured cognitive load in sport within perceptual-cognitive tasks.

As technology has developed, more sophisticated techniques and analysis methods have presented the possibility to both delve deeper into the underpinnings of cognitive processing in general, and to examine athletes at different skill levels, more specifically. For example, studies utilising EEG have compared athletes and non-athletes in quiet standing (Del Percio et al., 2009), resting state with eyes closed (Babiloni, Marzano, Infarinato, et al., 2010), and eyes open vs. eyes closed resting states (Del Percio et al., 2011). There are several approaches and technologies that have been used or suggested for use in measuring underlying cognitive processes. These approaches broadly fit into the category of psychophysiology, i.e., the study of "physiological responses as they relate to behaviour" (Andreassi, 2013, p. 1). It is important to note that psychophysiology is not solely linked to neural activations in the brain but can also include measures of physiological responses from other parts of the body including the muscles (e.g., electromyography, EMG) and the heart (e.g., electrocardiography, ECG). As such, the broad spectrum of behaviours that are studied in psychophysiological research include cognition and decision making, but also other behaviours, such as sleep (Šušmáková, 2004), balance (Amiridis et al., 2005), and aiming tasks e.g., rifle shooting (Konttinen et al., 2003).

The use of psychophysiological techniques (e.g., electroencephalography, pupillometry, functional magnetic resonance imaging, positron emission topography) and self-report questionnaires (e.g., NASA-TLX, task load index questionnaire in which participants provide a subjective assessment of workload, devised by NASA; Hart & Staveland (1988)), have allowed researchers to provide more detailed analyses of cognitive processing and proposed explanations for the expert advantage. For instance, Del Percio et al. (2009) and others (Babiloni, Marzano, Infarinato, et al., 2010; Costanzo et al., 2016; Duru & Assem, 2018) show that experts have lower cortical activation despite superior cognitive processing scores (in the case of general intelligence) demonstrating a "neural efficiency". This hypothesis posits that experts (or high-level performers) generally demonstrate a more efficient cortical activation during cognitive tasks (Ludyga et al., 2016). This level of cortical efficiency has often been interpreted as the novice brain utilising more resources (effort) compared to the expert brain. An alternative hypothesis developed and tested using psychophysiological techniques and self-report questionnaires is that experts possess an overall greater pool of resources to complete tasks (Duru & Assem, 2018). In this alternative view, it has been suggested that when the demand for mental resources is minimised the performance of cognitive tasks is maximised (Rypma et al., 2002).

These competing explanations for the neural efficiency hypothesis (greater efficiency versus greater capacity/resource) provide a challenge for researchers seeking to understand underlying mechanisms of executing complex tasks that often differentiate experts from novices, such as decision making. Is it that athletes have a greater pool of resources available to them to complete these tasks or are they just more efficient in their allocation? So far, in the sport science literature, this has remained largely unanswered. In order to test these two hypotheses in athletes, to generally increase our understanding of athlete cognition, and in particular, to understand and measure cognitive load, we need a greater understanding of measurement fit for this population. Indeed, a challenge for researchers interested in understanding cognitive workload and neural efficiency in general is how to measure this phenomenon in a valid, reliable, and feasible way. Early work from Daniel Kahneman (1973) suggested that any physiological marker of cognitive processing effort should: i) be sensitive to detect within-task variations in load produced by task parameters; ii) reflect differences between tasks with qualitatively different cognitive operations; and iii) be sensitive enough to detect differences between individuals with different abilities on the same cognitive operations. We can now apply these criteria to the current technologies that are available, examining the research that compares athletes at different performance levels and evaluate them in the terms of feasibility within sporting contexts.

In sum, the primary aim of this systematic review was to synthesise and discuss the literature that has measured cognitive load in sport within the specific context of judgement and decision making. While there is a body of evidence that exists more broadly (Brünken et al., 2010; Paas et al., 2003; Plessner et al., 2011), sport provides a particularly rich domain in which to understand human functioning. To this end, given the range of possible options to measure cognitive load in this context, this review sought to determine how cognitive load has been measured in athletes, specifically within perceptual-cognitive tasks. As an additional aim, as there are possibly multiple different analysis techniques even within one measurement approach or technology (e.g., EEG studies might utilise alpha-band or theta-band activity), we examined the specific analysis methods adopted beyond simply the technology. A final aim of this systematic review was to examine the literature with reference to the suggestions of Kahneman (1973) for the key ways to assess a measure. Specifically, this study sought to assess the research conducted to date on the three criteria of being sensitive to detect within-task variations, reflecting differences between cognitively different tasks, and sensitivity to differences between individuals with different levels of expertise to provide an evaluation of feasibility for use in sport.

3.3 METHODS

3.3.1 Search strategy

The PRISMA guidelines (Liberati et al., 2009) were followed in designing the present study and reporting the review findings. A literature search of electronic databases was conducted in September 2020 using five relevant databases: Web of Science, SPORTDiscus, PsychINFO, PubMed, and EMBASE. The search was conducted on title and abstracts to identify articles that measured cognitive effort or load in athletes. The search included two categories of search terms which were: i) the concept (cognitive load OR cognitive overload OR cognitive workload OR cognitive work-load OR mental load OR mental overload OR mental workload OR mental work-load OR memory load OR memory overload OR memory workload OR memory work-load OR cognitive demand OR mental demand OR memory demand OR cognitive effort OR mental strain OR load OR workload OR overload OR work-load) and ii) the population of interest (team sport OR field sport OR sport OR athlete OR athletic). Following PRISMA, the bibliographies of the relevant articles identified through the systematic search were manually searched for any additional relevant articles that were subsequent included.

3.3.2 Selection criteria

Full-text articles with versions available in English and published any time before September 2020 were eligible for inclusion in this review. To be eligible for inclusion in the systematic review, articles were required to: i) include at least one measure of cognitive load; ii) measure cognitive load within a perception or decision-making context; iii) be written in English; and iv) be an original full-text articles (i.e., not a conference abstract, book chapter, systematic review, or meta-analysis). A PRISMA flow diagram of this process is provided in Figure 3.1.

Regarding the first eligibility criterion that at least one measure of cognitive load was included, studies that included a manipulation of cognitive load e.g., through including a secondary or dual task, were only included if the study also specifically measured the load experienced.

After removing any duplicate entries, to complete the screening process, the remaining articles were imported into an online systematic review tool, Rayyan (Ouzzani et al., 2016). Initially titles and abstracts were screened by the main researcher and any articles that did not meet the inclusion criteria described above were excluded for further analysis. If the suitability of a paper could not be clearly determined based on its title or abstract, it was included for further review in the full-text review stage. Studies that were eligible for inclusion were subjected to data extraction. Where there were any uncertainties whether to include an article following the full text review, a second researcher independently evaluated the study, and the inclusion status of the article was discussed until a final consensus was reached. If consensus could not be reached, a third researcher evaluated the study, and the final decision was made.

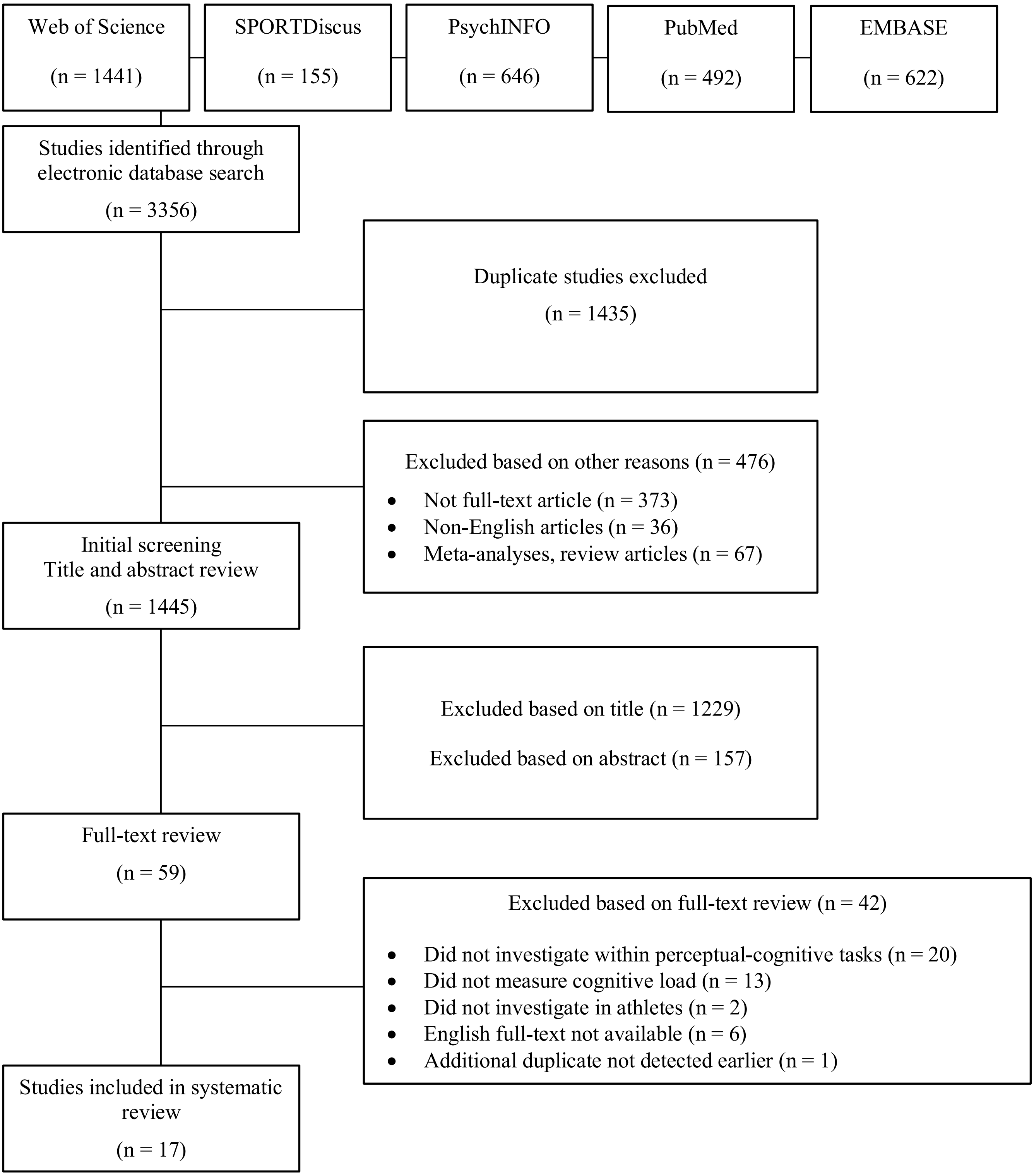

Figure 3.1: PRISMA flow diagram outlining the implementation of the systematic search strategy and review process.

3.3.3 Data extraction

The following details were extracted from the identified articles: demographics (number and age of experimental groups); cognitive load measure (method and technology used – if relevant); decision making variable (method and outcome measure); major findings.

3.4 RESULTS

The initial search across the five databases returned 3,356 results for consideration to be included in the systematic review. Of these results, 1,435 duplicates were excluded, 373 were not full-length original research articles (e.g., theses, book chapters, conference abstracts), 36 were not available in English, and 67 were meta-analyses or review articles. The titles and abstracts of the remaining 1,445 results were screened for inclusion. During this stage of screening, 1,229 were excluded based on title and 157 records were excluded based on the abstract. The remaining 59 records were further considered for full-text review which resulted in a further 42 manuscripts being excluded. Of these 42 exclusions, 20 did not investigate cognitive load within a perceptual-cognitive perspective, 13 did not measure cognitive load, two did not investigate cognitive load in athletes, six were not available as full-text original research articles in English, and one was a further duplicated not detected in earlier screening. The reference lists of the remaining 17 papers were searched in case any additional potentially relevant papers were missed during the systematic search procedure. This manual search of the reference lists did not identify any additional papers for inclusion. This left a total of 17 papers being included for analysis in this systematic review (see Table 3.1).

Table 3.1 Data extraction table outlining the experimental groups, level of expertise, technology used and analysis measures, task/action required, and major findings of the studies included

Article	Experimental Groups (Mean Age ± SD)	Level of Expertise	Task/Action Required	Technology Used	Outcome Measures	Major Findings
Aggarwal & Agarwal (2020)	25 football players (19.51 ± 1.08)	NR*	Multiple Object Tracking (MOT) with four levels of difficulty (number of targets)	Electroencephalography (Emotiv epoc+) **Sample rate:** 128Hz **Num electrode:** 14 **Impedance:** 5kΩ	Average performance accuracy, % change power spectral density (beta frequency band)	Percentage changes in power spectral density were greater in high cognitive load than in low cognitive load conditions.
Babiloni et al. (2009)	15 rhythmic gymnasts (21.4 ± 1.0) 13 non-gymnasts (20.8 ± 0.9)	Elite gymnasts – participated for more than 8 years at least 5 times per week. Regularly competed in national and international tournaments.	Judgement of artistic/athletic level of gymnasts (scale of 0 to 10) from video scenarios	Electroencephalography (EB-Neuro Be-plus) **Sample rate:** 256Hz **Num electrode:** 56 **Impedance:** 5kΩ	Mean judgement error, event-related desynchronisation (ERD) amplitude of low- and high-frequency alpha bands (gymnasts vs non-gymnasts), ERD magnitude (high vs low error condition in gymnast group)	Low- and high-frequency alpha ERD low lower in amplitude in elite gymnasts compared to non-athletes. High-frequency alpha ERD was higher in amplitude for videos characterised by a high judgement error in elite gymnasts.
Babiloni et al. (2010)	17 elite karate athletes (23.8 ± 1.0) 15 amateur karate athletes (21.5 ± 2.0) 17 non-athletes (24.6 ± 1.4)	Elite karate athletes (from Italian national team). Had been practicing for more than 12 years at least 5 times per week. Regularly competed in national and international tournaments.	Judgement of technical/athletic level of karate exercises (scale 0 to 10) from video scenarios	Electroencephalography (EB-Neuro Be-plus) **Sample rate:** 256Hz **Num electrode:** 56 **Impedance:** 5kΩ	Judgement error, event-related desynchronisation/synchronisation (ERD/ERS) magnitude of low- and high-frequency alpha bands (between groups)	Low- and high-frequency alpha ERD was less pronounced in dorsal and "mirror" pathways in elite athletes than non-athletes. Low- and high-frequency alpha ERD was less pronounced in dorsal pathways across all groups.

Cardoso et al. (2019)	36 soccer players (14.89 ± 1.42)	Male academy players from a Brazilian first-division soccer club. Players engaged in regular soccer-specific training at least five weekly sessions of 1.5 hours each and participated in national or international competitions.	Verbal response ("what the ball carrier should do") to video projection	Pupillometry (ASL Mobile Eye XG)	Pupillary diameter (mm)	Players with higher declarative and procedural tactical knowledge (DTK & PTK) displayed less cognitive effort.
Costa et al. (2018)	34 volleyball coaches (32.5 ± 9.4)	Experienced – had more than 10 years of experience. Novice – averaged 2.8 years of experience.	Selection of presented response options after watching videos of attacking situations.	Functional near-infrared spectroscopy (NIRSport)	Decision making accuracy, cerebral oxygenation (O_2Hb HHb concentration)	No significant different in decision making accuracy between novice and experienced coaches. Novice coaches showed greater blood flow of the pre-frontal cortex when visualising game situations.
Del Percio et al. (2019)	13 soccer players (25.1 ± 0.3) 8 non-players (25.6 ± 0.2)	Non-professional soccer players had been practicing football in regular regional and national tournament levels for at least 10 years and a minimum of 4 times per week.	Key press (left or right) in two conditions after watching video scenarios: (i) estimation of distance between players during the video (FOOTBALL) (ii) estimation if fixation target was coloured for a longer time in red or blue, CONTROL	Electroencephalography (EB-Neuro Be-plus) **Sample rate:** 512Hz **Num electrode:** 56 **Impedance:** 5kΩ	Accuracy of responses (%), mean reaction time of responses, event-related desynchronisation of alpha band	Greater cortical activation found in football players compared to non-players in FOOTBALL condition. No difference in the CONTROL condition. No differences for response accuracy or reaction times between groups.

Del Percio et al. (2008)	11 karate athletes (25.3 ± 1.5) 11 fencing athletes (25.5 ± 1.5) 11 non-athletes (29.6 ± 1.2)	Elite karate and fencing athletes – practiced for more than 10 years and usually 5 times per week.	Judging side (left/right) of the attack in karate and fencing attacking scenarios presented as still image, using a keypress	Electroencephalography (EB-Neuro Be-plus) **Sample rate:** 256Hz **Num electrode:** 56 **Impedance:** 5kΩ	Accuracy of responses (%), movement-related potentials (MRPs) – preparation (RP) and initiation (MP) of the movement	No significant differences between groups for accuracy of responses or reaction times. For right movements, non-athletes showed a higher amplitude in the supplementary motor and contralateral sensorimotor areas. Amplitude of motor potential (MP) over ipsilateral sensorimotor area was higher in elite karate athletes than fencing athletes. For left movements, the analysed potentials showed no difference between groups.
Fuentes-García et al. (2018)	1 male chess player (33)	National chess champion and competed in chess Olympiads. Player was ranked among the 300 best chess players in the world and had an ELO higher than 2550 points. Player practiced chess for more than 26 years and trained between 3 and 4 hours per day.	Playing a chess match against a computer chess engine	Electroencephalography (Enobio), Heart Rate Variability (HRV, Polar RS800CX) **Sample rate:** 500Hz **Num electrode:** 2 **Impedance:** 10kΩ	HRV (time domain): mean heart rate, mean RR, standard deviation of al NN intervals (SDNN), NN50 count divided by total number of all NN intervals (Pnn50), square root of the mean of the sum of the squares of differences between adjacent NN intervals (rMSSD) HRV (frequency domain): ratio Low Frequency / High Frequency. HRV (non-linear): sample entropy, SD1 & SD2 (Poincaré plot) EEG: critical flicker fusion threshold (CFFT), theta Fz/alpha Pz ratio	Cortical arousal measured by critical flicker fusion threshold and theta Fz/alpha Pz ratio increased during the chess game. Heart rate variability decreased during the chess game.

Fuentes-García, Pereira, et al. (2019)	13 chess players (15.45 ± 1.64)	Adolescent chess players averaged an ELO score of 1403	Solving two low-level and two high-level chess problems using a computer-based chess engine	Electroencephalography (EEG100C amplifier), Electrocardiography, (ECG100C amplifier), Heart rate variability (3 x AgAgCl electrodes) **Sample rate:** 250Hz **Num electrode:** 13 **Impedance:** 5kΩ	HRV (time domain): mean RR, standard deviation of all normal-to-normal RR intervals (SDNN), the root mean square of successive RR interval differences (RMSSD) HRV (frequency domain): low frequency power (LF), high frequency power (HF), ratio between LF/HF, and total power EEG: theta power spectrum	Heart rate variability decreased during the high difficulty level. EEG theta power spectrum increased during the high difficulty level.
Fuentes-García et al. (2020)	14 chess players (35.36 ± 13.77)	Chess players had an average ELO score of 1921.07.	Playing chess matches against a computer-based chess engine at three difficulty levels	Electroencephalography (Enobio) **Sample rate:** 500Hz **Num electrode:** 17 **Impedance:** NR*	Spectral analysis in theta (4-8 Hz), alpha (8-12 Hz), and beta (13-29Hz) bands	The winning group showed higher theta power in the frontal, central, and posterior brain regions when difficulty increased. In addition, alpha power showed higher values in hardest difficulty compared to easiest difficulty. The losing group showed a significant decrease in the beta and alpha spectrum in frontal, central, parietotemporal, and occipital areas when difficulty increased. Higher theta power found in the losing group compared to the winning group.

Fuentes-García, Villafaina, et al. (2019)	16 chess players (35.19 ± 13.44)	Players were divided into two groups: High Performance (n = 8; ELO = 1974 ± 161) or Low Performance (n=8; ELO = 1882 ± 172)	Completion of six chess problem-solving tasks (two low-level, two medium-level, and two high-level) using a computer-based chess engine.	Heart rate variability (Polar RS800CX) Subjective measures (Visual Analogue Scale, 0-10)	Time domain: heart rate, standard deviation of all normal-to-normal RR intervals (SDNN), percentage of trials >50ms different from preceding interval (pNN50), and root of the mean of the squares of successive RR interval differences (RMSSD) Frequency domain: ratio between Low Frequency (LF) / High Frequency (HF) Non-linear measures: Sample Entropy (SampEn) and Poincaré plot metrics	A significant effect of tasks in HRV indices and perceived difficulty, stress, and complexity in both high and low performance groups. A decrease in HRV was found in both groups when chess problems increased in difficulty. HRV was significantly higher in the high-performance group than in the low performance group during chess problems.
Grabner et al. (2006)	47 chess players (37.45 ± 13.16)	Chess players had an average ELO score of 1893 ± 227.	Speed task: task to count number of minor pieces presented on a screen as fast as possible (two conditions: chess positions and random positions) Memory task: select from four presented alternatives which chess pieced has been moved from its original position Reasoning tasks: determine the next best move for a given position (vocal response)	Electroencephalography (DELTAMED amplifier) **Sample rate:** 256Hz **Num electrode:** 33 **Impedance:** 5kΩ	Event-related desynchronisation (ERD) in the upper alpha band	Brighter participants (assessed using an established German intelligence test) performed better than less intelligent ones which was also associated with a more efficient brain function (lower ERD).

Gredin et al. (2020)	17 soccer players (21.0 ± 1.0)	Expert male soccer players – mean of 11 years competitive experience in soccer and took part in an average of 7 hours of practice/match play per week.	Predict the direction of opponent's final action depicted as video projections onto a wall via handheld responses devices	Electroencephalography (EEGo Sports) **Sample rate:** 500Hz **Num electrode:** 32 **Impedance:** 10kΩ	Anticipation accuracy and time of responses, spectral power ratio between frontal theta and parietal alpha activity.	Response accuracy was higher when provided with contextual priors compared to the control condition. No difference in response accuracy when contextual priors were provided while required to complete a secondary task (cognitive more demanding). Cognitive load was higher in the conditions where contextual priors were provided compared to the control condition.
Khacharem et al. (2013)	24 expert soccer players (24.2 ± 1.8) 24 novice soccer players (23.5 ± 2.7)	Expert soccer players had played soccer for an average of 13.2 years and trained or played for an average of 11 hours per week.	Reconstruct (recall) the scenes of play presented by drawing on a sheet of paper	Self-report subjective measures (9-point)	Recall performance, number of repetitions needed to memorise the scene, mental effort (9-point subjective scale)	Expert participants were more accurate in recall performance than novices. Novice participants had to invest greater mental effort than expert participants.
Qiu et al. (2019)	23 basketball players (20.43 ± 1.56) 24 non-athletes (20.71 ± 2.03)	Basketball players were first- and second-level national athletes. The athletes had trained an average of 14.35 ± 2.29 hours per week for 6.48 ± 1.47 years.	Multiple object tracking task (10 objects) – initial targets (2, 3 or 4) were highlighted before moving at random for 8 sec. At the end of tracking period, a subset of targets turned green (probe). Participants were to indicate the number of probe items that matched the targets.	Functional Magnetic Resonance Imaging (3-T Siemens scanner)	Accuracy of targets matched, attentional load (two, three, and four targets)	Tracking accuracy declined as tracking load increased. Accuracy scores were higher for athletes than for non-athletes tracking three targets and four targets, but not tracking two targets. Non-athletes had greater cortical activation than non-athletes in several brain areas (including left FEF & bilateral aIPS). Athletes showed greater activation than non-athletes in the medial superior front gyrus

Wolf et al. (2014)	14 expert table tennis players (23.8 ± 4.86) 15 amateur table tennis players (22.8 ± 4.16) 15 young elite table tennis players (14.9 ± 0.96)	Young elite table tennis players were the best upcoming teen table tennis players in Baden-Wurttemberg with a realistic chance to become an elite expert in their career.	Motor imagery task – participants instructed to imagine themselves reacting to an opponent serving	Electroencephalography (Nexus 32, Mind Media) **Sample rate:** 2048Hz **Num electrode:** 21 **Impedance:** NR*	ERD/ERS at the motor cortex & fronto-parietal cortex	Significantly stronger 8-10Hz ERD in experts compared to amateurs (in motor cortex). Trend towards stronger (but not significant) 8-10Hz ERD in frontal and parietal cortex in experts and young elite athletes compared to amateurs
Wright et al. (2013)	17 higher-skilled soccer players (22.6 ± 4.0) 17 lower-skilled soccer players (22.1 ± 3.7) 17 participants with minimal soccer experience (20.1 ± 1.1)	Higher-skilled players – those playing currently or within the last year in a league with regular fixtures and for a named club whose provenance could be checked on the internet. Lower-skilled players – nonplayers or recreational players but included some with previous experience (more than 1 year previous) of playing competitively for local sports clubs.	Viewing point-light (15-point, plus ball) displays of soccer player dribbling. Two temporal occlusion points, -160ms and 0ms. Session 1 - Predict which direction a soccer player dribbling a ball in a video would turn using a button press – half of video sequences were deceptive movements, and the other half were normal Session 2 – Predict whether the move performed by the player in the video was deceptive or normal	Functional Magnetic Resonance Imaging (MAGNETOM Trio 3T MRI scanner)	Identification accuracy (% of correct responses), individual whole-brain fMRI t-contrasts	Higher accuracy for normal and late occlusion trials, compared to deceptive and earlier occlusion trials. Higher-skilled males were more accurate than lower-skilled males and females. Higher-skilled participants showed superior performance on deceptive trials. Higher-skilled players showed significantly greater activation than lower-skilled players in a subset of action observation network (AON) areas. Activation was different in some areas between the deception identification and direction identification tasks

*NR – not reported

3.4.1 Sports analysed

There were several different sports analysed in the included studies that ranged from individual sports (n=9, 53%) through to team sports (n=8, 47%) including invasion games. The most studied sport was football (soccer) with six (35%) of the studies focusing on football players. The next most examined sport was chess, which was analysed in five (29%) of the included studies, however it is worth noting that one of these studies utilised a single participant study design. Of the remaining studies the sports that were studied included karate (n=2, 12%), rhythmic gymnastics, volleyball, fencing, basketball, and table tennis (n=1, 6% respectively).

3.4.2 Comparison group and level of expertise

Of the 17 included studies, eight (47%) included a comparison group in their design, while the remaining studies did not include any such comparison. Of the eight studies that did include a comparison group, the level of expertise either included participants from the same sport but were reported as lower skilled or amateur (n=2, 12% of studies) or participants that were non-athletes (n=4, 24%). Two of the included studies (12%) included both a non-athlete group and lower-skilled group for comparison. Of the two studies that utilised both a non-athlete and a lower-skilled group, one focussed on karate athletes while the other focused on football (soccer). The studies that reported using expert/skilled participants varied in the criteria for this designation, including the number of years' experience within their sport, the highest level achieved in the specific sport, the amount of weekly practice performed, representation in international competition, and the Elo rating (in the case of chess players; the Elo rating system is a method to calculate and determine an individuals' relative skill level).

3.4.3 Technology and analyses methods used

Overwhelmingly, the most common technology used in the studies included was electroencephalography (EEG) with 11 of the 17 studies (65%) adopting this technology. The remaining studies utilised a range of other technologies or systems which included pupillometry (n=1, 6%), functional near-infrared spectroscopy (n=1, 6%), electrocardiography (n=1, 6%), heart rate variability (n=2, 12%), functional magnetic resonance imaging (n=2, 12%), and subjective measures (n=2, 12%).

Within the 11 studies that utilised EEG as their measure of cognitive load, the specific analysis method varied greatly. Five of the 11 studies (45%) adopted a similar approach in which cognitive load was analysed using event-related desynchronisation/synchronisation (ERD/ERS) in the alpha band frequency. The remaining papers utilised analysis techniques that included percentage change in power spectral density of beta frequency band, amplitude of movement-related potentials, ratio of frontal theta and parietal alpha activity, spectral density of the theta band, and power spectral analyses on multiple bands.

3.4.4 Perceptual-cognitive tasks

The studies included used different perceptual-cognitive tasks as the stimulus to compare cognitive effort. Of the included studies, two (12%) utilised a non-sport specific experimental task. In both cases the task adopted was multiple object tracking (MOT) in experimental tasks with varying levels of difficulty in athletic populations. The remaining 15 studies (88%) utilised sport-specific stimuli and tasks but ranged in the response required of participants. Five (33%) of the studies that used sport-specific stimuli utilised an approach that required participants to make a sport-specific decision (e.g., what should happen next? Is this a left or right attack?) while another three of the studies (20%) required participants to make a judgement (e.g., judge the technical ability). Of the remaining studies the context in which cognitive load was examined included simulated/real matches in chess (n=3, 17%), solving sport-specific problems (n=3, 17%), pattern recall (n=1, 6%), motor imagery (n=1, 6%) and one study (6%) included multiple perceptual-cognitive tasks.

3.4.5 Cognitive load measures

The outcome measures for cognitive load were compared between the studies. In three (18%) of the studies, athletes (compared to non-athletes or less skilled participants) demonstrated a lower alpha event-related desynchronisation, whereas, in another two (12%), alpha event-related desynchronisation was higher. While all the studies included in this systematic review reported differences in cognitive load between levels of expertise, the direction of their finding (e.g., higher, or lower event-related desynchronisation) was not always consistent. For example, two (12%) of the included studies reported a greater total activation in non-athletes which is contradictory to another included study that reported greater activation in elite athletes. It is important to note, however, that there is a range in methodologies and technologies used to measured cognitive load in the included studies, thus directly comparing results may not be entirely informative. Nevertheless, there appears to be a range of inconsistent results.

3.5 DISCUSSION

The primary aim of this systematic review was to synthesise and discuss the literature that has measured cognitive load in sport within the specific context of judgement and decision making. As an additional aim, this review sought to understand what specific type of analysis techniques have been adopted to measure cognitive load in athletes to assist in evaluating their feasibility/usefulness in the context of understanding the dynamic nature of expertise in sport. The results of the review highlighted: i) the most commonly adopted technology utilised to measure cognitive load in sport is electroencephalography (EEG); ii) there are variations in the findings reported regarding the specific differences found in cognitive load; iii) outside of football (soccer) and chess, many other sports have been underexamined; and iv) less than half of the included studies compared experts and novices.

With the exception of one study, all of the studies examined utilised some form of objective psychophysiological technology to measure cognitive load. The exception utilised a self-report score on a 9-point subjective scale. The most common objective psychophysiological technology utilised was EEG. Within the EEG studies more specifically, the choice of analysis performed varied, and the results are mixed. In three of the EEG studies, the researchers found that event-related desynchronisation in the alpha band was lower in athletes compared to non-athletes, while in another two studies the opposite was found. This has important implications for researchers seeking to adopt this technology, as the evidence is mixed regarding the direction (in terms of higher or lower) cognitive load would be expected to change between athletes and non-athletes.

A finding of note was that only one included study used pupillometry. Eye movement registration devices work by tracking the pupil and corneal reflection through video footage and record the pupils while simultaneously recording the scene (real-world) in front of the individual. They have not traditionally been used to measure pupil dilation, even though, and by necessity they measure pupil size to track fixation-based metrics like, number, location, and duration of fixations (Duchowski et al., 2018). Pupillometry has a strong history of use as a cognitive load measure in fields outside of sport e.g., Szulewski, Gegenfurtner, et al. (2017), but it appears it has not yet reached widespread adoption within sporting contexts. This is of interest, given the large number of studies that have utilised eye tracking technologies in sport. For example, a recent systematic review by Kredel et al. (2017) identified 60 studies since 1976 that had utilised eye tracking technology to investigate gaze behaviour. While this gives an indication of the use of eye tracking in sport, it is likely an underestimation, as Kredel et al. (2017) excluded any studies that were exclusively based on temporal or spatial occlusion paradigms and studies that assessed only one fixation location e.g., studies on the “Quite Eye”. A systematic review by McGuckian et al. (2018) examining visual exploratory behaviour found 38 studies that all utilised some form of eye tracking technology. The number of studies, therefore, that have used the pupillometry abilities of such devices in a sport related context is surprisingly low (only one in the current review). This presents an opportunity for sport science researchers to incorporate a commonly used tool and well researched method in new and novel analysis techniques.

Reflecting on the suggestion of Daniel Kahneman (1973) that physiological measures should meet three key criteria (1. be sensitive to detect within-task variations in load produced by task parameters; 2. reflect differences between tasks with qualitatively different cognitive operations; and 3. be sensitive enough to detect differences between individuals with different abilities on the same cognitive operations), this systematic review makes evident that there is limited research that has addressed all three of these criteria. The studies included in this review have demonstrated that the approaches adopted are sensitive to detect within-task variations in task load and they are able to distinguish differences in cognitive load across different levels of difficulty or accuracy (i.e., within-task – criterium 1). With few exceptions, the studies presented in the current systematic review also demonstrated that the chosen analysis methods were sensitive to detect differences between individuals with different abilities on the same cognitive tasks e.g., experts vs. novices, as suggested by Kahneman (1973) – criterion 3.

A surprising finding from this review was that very few studies in sport have utilised a design that reflect changes between tasks with qualitatively different cognitive operations (i.e., between-task – criterium 2) in that many of the studies examined performance within only a single task. While the studies differed in the tasks utilised, they also differed in the range of analysis approaches adopted, presenting a barrier to this comparison. Thus, any comparison to detect difference in cognitive load in different cognitive operations is hampered.

It is useful to examine in detail the only study that did address all three of Kahneman's criteria in assessing measures of cognitive processing effort. Wright et al. (2013) included three distinct groups of participants with ranges in experience (highly skilled through to minimal experience). This allowed the authors to compare differences between individuals with different abilities on the same cognitive tasks (criterium 3). Importantly, the study also included two separate sessions that had slightly different (although somewhat linked) tasks (criterium 2). In session one, participants were required to predict the direction of a soccer player dribbling a ball using a button press. Half of the trials included deceptive movements, and the other half did not ('normal'). In the second session, participants were required to indicate whether the move performed by the player in the stimulus was deceptive or not ('normal'). The same stimuli were used for both sessions and was comprised of point-light (15 points plus the ball) representations and included two temporal occlusion points (-160 ms and 0 ms). The manipulation of difficulty (through earlier temporal occlusion points) in this design, allowed for an analysis of within-task differences (criterium 1). However, the stimuli utilised (point-light display) reduced the fidelity of the videos and potentially influenced decision accuracy and the level of cognitive effort that would otherwise have been required in normal video stimuli. Further, while this study used two distinct tasks which allowed for a between-task analysis, the tasks were highly similar. Arguably these tasks, while completed in a counterbalanced order, may not have required qualitatively different cognitive operations.

A study of note that addressed two of the criteria identified by Kahenman (1973) was Del Percio et al. (2019). In this study two groups with vastly difference experiences (13 soccer players and 8 non-players) were included to allow for a comparison of expertise (criterium 3). In the task, participants were presented with videos of typical football actions of two attacking players running towards the goal (one on the left and the other on the right of a fixation cross in the centre of the screen). In the videos, two defending players were simultaneously running nearby controlling the movement of the attackers in the video. During the trial, the fixation cross changed colour from red to blue or vice versa, with one colour appearing for a longer period of time (with trials presented in a randomised order). No trial had equal amounts of time for both colours i.e., one colour was always presented longer. This led to participants completing two distinct conditions (criterium 2). In the FOOTBALL condition, participants responded by estimating if there was a greater distance (i.e., more space) between the attacker and the defender on the left or right side of the screen. In the CONTROL condition, they were simply required to indicate the predominant colour of the fixation cross; that is, the colour it had appeared in for longer. All responses were made using one of the keyboard buttons (left or right) depending on the condition (e.g., if the cross was red for longer, the participant responded by pressing the left key).

Del Percio et al. (2019) found that football players had greater cortical activation (as a proxy for cognitive load) compared to non-players in the FOOTBALL condition but no difference in the CONTROL condition. While this study included level of expertise (criterium 3) and multiple tasks (criterium 2), the specific tasks adopted are limited in representativeness and ecological validity and didn't indicate any within-task differences e.g., more or less difficult within each condition (criterium 1). This study is thus limited in providing deep insights in applying the findings to how athletes make sport-specific decisions.

The Del Percio et al. (2019) study, however, presents a useful paradigm that can be used in future research to understand sport-based decision making and the underpinning processes. Including both sport-specific (e.g., perception of space in a sport stimulus) and non-sport specific (perception of time) tasks can shed light on the delicate process of athlete decision making. Specifically, by adopting an experimental design that utilises domain-specific and domain-generic tasks, researchers can determine differences between tasks with different cognitive operations while simultaneously identifying any differences between individuals with different experience, training, and abilities on the same cognitive operations.

In conclusion the current systematic review sought to synthesise and discuss the extant literature that has examined perceptual-cognitive tasks in sport through the measurement of cognitive load. Overwhelmingly, the most common technology adopted to measure cognitive load within this context was electroencephalography (EEG), while there was also a range of other technologies or approaches that have been successfully used. Another key finding is the lack of a consistent approach in the analysis of the EEG signals and data that this technology produces. The review highlights how one commonly used technology within sport science (eye tracking) is largely underutilised in its potential to measure cognitive load in athletes (via pupil diameter), despite often being available for analysis and presents as a feasible option to measure cognitive load in dynamic sport contexts.

In summary, this systematic review has answered a central question of this thesis; what technologies have been utilised to measure cognitive load within a perceptual-cognitive perspective in athletes. It highlighted a useful paradigm of comparing measurement in domain-generic and domain-specific tasks for participants with different levels of experience (Del Percio et al., 2019). The review also provided more insight into the landscape of the literature base and specifically highlighted a potential gap in the literature given the absence of studies adopting pupillometry measures for understanding cognitive load in sport.

Chapter 4: Measuring intuitive decision-making strategies using pupillometry

4.1 ABSTRACT

Intuitive decision-making approaches suggest that individuals are able to make fast and accurate decisions without the need for extensive deliberation. In doing so, intuitive decision-making strategies can explain how individuals make effective decisions in situations with limited information and under time pressure, such as the case in sport. In the current study we aimed to present and test a method to measure the underlying cognitive load of individuals within a decision-making context. Participants were presented with two different tasks aimed to elicit intuitive and deliberative decision-making processes, respectively. Cognitive load was assessed using pupillometry during task performance, measured with a head-mounted eye tracking device (ASL MobileEye XG). Results confirm that cognitive load significantly increased in the deliberative-based task compared to the intuitive-based task. Interestingly, the order in which participants completed these decision-making tasks influenced the amount of cognitive load experienced, perhaps signalling cognitive processing priming effects. These findings provide a proof-of-concept that comparison and measurement of intuitive and deliberative decision processes is possible using pupillometry from mobile eye tracking glasses. This provides valuable insight into the nature of decision making in general, and in particular to intuitive decision making. The results are discussed in the context of intuitive decisions in sport as well as decision making approaches more broadly.

4.2 INTRODUCTION

Given that action choices, such as in many sports or other performance environments, are often made in uncertain circumstances and under extreme time pressures, it is virtually impossible for an individual to know all the possible alternative options and their consequence in the moment. Yet, elite athletes are reliably successful in selecting the correct option, indeed, as a hallmark of expertise (Raab & Farrow, 2013). In order to understand and thus to be able to train this skill, research seeks frameworks that can be used to explain the underlying process that individuals adopt to allow them to make effective decisions. One framework that has received greater attention in the judgement and decision making literature recently, is the use of intuitive decision making strategies (Harteis & Billett, 2013; Kahneman & Klein, 2009).

Because intuitive decisions are categorised as occurring rapidly while preserving cognitive resources, examining how they function within the domain of sport – a time-pressured domain that includes uncertain environments, is an appealing area of interest for research. Within the decision making literature, one of the more widely accepted approaches for studying complex intuitive decision making domains like sport and medicine is the fast-and-frugal heuristics approach (Raab & Gigerenzer, 2015). Heuristics are defined as basic “rules of thumb” that allow an individual to take a “shortcut” to a decision (Volz et al., 2006). They are strategies whereby individuals selectively attend to available information or focus on only a few key points of data to form a decision, rather than more complicated approaches where they compare many sources of information and weigh them up to make decisions (Raab, 2012). While there is a small but emerging body of work in sport that examines intuitive decision making (e.g., Johnson & Raab, 2003; Raab & Laborde, 2011; Roberts et al., 2020), there is a richer existing literature in fields such as economics, management science, psychology, and social sciences (Plessner et al., 2011). With the limited work on intuition in sport in mind, the current study aimed to test a proof-of-concept method of determining if a decision has been made more intuitively or deliberatively.

One of the major difficulties in the understanding of intuition is its many and varied definitions (see Table 2.2 for a summary). Nevertheless, what is generally accepted about intuitive decisions is that they are faster than deliberative decisions, relatively unconscious, difficult to articulate, and formed without deliberation of a conscious choice, yet they are still strong enough to act upon (Raab & Laborde, 2011). In contrast, deliberative decision making can be defined as the process of consciously analysing all of the available options, weighing them up, and deciding on an appropriate (and rational) choice (Kruglanski & Gigerenzer, 2011). These two types of decision making have also been classified as System 1 (e.g., intuitive decisions) and System 2 (e.g., deliberative or analytical decisions) (Kahneman, 2011). In this classification, System 1 is described as the fast and automatic system whereas System 2 is slower and more effortful (Kahneman, 2011).

What is clear with respect to deliberative processes is that they are naturally slower and require more cognitive effort than intuitive decision-making processes. Thus, in a sporting context where the human limits of cognition are especially challenged by extreme time pressures, these slower deliberative processes are unlikely to yield useful outcomes, particularly for decisions that require action choice (e.g., to pass or shoot). As such, it has been argued that athletes must rely on intuitive decision-making strategies, such as heuristics, to account for the time pressures experienced in competition (Raab, 2012). Given that intuitive processes are generally faster, more automatic, and more difficult to verbalise, the ability to measure the underlying processes poses a unique challenge for motor learning and expertise researchers.

Within the literature several research paradigms have been described to measure overall decision-making performance in sport (see Table 2.1 for a brief summary). Many of these paradigms involve the use of video as the decision-making stimulus. While video-based tasks can provide measures for decision elements like speed and accuracy relatively easily, it is more difficult to assess the underlying decision processes, which is what is needed to assess intuition and of particular relevance for the current thesis. Indeed, it is hypothesised that intuitive decisions are those that are made with little cognitive effort (and hence lower cognitive load). Kahneman (2011, p. 59) describes cognitive ease as occurring in a situation where things are going well and there is no need to redirect attention. Thus, if intuitive decisions are cognitively easier, with less need to redirect attention, measurement of the amount of cognitive load, and attention (or attention redirection) during tasks would allow researchers to make conclusions about the type of processing used. Current sport decision making paradigms do not typically incorporate this measurement, and thus additional tools are necessary.

Research into cognition and decision making in sport has begun to utilise neuroimaging technologies, such as functional magnetic resonance imaging (fMRI), to provide insight into the neurophysiological underpinnings of performance (Parkin et al., 2015; Pitcher et al., 2012). Table 4.1 below is a brief summary of some common approaches to incorporating psychophysiological tools in sports cognition, and the pros and cons for their use. Outside of sport, the power of psychophysiological tools is shown by Volz et al. (2006) who used fMRI to measure the neural correlates of decisions that follow an intuitive decision making approach called the recognition heuristic. In this task participants were presented with the names of two cities and asked to select which had a greater population. The results showed that participants selected the recognised alternative more often, in line with the recognition heuristic. The use of the recognition heuristic was also associated with an increased activation within the anterior frontomedial cortex and the retrosplenial cortex, demonstrating differences in neural activity.

While Volz et al. (2006) illustrated the usefulness of neuroimaging in examining intuitive decision processes, for observable differences in brain activity to be detected using fMRI, the actions (or decisions) performed require time to produce metabolic changes that are reflected in the MRI signal. This timescale can sometimes be in the tens of seconds or even minutes (Latash, 2008). To combat this limitation, researchers have begun to utilise electroencephalography (EEG) techniques. The major advantage of EEG over other imaging techniques is its higher temporal resolution, which can be between 500 and 1,000 milliseconds (Andreassi, 2013). However, EEG also has some limitations that are worth noting. Firstly, EEG devices can be expensive and require extensive setup and calibration (Eckstein et al., 2017). There are also issues with movement artefact in most settings and in many cases, EEG can be somewhat intrusive to participants. Furthermore, the analysis of the signals that EEG devices record has been somewhat inconsistent in both the choice of analysis technique but also in the findings reported (see Chapter 3 of this thesis). For example, in three of the 17 studies included in the systematic review (Chapter 3) we found that athletes, when compared to non-athletes or less skilled participants, demonstrated a lower alpha event-related desynchronisation (ERD) in the EEG signal. This reflects a reduced cortical activation in athletes and a potential indication of lower cognitive load being exerted or a possible "neural efficiency" (Babiloni et al., 2009; Babiloni, Marzano, Infarinato, et al., 2010; Grabner et al., 2006). On the other hand, two studies found the exact opposite and that alpha ERD was higher in athletes compared to non-athletes suggesting increases in cortical activation and rejection of the neural efficiency hypothesis (Del Percio et al., 2019; Wolf et al., 2014).

Table 4.1 A brief summary of commonly used psychophysiological techniques and some pros and cons for their use.

Psychophysiological technique	**Common measurement approaches**	**Pros**	**Cons**
Positron emission tomography (PET)	• Levels of glucose and oxygen in brain structure • Cerebral blood flow • Cerebral blood volume	• Provides cross-sections of brain regions that can indicate different levels of activation	• Requires radioactive substances • Requires participants to remain still • Requires expensive equipment and dedicated space
Functional magnetic resonance image (fMRI)	• Blood oxygen concentration • Blood flow • Blood volume	• Better temporal and spatial resolution compared to PET • Does not require radioactive material	• Lower temporal resolution compared to EEG • Requires participants to remain still • Requires expensive equipment and dedicated space
Electroencephalography (EEG)	• Spectral analysis • Coherence • Event-related potentials	• Higher temporal resolution compared to fMRI • Allows more movement compared to fMRI and PET	• Requires expensive equipment • Requires extensive setup and calibration • Relatively intrusive for participants
Pupil dilation	• Change in pupil size	• Allows for more movement compared to other techniques • Less intrusive than other options • More affordable than other options	• Can be influenced by external factors • Not a direct measure of cerebral activity

A final important finding from the systematic review in Chapter 3 is the apparent gap in the literature which presents an opportunity to use pupillometry as a proxy measure of cognitive load in athletes, specifically within decision making contexts. We know that the size of the pupil changes (dilates and constricts) in response to the amount of light that enters the eye which is controlled by the autonomic nervous system (ANS) (Andreassi, 2013). It is also commonly reported that the increase in pupil size is related to an increase in mental workload (Hoeks & Levelt, 1993; Hyönä et al., 1995). Research has demonstrated that pupillometry is a common psychophysiological measure that can provide information and evidence about the amount of cognitive load individuals exert during demanding tasks. It has been shown that the size of the pupil changes, and is positively correlated with the cognitive load experienced by an individual (Laeng et al., 2012; Piquado et al., 2010).

In a seminal study by Beatty and Kahneman (1966), increased difficulty and cognitive demands experienced by participants was reflected by an increase in pupil diameter (i.e., pupil dilation). These findings have also been replicated in numerous studies that show the pupil size increases (dilates) as the demand to allocate attention increases (Verney et al., 2004) and with greater task difficulty (G. Porter et al., 2007). In the study by G. Porter et al. (2007), participants completed a series of tasks with a progressively increasing number of elements and difficulty. The first two tasks participants completed were a search task in which they were presented with a display that utilised Landolt "c"s, a standardised symbol used for testing vision, enclosed in a circle. The target stimulus for these tasks was a forward-facing "c", while distractors were rotated in either 90°, 180°, or 270° (see Figure 4.1 for illustration). In the easy search task, the display only showed upward-facing distractors whereas in the hard search task all three distractor symbols were used. Participants' task in these trials was to respond to the question "is there a target present?" by using a keyboard response. The final easy task participants completed was a counting task which utilised the same stimulus displays as the hard search task but instead they responded to the question "is there an odd number of symbols?" also using a key press. Participants completed these tasks across four conditions of set size (number of items displayed) namely, 29 or 30 items (large set size) and 9 or 10 items (small set size).

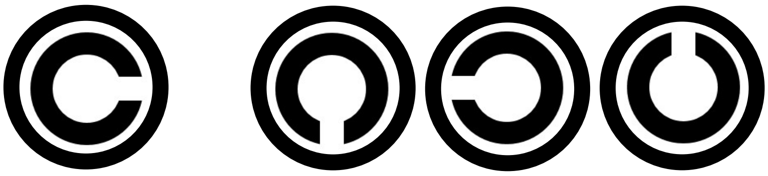

Figure 4.1 Example Landolt "Cs" used in Porter et al. (2007). The leftmost is the target, followed by three example distractor stimuli.

The authors found a small increase in the dilation of the pupils in the hard search task as compared to the easy search task. They also reported that the pupil size increased more as the set size (i.e., number of presented targets and distractors) increased. Taken together, the authors suggested that the increase in recorded pupil dilation reflected an increase in processing difficulty of the tasks as presented. This study supports the early seminal work of Beatty and Kahneman that has shown task-evoked pupillary responses are sensitive to small changes in task difficulty.

Within the context of intuitive and deliberative decision-making strategies, intuitive decisions are those that are reached with an apparent "cognitive ease" or a lower level of cognitive effort (Hogarth, 2001; Kahneman, 1973). Given the interest within the sport science field in understanding intuitive decisions, researchers should seek technologies and methodologies that can measures these decisions. Of the factors that underpin intuition (i.e., speed, cognitive load), cognitive load stands out as an appropriate characteristic to measure. Based on the research that has shown that pupil size increases are related to increases in cognitive load (G. Porter et al., 2007; Verney et al., 2004) pupillometry appears, therefore, to be a measure that can provide insight into intuitive decision making.

Despite technological advances in eye tracking devices that now allow measurement of pupil size, (e.g., improved accuracy, higher sampling frequencies, decreased intrusiveness) there has been very limited research adopting pupillometry (Partala & Surakka, 2003) particularly within sport. In Chapter 3, only one study was found that utilised pupillometry to measure cognitive load in decision making contexts within athletes. Within sport science research, eye tracking technology is abundantly used across several sports and methodologies. A recent systematic review of eye tracking research found 60 studies that covered a wide range of different sports (21 in total) (Kredel et al., 2017). Despite the extensive number of articles in this domain, however, and the fact that many of the devices used typically provide pupil size measures, there are very few studies that have utilised pupil size as an index for cognitive load (Beatty, 1982; Partala &

Surakka, 2003). In order to progress the use of pupillometry for sport-specific tasks, this study begins outside of sport to compare intuitive and deliberative decision processes.

4.2.1 Current study

Building on the literature that has shown pupillometry is sensitive to detect differences in cognitive load, this study aimed to test a proof-of-concept method of determining if a decision has been made more intuitively or deliberatively. Given how little is known about the underlying psychophysiology of intuitive decisions and whether the use of pupillometry is sensitive enough to detect important differences, the current study tested pupillometry as a method to measure cognitive load between intuitive and deliberative decision-making processes. To eliminate any potential expertise effects, the cognitive demands of two domain-generic tasks were recorded. The first task sought to elicit intuitive-based processing (through a face perception task) while the second sought to elicit deliberative/analytical processing (using the Tower of London). We hypothesised that participants would demonstrate a lower cognitive load for the intuitive-based task (Face Perception) as shown by less pupil dilation when compared to the deliberative-based task (Tower of London). We also hypothesised that participants who completed the deliberative-based task first would be essentially "primed" to act deliberatively and would find it harder to switch to making intuitive-based choices. This priming effect was expected to be shown by a higher pupil dilation and thus cognitive demand in the intuitive-based task for the group of participants who completed it second.

4.3 METHODS

4.3.1 Participants

Participants were 19 males aged 18 to 34 years (M = 24.90, SD = 4.42). Participants gave informed consent prior to taking part in the experiment and were free to withdraw at any stage. The research protocol and study methods were approved by the La Trobe University Human Research Ethics Committee (Application ID: HEC19076)

4.3.2 Procedure

Participants completed two different tasks in a counterbalanced order while seated comfortably in front of a touch screen device (Microsoft Surface Go). Pupil diameter was recorded during both experimental tasks using an ASL Mobile Eye Tracking-XG device (Applied Science Laboratories, Bedford, MA, USA).

The first task (Intuitive Task, IT) adopted a similar method to that used in S. Porter et al. (2008). In this task, participants were shown an image of a face while simultaneously presented with text of two occupations. The face image was presented in the centre of the screen while the two occupations were presented with one on the bottom-left and the other on the bottom-right of the screen (see the second image in Figure 4.2 as an example). The face images were sourced using the NimStim database (Tottenham et al., 2009). The occupations were sourced from an online search of common occupations/jobs and then were randomly assigned to the face images. Forty-two different face images (22 male and 18 female) were selected from the database and each face was presented only once during the experiment, for a total of 42 trials. All the faces had a happy facial expression with an open mouth. The occupations presented with each face and the side on which they appeared remained consistent for each of the trials, but the order of the trials was presented randomly. The participants were asked to match the image of the face to one of the occupations presented on the screen as quickly and as accurately as possible by touching the occupation on the touch screen device. The face image and the occupations were presented for 4 seconds after which the screen went blank and displayed a fixation dot (see Figure 4.2 for a diagram of the experimental procedure).

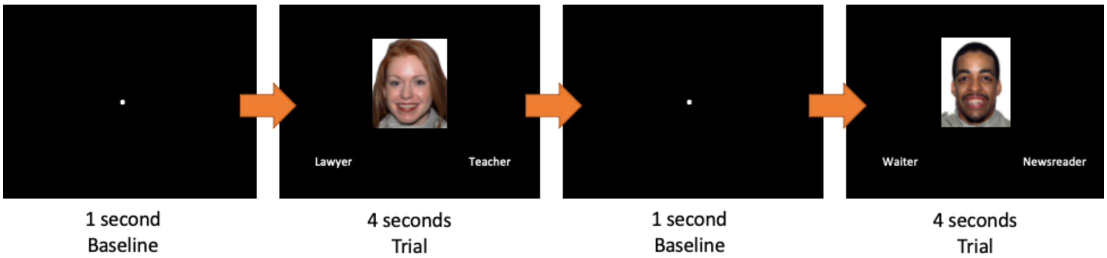

Figure 4.2: Flow diagram of the experimental procedure for the intuitive task

The second task (Deliberative Task, DT) utilised a common well-known test for the assessment of executive function called the Tower of London (ToL) (Mueller & Piper, 2014; Schnirman et al., 1998). The task was presented using the Psychology Experiment Building Language (PEBL) software package (Mueller & Piper, 2014). In this task, participants were presented with two pictures of three different coloured discs arranged in three stacks. The picture at the bottom of the screen shows the starting configuration for the task while the picture at the top depicts the target configuration of the discs (see Figure 4.3). The goal of this task is for participants to move the discs, one at a time, from the original starting positions to the target positions in as few moves as possible within the set time limit (2 minutes). The version of the ToL utilised in this study included both a limit on the number of moves and an overall time limit per trial. For a participant to correctly solve each given trial, they needed to complete the task in the minimum number of moves possible. In other words, if they made an error in moving a disc the problem was not solvable within the given moves limit. In this case participants were instructed to attempt to place as many discs as possible in the correct positions.

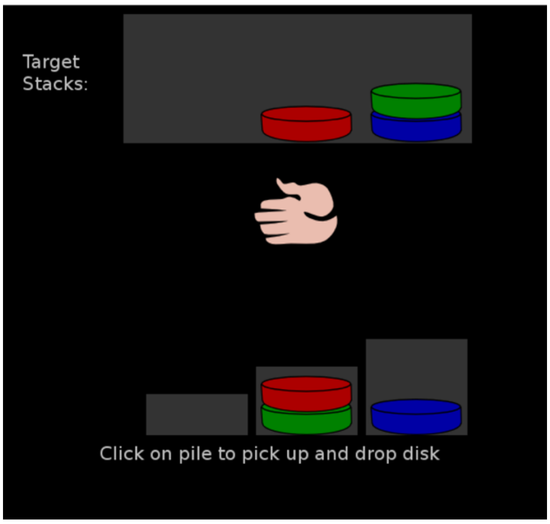

Figure 4.3: Example of the stimuli presented to participants for the deliberative task

The Deliberative Task was split into two distinct phases. The first phase was from the moment that the trial was presented (i.e., the target and starting positions were displayed on screen) until the first movement was made, to represent the processing phase (DT-Processing). The second phase began from the end of the processing phase until the trial was completed (either successfully or unsuccessfully). This was designated the decision phase (DT-Decision). These time periods were selected as the ToL task is an "active" task that requires participants to take action (touch screen) to reflect their decisions and does not have a standard "decision moment" as is the case in the face perception task. By using these phases in the deliberative task, we were able to measure the cognitive load while the participants were planning their moves (DT-Processing) compared to the cognitive load while they were actively solving the ToL problem.

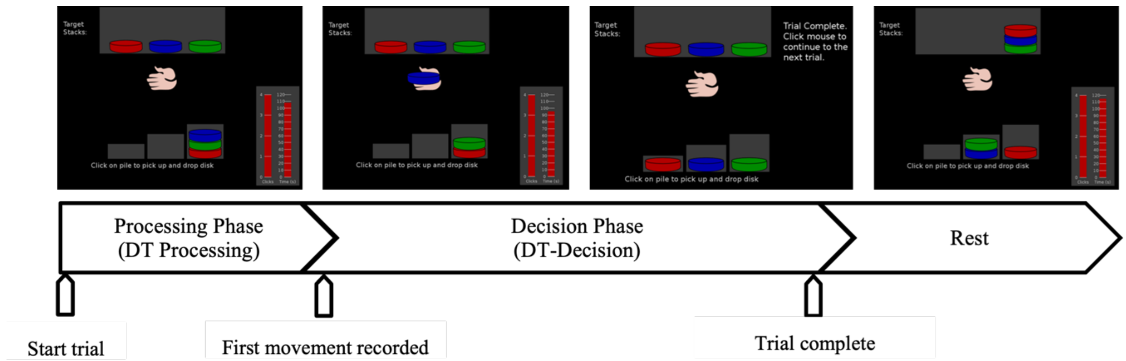

Figure 4.4 Flow diagram of the deliberative task, showing the breakdown of phases

4.3.3 Statistical analysis

The sample size for the current study was guided by the sample sizes and analyses conducted in similar studies, including Lorains et al. (2014; n = 6), Dicks et al. (2010; n = 8), Panchuk and Vickers (2006; n = 8), and G. Porter et al. (2007; n = 12). Based on a predicted moderate effect size, using G*Power v.3.1.9 (Faul et al., 2007) it was determined that a minimum number of 16 participants was required (Effect size = 0.52, Power = 0.80, $p = 0.05$). Given this effect size calculation, the recruited sample of 19 participants was considered appropriate.

A repeated measures analysis of variance with pre-planned simple post-hoc contrasts on effects that reached the nominal significance level ($p < 0.05$) was used to compare pupil dilation (cognitive load) across the two presentation orders (IT or DT first) and across the tasks and phases (IT, DT-Processing and DR-Decision; see Figure 4.4). Prior to statistical analysis, the data were screened for outliers. Trials that had more than 25% of pupillometry data missing (either through excessive blinks, low quality tracking etc.,) were excluded from further analysis (Cardoso et al., 2019). Upon screening, it was discovered that one participant had a large majority of trials that were excluded based on the screening above and consequently all of their trials were excluded from analysis. Mauchly's test of sphericity indicated that the assumption of sphericity had been violated, χ^2 (2) = 14.45, $p = 0.001$, therefore the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.58$).

Effect sizes are calculated as omega squared (ω^2), with reference values of less than 0.01 for a low effect, between 0.02 and 0.06 as a medium effect, and greater than 0.14 as large effects (Kirk, 1996).

A baseline value for pupil size was taken at the beginning and end of the experiment (baseline_{start}, and baseline_{end}, respectively). In addition, two more baseline values were measured (baseline_{face} and baseline_{tol}). The baseline_{face} value was calculated as the average pupil size between trials in the face perception task, during which the fixation dot was displayed. The baseline_{tol} value was calculated as the average pupil size between trials in the Tower of London task.

An initial correlation analysis was conducted on the baseline values measured during the task. All the baseline values were highly correlated with each other (see Table 4.2). Given the strong correlations between all baseline conditions, and to eliminate any task-related effects on comparisons using baseline values, for the remaining analyses we used baseline_{start}.

Table 4.2 Correlations of baseline values

	Baseline_{start}	Baseline_{end}	Baseline_{face}	Baseline_{tol}
Baseline_{start}		0.940*	0.888*	0.917*
Baseline_{end}	0.940*		0.945*	0.977*
Baseline_{face}	0.888*	0.945*		0.969*
Baseline_{tol}	0.917*	0.977*	0.969*	

* Correlation is significant at the 0.01 level (2-tailed)

4.3.4 Measures

For both tasks (Intuitive Task and Deliberative Task) pupil diameter measures from the eye tracker and the speed of response by the participants was recorded. These measures were selected to allow analysis of the decision-making process, rather than the outcome of the specific decision (i.e., which occupation was selected or the number of correctly solved trials in the Tower of London task).

4.4 RESULTS

Descriptive statistics are reported in Table 4.3. The ANOVA revealed a significant main effect of Task, F (1.16, 13.86) = 103.30, $p < 0.001$. Pre-planned post-hoc simple contrasts show that pupil dilation was greater for both the DT-Processing and DT-Decision tasks compared to the IT (F (1, 12) = 70.66, $p < 0.001$, $r = 0.92$ and F (1, 12) = 146.61, $p < 0.001$, $r = 0.96$, respectively). The simple contrasts did not distinguish between the two Deliberative Phases (Processing and Decision), however, and therefore post-hoc pairwise comparisons were performed, with a Bonferroni correction to adjust the alpha level for multiple comparisons. These pairwise comparisons further revealed a significant difference between the two different phases within the Deliberative Task ($p < 0.001$) with greater dilation seen in the Decision Phase compared to the Processing Phase (see Figure 4.5).

Table 4.3 Descriptive statistics for pupil dilation (in pixels) across group orders

	IT		DT- Processing		DT-Decision		
Order	M	(SD)	M	(SD)	M	(SD)	n
IT→DT	-4.16	(9.13)	9.01	(7.22)	13.54	(6.65)	7
DT→IT	-4.80	(9.29)	3.13	(8.40)	5.26	(8.09)	7
Total	-4.48	(8.86)	6.07	(8.12)	9.40	(8.31)	14

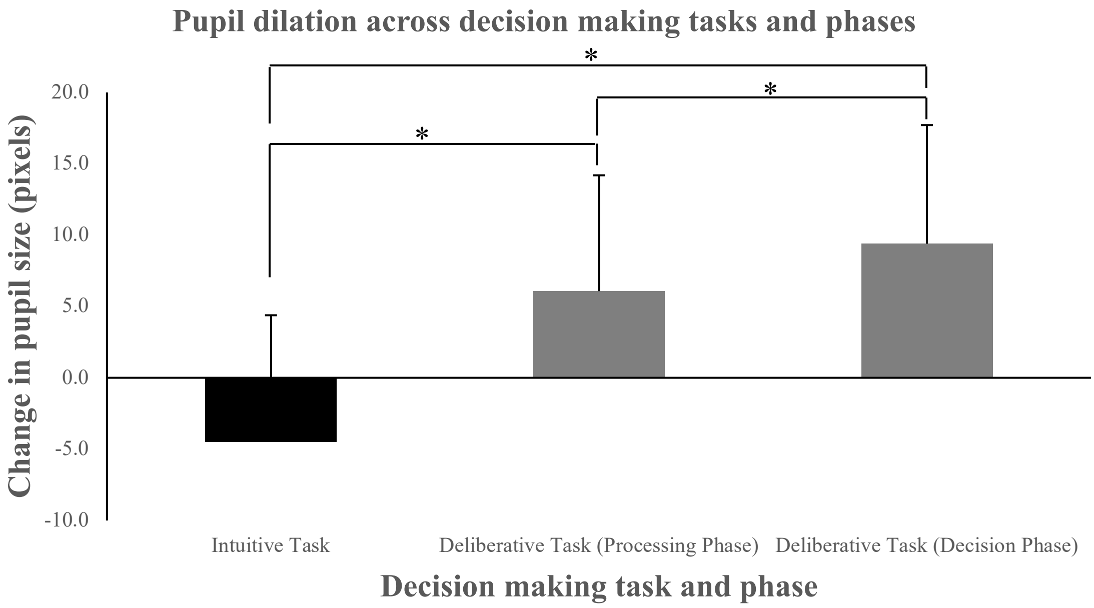

Figure 4.5 The mean pupil dilation across decision making tasks and phases in the deliberative task. Significance: *$p < 0.001$.

In addition, a significant interaction was found between Task and Order, F (1.16, 13.86) = 7.53, $p = 0.013$). Post-hoc analyses using pre-planned simple contrasts showed a statistically significant effect of task (F (1, 12) = 11.14, $p = 0.006$, $r = 0.69$) on the pupil dilation recorded between the Intuitive Task and the Deliberative Task's Decision Phase (see Figure 4.6). Specifically, participants that completed the Intuitive Task first displayed a greater increase in pupil size in the DT-Decision Phase compared to those that completed the Deliberative Task first (increase of 17.7 pixels and 10.06 pixels, respectively). The post-hoc analysis did not reveal any significant effect of order between the Intuitive Task and the Deliberative Task's Processing Phase, although this approached a statistically significant level (F (1, 12) = 4.38, p = 0.058).

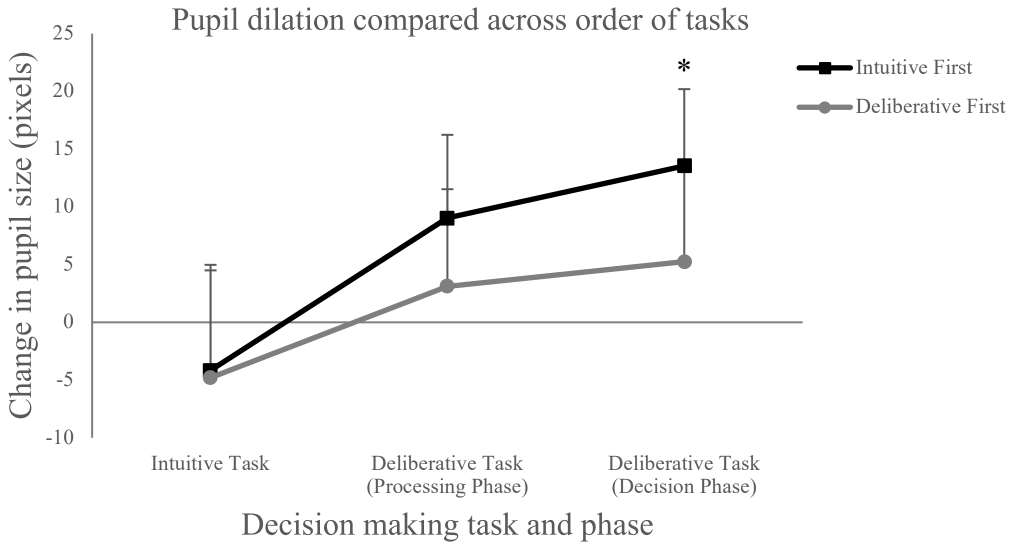

Figure 4.6 Mean change in pupil size across task/phase and order of completing tasks. Significance: *p = 0.006 for difference between task order

4.5 DISCUSSION

Intuitive decisions, as opposed to deliberative decisions, have been theorised as those that are fast, relatively easy, and require little cognitive effort. Kahneman (1973) suggested several criteria for physiological measures of cognitive load, which include that the measure should reflect differences between tasks with qualitatively different cognitive operations (criterium 2). To that end, the current study presented and tested a method to measure the cognitive load of individuals using pupillometry measures in the context of intuitive and deliberative decision making. More specifically, this study sought to detect and assess differences in cognitive load of two distinct tasks that required very different decision-making processes (intuitive and deliberative), therefore addressing criterium 2 suggested by Kahneman (1973).

Our hypothesis that the deliberative Tower of London (ToL) task would demonstrate a greater increase in pupil size (dilation) as compared to the intuitive Face Perception task was supported. Our results indicated that, irrespective of the order in which participants completed the two tasks, the ToL task elicited a statistically significant greater pupil size. This increase indicates that the ToL required more cognitive load which we interpret as an indication of a deliberative decision-making approach. In comparison, the Face Perception task required a lower degree of cognitive load, as indicated by the absence of pupil dilation, which is interpreted as an indicating an intuitive decision-making approach.

Our results also indicated that, although all participants demonstrated an overall higher cognitive load (as indicated by pupil dilation) for the ToL task, participants who completed the Face Perception task first demonstrated an even greater increase when completing the ToL (as evidenced by the significant interaction effect). While both groups (orders) demonstrated a similar change in pupil size from baseline for the Face Perception task (-4.16 and -4.80 pixels), the changes in pupil size for the ToL were statistically significantly different. Specifically, although both groups demonstrated a greater pupil size for the ToL, the group who performed the Face Perception task first had a greater ToL pupil size (9.01 ± 7.22 pixels) compared to the group who performed the ToL first (3.13 ± 8.40 pixels). This interaction effect between task and task order suggests that the first task completed by participants may have primed their processing style and this carried over into the next task completed i.e., the face perception task primed intuition and the ToL task primed deliberation. With deliberation primed (ToL task first), the intuitive face perception task was less demanding, and with the intuition primed (face perception task first), the deliberative ToL task was more demanding. As such, switching from intuition to deliberation may require more cognitive effort, as signalled by a relative increase in pupil diameter. Priming participants to rely on their gut instinct, in deliberative decisions that they were likely not expecting, may have contributed to the reported interaction effect.

Upon further examination, the findings of greater effort for a deliberative task after an intuitive task align with phenomena highlighted in previous research. There is evidence that suggests cognitive task performance (i.e., engaging in mentally demanding activities) can influence the effort, manner, or order in which a subsequent task is performed. For example, in a study by VonderHaar et al. (2019), participants were invited to select the order in which they performed a cognitively demanding item-generation task while performing a relatively non-demanding box-moving task. In the computerised box-moving task participants were presented with boxes labelled from 1 to 10 positioned in a random numerical order on the bottom of the screen. Also presented were two “tables” (represented by rectangles on screen) labelled as either “odds table” or “evens table”. Participants were required to move each of the boxes in ascending numerical order onto the relevant table. The cognitively demanding item-generation task involved participants generating a specified number of items from a provided category. For example, the category kitchen items, with items such as knife, saucepan, and toaster. The number of items to be generated was either 5, 10, or 15. Participants were informed that they could complete the item-generation at any time of their choosing e.g., before clicking any boxes, between moving boxes, or after moving all of the boxes, however, once they began the item-generation task they needed to complete it (i.e., were required to generate the specified number of items in that category) before being able to continue with the box-moving task. The authors hypothesised that most participants would complete the item-generation task first, in support of the cognitive-load-reduction (CLEAR) hypothesis, which proposes that individuals seek to reduce cognitive load as a priority by completing cognitively demanding tasks sooner. They found that half of their participants chose to complete all of the cognitively demanding tasks before performing any of the cognitively easier tasks, and most of the remaining participants chose to complete a majority of the demanding tasks first. They suggested this finding is consistent with the CLEAR hypothesis and this pattern is linked to an individual’s ‘preference’ for less-demanding tasks.

The study by VonderHaar at al. (2019) and discussion of the CLEAR hypothesis presents a useful approach for understanding why individuals choose the order of tasks that they do i.e., how task order impacts ‘choice’ or ‘preference’. It does not explain the specific impact one task has on a subsequent task, however. MacMahon et al. (2019) examined sequential task patterns (in particular, the impact of a cognitively demanding task) and tested whether results on a physical performance task (the beep test) were influenced by the prior completion of a cognitively demanding task. The participants in this study completed 30 mins of either a high cognitive load condition (incongruent Stroop task) or a low cognitive load condition (congruent Stroop task) after which they performed the beep test (an intermittent running test used as a standard indicator of fitness). MacMahon et al. (2019) found that participants withdrew from the beep test significantly earlier if they had completed the higher cognitive load task first. This demonstrated that completing a cognitively demanding task can have a significant impact on subsequent task performance and perception of effort.

Taking the results of the VonderHaar et al. (2019) and MacMahon et al. (2019) studies, it is evident that a) individuals prefer to complete cognitively harder tasks first; and b) performance on a subsequent task is impeded after completing a cognitively demanding task. In a similar fashion, the current study found that the order in which tasks were completed had significant effects on the amount of cognitive load exerted on subsequent tasks. What is unique about the current study is that we have demonstrated that the order of tasks (as opposed to preference, as we did not provide participants with a choice) influenced subsequent performance (MacMahon et al., 2019) and demonstrated this effect between two cognitive or perceptual-motor tasks (VonderHaar et al., 2019) as opposed to a subsequent physical task (the beep test). This highlights an important consideration for future research to be mindful of in designing decision making tests and tasks. Specifically, when designing decision making tests, tasks, or even training programs, attention should be paid to any tasks that are completed prior.

The findings of this study confirmed that cognitive processing increased in line with the demands of tasks, with greater processing for more demanding tasks and the demand and amount of cognitive processing is evidenced through an increase in pupil size. For cognitive tasks that are performed under time pressure and where cognitive processing may be difficult to measure otherwise (like sport action choices), pupil size as a proxy for the amount of cognitive load can be used and can distinguish between intuition and deliberation. In addition, the use of pupillometry to measure cognitive load can help researchers understand the impact of decision-making training programs and understanding the cognitive function of experts.

The findings from this study have several implications for future research and application for testing and training decision making. First, this study presents a method of measuring differences in the demands and processing for different task-specific decision-making tasks. This study showed that pupillometry (as a proxy measure of cognitive load) was able to distinguish intuitive and deliberative decision processes using a within-subjects design (that is, pupil dilation compared relative to an individual's baseline). There is a large body of work in the exercise and sport sciences (e.g., D. L. Mann et al. (2019), Hüttermann et al. (2018), Panchuk et al. (2015), also see Kredel et al. (2017) for an extensive review) that has utilised eye tracking technologies. These studies typically focus on visual search behaviours (i.e., fixations, saccades etc.,) as a process measure to compare experts and novices. These studies suggest that experts display differences in visual search behaviours e.g., fewer fixations of longer durations compared to lesser skilled individuals (Savelsbergh et al., 2002). One of the criticisms fielded against eye tracking research is that a fixation does not necessarily refer to focus of attention; that is, because an individual is looking at (i.e., fixating) a particular location in the display or environment, does not mean that they are necessarily focussing their attention on that location (Vater et al., 2020). The addition of pupillometry data (which is often already provided by the technologies used) can provide powerful insight about cognitive load, to add depth to analysis of *how* an individual is arriving at a key decision. As has been shown in this study, pupillometry can further our understanding of the automatic nature of intuitive-based decisions, above and beyond *where* an individual looks for key information.

Beyond the novelty of measuring intuitive decisions through the amount of cognitive load invested, from a practical perspective, analysing typical gaze behaviour data is generally time demanding (i.e., often requires watching videos frame-by-frame and manually digitising fixations and saccades). If pupil dilation can also distinguish between expert and novice behaviour, this has the potential to provide a more time-efficient analysis technique. Furthermore, manually digitising gaze data has an element of subjectivity. For example, deciding if an individual is fixating their gaze on the hand vs. the arm can be a subjective decision that is potentially prone to bias. In addition the definition of a fixation also varies in the literature and can range from 40ms to 100ms (McGuckian et al., 2018). Using cognitive load as the defining factor in analysis can remove some of this subjectivity. Therefore, the addition of cognitive load metrics to some of these studies, could provide further insight into expertise differences and may allow for a richer understanding of the link between visual search and cognitive load.

The finding from this study that participants who completed a cognitively 'easier' task first (i.e., the Intuitive Task) demonstrated a significantly greater increase in cognitive load when confronted with a more demanding task later did not support our hypothesis. In designing our tasks, we hypothesised that once participants were 'primed' to act deliberatively (by completing the Deliberative Task first) they would find it harder to switch to making intuitive-based choices. Our results, however, revealed the opposite effect. Rather, it seems that having participants "trust their gut" and make intuitive-based decisions essentially "primed" them to make these types of decisions and when required to make deliberative-based decisions instead, they found this more challenging, as reflected by pupil dilation and associated increased cognitive load. An alternative explanation for this finding is that Intuitive Task was generally easier than the Deliberative Task. It is possible that the Intuitive Task (face perception) is a more practiced (and perhaps easier) task that would explain the smaller difference in pupil dilation. While we don't have data in this experiment to verify this explanation, it is a consideration for future studies.

The finding that completing an intuitive-based task (lower cognitive load) may prime more intuitive processing and interfere with subsequent deliberative processing, which has a greater cognitive load (i.e., is more difficult) has an important practical application for decision making and in particular coaching or training of decision making. Research has shown that experts' first choices (intuitive) are typically the best option (Johnson & Raab, 2003). An important applied consideration for coaches based on the results of this study is that instructions can (and do) influence how individuals process information and make their decisions. Given that intuitive decision making is characterised by a lower cognitive load, or relative ease (Kahneman, 2011), asking experts to explain their decision (cognitively) potentially creates more deliberation, influencing experts' use of intuitive strategies leading to potentially poorer decision making in the next instance e.g., asking players at half time or during time outs to explain their decisions might interfere. These findings have implications for coaches and practitioners in considering how best to test and train decision making, as well as considerations for future research interested in perceptual-cognitive skills and in particular intuitive decision making strategies (Hogarth, 2011).

4.6 LIMITATIONS

There are some important limitations that must be considered when interpreting the findings of this study. First, the nature of the tasks selected (i.e., computer-based) and the eye tracking device used (monocular and head worn) posed a measurement limitation that prevents broader application of our findings. As we did not consider any expertise effects (given the generic nature of the tasks used) or included a domain-specific decision-making task, our findings are more general in nature. Based on the finding that pupillometry can detect the differences in cognitive load of domain-generic tasks, an area that future research should investigate is to expand this into domain-specific tasks and examine effects of expertise. Another limitation that was outside the scope of this study was consideration of individual preferences for intuition or deliberation. Raab and Laborde (2011) found that athletes who had a preference for intuition made faster and better choices compared to athletes who preferred deliberative decision making. It is therefore possible that the results may have been influenced by prompting participants to make decisions in a particular way, which did not align with their preference.

Similarly, in this study we did not measure Decision-Specific Reinvestment (DSR) of the participants. It is possible that individuals with low DSR scores may tend to make more intuitive-based decisions and therefore would be reflected in the pupil dilation values recorded. It has been suggested that individuals with a high propensity for decision-making reinvestment make slower (i.e., more deliberative) anticipatory decisions which is linked with disrupting the process that individuals adopt to recognise an opponent's kinematics (Sherwood et al., 2019). Finally, while the results of this study are in line with our hypothesis that intuitive decisions are characterised by lower cognitive load (measured by pupillometry), this study did not include any additional measures to verify this hypothesis. Future research should utilise additional measures to further verify this hypothesis e.g., subjective, or self-report measures.

4.7 CONCLUSION

The aim of this study was to present and test a method of distinguishing between decisions made either intuitively or deliberatively through a key component of the decision-making process, cognitive load (as measured by pupil dilation). We utilised two different tasks that required different approaches that correspond to characteristics of intuitive and deliberative decision making, in line with criterium 2 suggested by Kahneman (1973). In doing so, we demonstrated that pupil dilation, as a proxy measure of cognitive load, can be used to understand when individuals utilise an intuitive ('gut' instinct) or a deliberative decision-making process. The results of the pupillometry/cognitive load measure in these tasks supported our hypothesis and were in line with the evidence that suggests intuitive decision making is characterised by lower cognitive load. We also found that the order in which these tasks were performed influenced the level of cognitive load experienced. These findings have important implications for the way in which intuitive decision making is measured. Being able to measure *how* people make decisions, with variables such as cognitive load signalled through pupil dilation, will help us obtain more sensitive measures of skill in this difficult-to-capture area. This detail on the level of measurement can then be translated and capitalised on as a key consideration within any design and measurement within decision making training programs.

Chapter 5: Measuring the Cognitive Load of Intuitive Decision-Making Strategies in Elite Field Hockey Athletes

5.1 ABSTRACT

Understanding "how" athletes are able to make good decisions under extreme time pressures is an important area of sport science research. This study measured the cognitive load and decision-making performance of athletes and non-athletes during a hockey-specific video-based decision-making task. To measure cognitive load, pupillometry as a proxy measure was adopted. We hypothesised that athletes would make more correct decisions than non-athletes and that athletes would demonstrate the use of a more intuitive-based decision-making process involving lower cognitive load, as measured by pupillometry. Results showed that cognitive load significantly increased across the phases of each trial, irrespective of expertise. Methodological concerns and suggestions for future work using pupillometry as a measure of cognitive load during decision making performance are highlighted. This study provides a strong foundation to expand our knowledge of intuition in action choices, as a pathway to improve performance and training of this key perceptual-cognitive skill.

5.2 INTRODUCTION

Advances in the methods and technologies to test and train elite athletes have led to significant improvements in the levels of performance seen in benchmark events. These advances allow expertise researchers to examine how performers progress from beginner to highly skilled. Expertise research seeks to understand the determinants of elite performance and there can be little doubt that experts demonstrate superiority when compared to their lesser skilled counterparts (Vaeyens et al., 2007). The perceptual-cognitive abilities which underlie their expertise, however, are still relatively unclear (D. T. Mann et al., 2007; Williams, Ward, et al., 2004). One of the key abilities that demonstrate this perceptual-cognitive expertise in athletes is their decision making ability (Broadbent et al., 2015). Decision making can be defined as the ability for an individual to rapidly and accurately select a correct option from a range of presented alternatives (Raab & Farrow, 2013). As identified by Hodges et al. (2006) sport provides an excellent vehicle to study and understand the decision making process because it is highly complex, is often performed under extreme time pressures, and in many situations made additionally difficult by athletes making judgments on incomplete or (sometimes deliberately) misleading information (Pizzera & Raab, 2012). Further complicating decision making ability is that it involves movements and requires the assessment of one's own action capabilities (Bruce et al., 2012). Despite the challenges imposed on expert athletes, however, they appear to possess "all the time in the world" and are still able to make fast and accurate decisions, a time paradox described by Abernethy (1991). In this context, the aim of the current study was to measure the cognitive load and decision-making performance of athletes and non-athletes during a hockey-specific decision-making task.

The time pressures imposed on decisions in sport, as well as the presentation of misleading cues by opponents, can create "gaps" in the information that an athlete can perceive (Plessner & MacMahon, 2013). The presence of these information gaps complicates the task of making and then executing good decisions. Athletes with a high level of decision-making skill are typically those that are better able to fill in or manage these information gaps, allowing them to make better decisions.

Effective decision making skill is particularly important in fast-paced team sports which emphasise strategy and tactics (Baker, Côté, et al., 2003). Thus, understanding how athletes make effective decisions under such extreme conditions while also performing physical skills (e.g., kicking, catching) is an important area of sport science research.

Moreover, understanding how athletes manage to perform this complex component of performance can help us to develop effective training programs to enhance their abilities.

To date, much of the research on perceptual-cognitive skills in athletes has tended to examine the underlying components, such as, anticipation (Chalkley et al., 2013; Müller et al., 2006), perception (Abernethy et al., 2001), pattern recognition (Gorman et al., 2011), and knowledge base (MacMahon & McPherson, 2009), that feed into an overall decision making process. Much of the perceptual-cognitive work has also been descriptive in nature, often utilising an expert-novice approach, while fewer studies have examined the nature of - and mechanisms underlying - the differences between experts and novices (Babiloni et al., 2009) and also between better or worse decisions/actions (Loze et al., 2001).

A common method for measuring decision making in sport is to utilise video-based tests that adopt an occlusion paradigm (Farrow et al., 2005). Occlusion studies involve presenting video scenarios to participants that have information removed either temporally (e.g., pausing or stopping the video at specific time periods prior to the key action) or spatially (e.g., removing key visual cues used for making decisions), thereby replicating the "information gaps" and time pressures mentioned earlier. With respect to temporal occlusion paradigms, once the video has been paused it is at this point that the participant is required to make their decision, often instructed to perform as quickly and accurately as possible. These methods provide researchers with several dependent variables (e.g., decision time/speed, decision quality/accuracy, and number of generated options) that have been used to infer and measure decision making behaviour.

A research example that utilised the temporal occlusion paradigm to investigate intuitive decision making strategies in sport was a study performed by Raab and Laborde (2011) who examined intuition in handball situations. In their study, 54 male and female handball athletes were presented with videos of handball situations during which the video froze on a particular frame. Once the freeze frame occurred, the athletes were asked to name (as quickly and accurately as possible) the first option that came to mind for the player in possession of the ball. They were then asked to generate additional appropriate options for the player before finally considering all identified options and choosing the one they considered the best. The authors recorded verbal responses, which provided them with dependent variables of decision time, option generation time, quality of first and final options, as well as total number of generated options. Decision time was measured by using the verbal response compared to a video signal from the start of the freeze frame to the first option generated. Further, option generation time was measured from the beginning of the video (not the freeze frame) until the athlete named the best option they identified. This was an important distinction, as the authors identified that the participants may have been generating options, and consequently verbalising, during the video so capturing this period was deemed necessary. Overall, Raab and Laborde (2011) found that experts were significantly better than non-experts in generating the first and best options, suggesting the use of intuitive-based decision making approaches.

To understand the links between cognitive load and decision making, research should seek methods that go beyond recording relatively simple action choices. For example, the study presented in Chapter 4 provides evidence that pupil dilation is a proxy for cognitive load that can detect differences between decision-making approaches i.e., intuitive, and deliberative. Cardoso et al. (2019) also utilised pupillometry when they examined the declarative tactical knowledge (DTK) of 36 male academy soccer players while simultaneously recording cognitive load. Cognitive load was measured through pupillometry as recorded by a mobile eye tracking device. The study revealed that players with higher levels of tactical knowledge demonstrated reduced cognitive load (less pupil dilation) when performing the soccer-based decision-making task. The authors suggested that this reduction in cognitive load in players with higher levels of tactical knowledge may indicate a more efficient use of mental resources, in support of neural efficiency theories (Cardoso et al., 2019; Costanzo et al., 2016).

While Cardoso et al. (2019) present a strong framework for future research, there are some important considerations. Firstly, they recruited youth football players as their expert population and then split them into groups based on their levels of procedural and declarative tactical knowledge. This provided a useful comparison of how cognitive load is related to skill level. However, what is not clear from this design is if these findings hold true more broadly; that is, if they are truly expertise-based. To do this, research should seek to include a truly novice population for comparison. This then allows research to consider physiological markers of cognitive processing that are sensitive enough to detect differences between individuals with different abilities on the same cognitive tasks e.g., experts vs. novices (Kahneman, 1973).

Second, a novel approach to ascertain the link between pupil-diameter and cognitive load that Cardoso et al. (2019) adopted was to split their experimental protocol into four distinct moments related to the specific events occurring during the videos. The purpose of doing so was to allow a more precise analysis and comparison of the pupil-diameter and associated cognitive load experienced during key phases of the video presentation. The moments used were:

a. M0 – the lowest value of pupil diameter obtained from the end of the calibration phase until the end of the experiment
b. M1 (Video) – pupil diameter while the participant was watching the video
c. M2 (Verbalisation) – pupil diameter during the phase when the participant provided their verbal response
d. M3 (Rest) – pupil diameter from the time from after the verbal response was provided until the next trial started.

The work by Cardoso et al. (2019) provides one of the first studies that demonstrates pupillometry as an alternative method to measure cognitive load for decision making in sport. Based on these findings, the evidence presented in Chapter 3, and the challenges that other more complicated techniques pose, pupillometry was selected for measuring cognitive load in this context.

5.2.1 Current study

This study aimed to measure the cognitive load and decision-making performance of athletes and non-athletes during a hockey-specific decision-making task. We hypothesised that cognitive load (regardless of group) would increase during the trial before returning to resting values. Furthermore, we hypothesised that athletes would make more correct decisions and would demonstrate a lower cognitive load as shown by pupil dilation when compared to non-athletes. Finally, we hypothesised that athletes would make their decision faster than non-athletes.

5.3 METHODS

5.3.1 Participants

Participants were 10 male field hockey athletes and 7 non-athletes aged 18 to 31 years (*M* = 21.80, *SD* = 2.74 and *M* = 28.29, *SD* = 1.89 respectively). The field hockey athletes had between 10 and 22 years of playing experience (*M* = 16.40, *SD* = 3.72) and the non-athletes had no previous formal experience in field hockey. Participants gave informed consent prior to taking part in the experiment and were free to withdraw at any stage. The research protocol and study methods were approved by Latrobe University's Human Research Ethics Committee (Application ID: HEC19076).

5.3.2 Experimental tasks

Participants were required to complete a hockey-specific video-based decision-making task while seated comfortably in front of a touch screen tablet device (Microsoft Surface Go). The decision-making task asked participants to view a series of videos depicting typical field hockey scenarios filmed from a broadcast (3^{rd}-person) perspective and taken from real matches. Each trial began with a black screen and a white fixation dot presented in the centre of the screen. This was presented for one second to prepare the participant for the upcoming trial and serve as a pupil size baseline for comparison within the trial (that is, a portion of the trial where no cognitive load was assumed to be present). Following the fixation dot, the first frame of the trial video was presented for two seconds which also included a red circle around the player or location of the ball. This was used to familiarise the participant with the initial conditions of the video in the trial and served as an additional baseline pupil dilatation value.

After the initial freeze frame, the video played. At a particular pre-determined point in each video clip the video froze. A freeze frame approach (as opposed to an approach where the final frame is replaced with a blank screen) was adopted to allow the participant to indicate their decision via the touch screen. This approach is commonly utilised within the literature for examining decision making (Johnson & Raab, 2003). It was at this point the participant was required to decide what they would do next in the specific scenario if they were the player in possession of the ball. Participants did this by pressing on the touch screen device to indicate either the teammate or free space that they would pass to. Participants could also press on the player with the ball if they felt the best decision was to hold the ball or continue dribbling. No specific tactical or primed knowledge was provided.

5.3.3 Measures

Decision making accuracy

The scoring of options were assessed independently by the head coach who listed all the possible options and rated them from most to least preferable. Each clip had either three possible options (n = 17) or two possible options (n = 4). These were scored based on the least preferred option scoring one point, and then each subsequent more preferred decision scoring an additional point (up to a maximum of 3). Any decision that was not deemed appropriate by the coach was scored with a zero.

For each clip, the decision selected by the participants was compared to the responses provided by the head coach. The maximum score possible on the test was 59 when the participant indicated all the same options as indicated as most preferable by the head coach.

Pupil dilation measures

Participants completed the experimental task while simultaneously having their pupil diameter measured using an ASL Mobile Eye Tracking-XG device (Applied Science Laboratories, Bedford, MA, USA). Similar to Cardoso et al. (2019), for analysis of the hockey task, each trial was split into four distinct phases for comparisons (see Figure 5.1). The first phase was from when the initial frame of the video was presented and lasted for two seconds until the video began playing (Video Baseline Phase, VB). The second phase was the section of each trial where the stimulus video was playing (Video Phase, V) until the pause on the final frame of the video. The third phase was the period between the video freezing on the final frame and the moment the participant made their response (Decision Phase, D). The final phase (Post-response, PR) was the time from the moment the participant made their response (by touching the screen) until the next trial began i.e., the next fixation dot screen appeared. These time periods were selected to allow measurement of the differences in cognitive load experienced across each trial, as participants completed the task.

For analysis, Cardoso et al. (2019) took the average value of pupil diameter across each of the phases, with the exception of M0 which they disregarded. They also indicated that for the analysis they compared the variations in pupil diameter percentage values, although how they derived this percentage is not clear. Presumably, this percentage change reflects a percentage increase (or decrease) in pupil size compared to the M0 phase so that changes are expressed on an individual basis. Even so, the use of a singular value for baseline reference (M0) poses a possible source of noise due to random fluctuations in pupil size (Mathôt et al., 2018). To account for the impact that these random fluctuations might have on pupil diameter, it has been recommended that experimental designs consider using baseline corrections *within* a trial (Mathôt et al., 2018). This approach essentially takes a baseline value for pupil size and then uses this value for comparison in the same trial, producing pupil size relative to baseline as the dependent variable. For further analysis, this *relative change* in pupil size for each trial is then used for comparison across trials (Mathôt et al., 2018). To that end, this study used the mean pupil dilation for each of the identified phases and compared with the mean baseline values recorded during the fixation dot presentation screens and the VB phase.

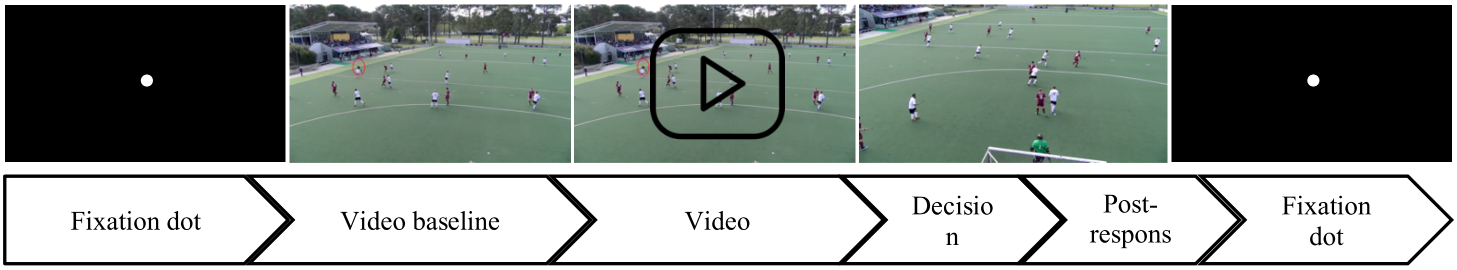

Figure 5.1 Flow diagram of the experimental procedure showing the distinct phases

Speed of decision

In addition to the pupillometry (dilation) measures recorded, the response time (RT) for participants was recorded using the stimulus presentation software. Response time was calculated as the time from when the video paused to when the participant made their decision by touching the screen (see Figure 5.1, Decision Phase).

Effects of screen luminance

To determine if there was any effect of screen luminance on pupil dilation, a correlation analysis and a paired sample t-test was performed on the baseline values for pupil dilation measured during the task (fixation dot screen and VB). The correlation analysis revealed a significantly very high positive correlation (r = 0.994, p < 0.001) between the baseline values recorded during the presentation of the fixation dot and the video baseline phase, indicating a strong relationship between the values measured during these phases. The paired samples t-test provided an additional check for any effects of screen luminance on pupil dilation during the baseline phases of the trials. This analysis revealed that the pupil size during the video baseline phase was smaller (M = 76.78, *SE* = 3.83) than the value recorded during the fixation dot phase (M = 83.90, *SE* = 4.07). This difference, -7.12, was significant, $t(16) = 14.62$, $p < 0.001$ indicating that there was an effect of screen luminance on the initial pupil size. This was likely due to the nature of the stimulus with the fixation dot, which was presented as a small white dot on a predominantly black screen. In comparison, the Video Baseline was the initial video frame with markedly less black screen. Given this difference in dilation due to the nature of the contents of the screen and the strong correlations reported earlier, for the remaining analyses the baseline value recorded during the VB phase was used as the baseline for comparisons. Specifically, changes in pupil size were compared relative to this baseline value for each video trial i.e., a positive difference indicated a relative increase in pupil size compared to the mean pupil size recorded for the freeze frame of that trial. In doing this, the difference in screen luminance was minimised, as the baseline values were compared on a trial-by-trial basis using the same video stimuli. Hence any changes in pupil size would therefore reflect changes in cognitive load.

Statistical analysis

The sample size for the current study was guided by the sample sizes and analyses conducted in similar studies, including Lorains et al. (2014; n = 6), Dicks et al. (2010; n = 8), Panchuk and Vickers (2006; n = 8), and Porter et al. (2007; n = 12). Based on a predicted moderate effect size, using G*Power v.3.1.9 (Faul et al., 2007) it was determined that a minimum number of 16 participants was required (Effect size = 0.52, Power = 0.80, p = 0.05). Given this effect size calculation, the recruited sample of 17 (10 athletes 7 non-athletes) participants was considered appropriate.

Prior to statistical analysis, the data were screened for outliers. Trials that had more than 25% of the pupillometry data missing over the course of the trial (either through excessive blinks, low quality tracking etc.,) were excluded for further analysis (Cardoso et al., 2019). This represented 5% of the total trials. Upon screening, it was discovered that two participants (one athlete and one non-athlete) had a large majority of trials that were excluded based on the criteria above. Consequently, all their trials were excluded from further analysis. Descriptive statistics are reported in Table 5.1.

Table 5.1 Descriptive statistics of the change in pupil size across phases in the decision-making task

	Video Phase		Decision Phase		Post-Response Phase		
	M	(SD)	M	(SD)	M	(SD)	n
Athletes	-0.24	(1.93)	3.32	(2.31)	6.52	(2.11)	10
Non-athletes	-1.26	(2.07)	1.97	(2.05)	6.35	(1.86)	7
Total	-0.66	(1.99)	2.76	(2.25)	6.45	(1.95)	17

For the main analysis, an independent samples t-test was conducted to compare decision making accuracy between groups. Additionally, a repeated measures analysis of variance with pre-planned simple post-hoc contrasts was used to test the effect of phase across the four time periods (Video Baseline, Video, Decision, Post-response) on pupil dilation and between groups (hockey athlete and non-athlete). In addition, for any significant effects, follow up pairwise comparisons were performed, using a Bonferroni adjusted alpha level. Mauchly's test of sphericity indicated that the assumption of sphericity had been violated, χ^2 (2) = 14.38, $p = 0.001$, therefore the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.61$). Finally, an independent samples t-test was performed to compare the RT between athletes and non-athletes.

5.4 RESULTS

5.4.1 Decision making accuracy

The independent samples t-test showed that on average, athletes scored slightly higher (M = 37.8, SE = 1.51) than non-athletes (M = 34.0, SE = 3.00) on decision making score. This difference, -3.80, BCa 95% CI [-9.810, 1.623], was not significant $t(15) = -1.24$, $p = 0.235$; however, it did represent a medium effect size, $d = 0.48$.

5.4.2 Pupil dilation

The repeated measures ANOVA revealed a significant main effect of Phase on pupil dilation, F (1.22, 47.80) = 133.49, $p < 0.001$. The analysis revealed no significant Group effect (athlete vs. non-athlete), F (1, 15) = 0.903, $p = 0.357$, $r = 2.92$. Finally, the ANOVA did not reveal any significant Phase x Group interaction effect (F (1.22, 47.80) = 0.966, p = 0.357).

To further understand the significant main effect of Phase, post-hoc pairwise comparisons revealed significant effects between each of the phases in the task (all $p < 0.001$) with the pupil dilation increasing at each phase (i.e., from Video Phase to Post-Response Phase) as seen in Figure 5.2.

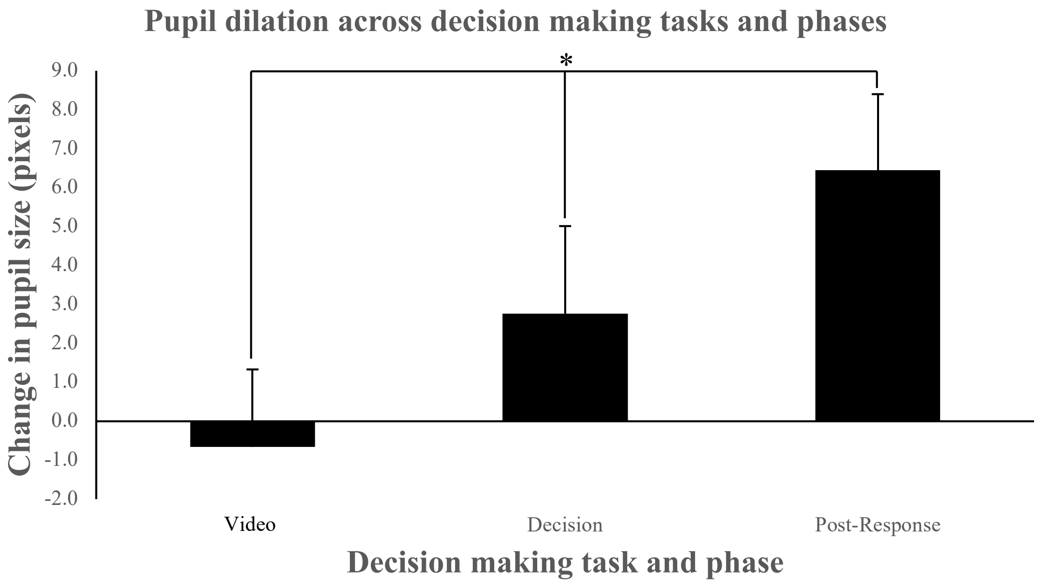

Figure 5.2 Changes in pupil dilation across phases in trial and groups. Significance: *$p < 0.001$.

5.4.3 Speed of decision

On average, athletes' response times were slightly faster (M = 2203.99, SE = 296.76) compared to non-athletes (M = 2221.68, SE = 385.36). However, this difference, -17.69 ms, 95% CI [-1038.36, 1002.97], was not significant $t(15) = -0.37$, $p = 0.971$, $r = 0.3$.

5.5 DISCUSSION

This study aimed to measure the cognitive load experienced by athletes and non-athletes in a domain-specific decision-making task. We expanded on the approach presented in Chapter 3 and utilised pupillometry as a proxy for cognitive load while participants completed a video-based hockey decision making task. We hypothesised that the hockey athletes would make more correct decisions when compared to non-athletes and that athletes would use a more intuitive-based decision-making strategy, evidenced by a lower cognitive load as shown by pupil dilation, when compared to non-athletes.

Furthermore, we hypothesised that cognitive load (regardless of group) would increase during the trial (across phases) before returning to resting values.

The main finding from the current study was that within the hockey-based decision-making task, there were distinct phases that exhibited more or less cognitive effort (as evidenced through pupil dilation) compared to an individualised baseline measure. Specifically, our results indicate that during the trials, participants' cognitive load significantly increased from the start to the end of each trial and over each of the identified phases. During the first phase (the Video Phase) where participants watched a video depicting a hockey-specific decision-making scenario, we found that pupil dilation did not increase above the individualised baseline values measured during the video baseline phase. During the phase immediately following the video pause, however, which was the point at which participants made their decision, pupil dilation significantly increased (M = 2.76, *SD* = 2.25), by 3.66%. This significant increase in pupil size indicated that participants, irrespective of group, experienced an increase in cognitive load because of the task. More specifically, participants did not demonstrate an increase in cognitive load while simply watching the video stimuli, but only when required to respond and make a decision.

This result was somewhat surprising. We expected the pupils to increase in size during the Video Phase, as the participants viewed the video playing as we presumed that participants would be processing the visual information within the video. It was assumed that during this phase, participants would first perceive information (increasing cognitive load) allowing them to then respond quickly after the occlusion point. Our results indicate, however, that participants did not engage in any cognitively demanding processing during the video, but instead waited until the occlusion point in the video to then process information and respond accordingly.

The results further indicate that after participants made their response, the cognitive load (as measured by pupil dilation) continued to increase. During this phase, which we termed 'Post-Response Phase' (from after participants made their response until the fixation dot for the next trial was presented) the pupil dilation increased a further 8.66% from baseline values (M = 6.45, *SD* = 1.95). While it is unclear what the direct cause of this finding is, a possible explanation for the increase in pupil dilation post-response is that participants were still processing and reflecting on their response. It is possible, for example, that participants following their initial response (as directed by the instructions to be as quick and accurate as possible) were still searching within the freeze frame for any alternative (and possibly better) options, or for confirmation of their choice. It is perhaps the case that participants adopted a take-the-first heuristic (an intuitive approach) and responded with the first option that came to mind that reached a particular criterion, commonly referred to as "satisficing" (Weigel, 2018). In doing so, participants were still engaged in a cognitively demanding task. We are unable to test this proposed explanation in this current study. Future work can consider this, however, by removing the freeze frame immediately following the response selection to prevent actively engaging in more stimulus search and therefore cognition.

We did not detect any differences between athletes and non-athletes on the decision-making strategy utilised in terms of cognitive effort on the decision-making task. This is contrary to our hypothesis that athletes would demonstrate less cognitive effort by adopting a more intuitive-based decision-making strategy, as indicated by less pupil dilation. One explanation for this finding is that the structure of the video-based task limited the ability for athletes to exploit their intuitive decision making and "trust their gut". One of the key elements of intuitive decision making strategies is that the ability to verbalise or provide reason is limited (Epstein, 2010), i.e., decisions are formed without conscious awareness. The current task asked participants to make a decision at a key, pre-determined, moment in time, however, not of their choosing. De-coupling the perception and action components of the decision and the angle of which the video footage was recorded may have removed or severely de-emphasised the need for an athlete to dedicate time to planning and carrying out the motor movement and thus relying on instinct to cope with the time pressure. This explanation is supported by the pupil data presented in this study which indicated that cognitive load did not increase above baseline levels until after the stimulus video had paused and participants were required to make their decision. Taking away the ability to decide "when" to make a decision and instead asking participants to actively (and arguably consciously) make an explicit decision, the task itself, potentially, forced athletes to become more deliberative.

Given that previous studies have found that experts (including athletes) utilise and often rely on intuitive decision making strategies (Hepler & Feltz, 2012; Raab & Laborde, 2011), it is possible that our study design forced experts (athletes) to act more like novices (non-athletes). This was evidenced by our finding that there were no differences in any of the performance metrics of decision-making score and response time, but also, interestingly, the process measure of cognitive load. This highlights an important consideration when designing video-based decision-making tasks aiming to examine underlying processes. It has often been demonstrated that experts perform better than novices on video-based decision making tasks (Bruce et al., 2012; Chalkley et al., 2013; Keller et al., 2018; Woods et al., 2016). Very few of these studies, however, interrogate the underlying mechanisms. It is possible that, despite scoring higher on such tests in outcome measures, the specific decision-making processes used by participants may have been different. This has important ramifications for the design of video-based training programs that aim to improve on-field decision making. If the underlying processes being tested (or trained) are different to what is utilised on-field e.g., intuitive decisions, then these tasks are limited in their ability to transfer.

Research has consistently demonstrated through a range of research paradigms that video-based decision-making tasks (and training programs) are able to detect subtle skill differences in athletes (Hadlow et al., 2018). Hadlow et al. (2018) also highlight that researchers have shown success in transferring the improved skills (on video-based training) into field-based settings through transfer tests. A concern that is discussed by Hadlow et al. (2018), however, is that occasionally video-based perceptual-cognitive training research lacks representative transfer tests (i.e., only uses computer-based tests) or fails to provide evidence of a task's reliability and discriminative validity (ability to discriminate level-based differences in performance). For example, this concern was raised by Bennett et al. (2019) who found that response accuracy in a football specific video-based assessment was able to discriminate youth academy players from novices using response accuracy. Their test, however, was not sensitive enough to determine differences in decision making performance between academy levels (i.e., higher, and lower skilled). In addition, they found that decision making performance declined (decreased response accuracy and increased response time) as the complexity of the specific situation increased.

It is also notable in the results of this study, that response times of athletes and non-athletes were not significantly different. While other studies have found similar results (e.g., Savelsbergh et al., 2002), this adds to the explanation that in this task the athletes behaved similar to novices and were not able to use their advantage (intuitive processing). Given that one of the elements of intuitive decisions is that they are generally faster (in addition to being cognitively easier) we expect expert athletes using intuitive processes to also respond faster. In addition, we asked participants to make their decision by touching a touchscreen device. It is therefore possible that the expertise effect has been masked by a response that bears no resemblance to the action that would typically be performed i.e., executing a hockey pass (Travassos et al., 2013).

An alternative explanation for why we did not find any expertise-based differences, as highlighted earlier, is that by removing the need for participants to decide “when” to make a decision, we limited the capacity for the athletes to exploit their true expertise. Participants (both athletes and non-athletes) were required to make a decision once the stimulus video had paused; however, participants had no information about when this point was approaching. They also had no information about which player in the video would be the final decision maker, therefore, there was no incentive to start the decision-making process any earlier than necessary.

5.6 CONCLUSION

We measured the cognitive load and decision-making performance of athletes and non-athletes during a hockey-specific video-based decision-making task. We hypothesised that athletes would make more correct decisions than non-athletes and that athletes would demonstrate the use of a more intuitive-based decision-making process characterised by lower cognitive effort, as indicated by pupillometry. Contrary to our hypothesis, we found no differences in response accuracy between athletes and non-athletes in the decision-making task. This was unexpected but highlights the difficulties in assessing decision making expertise and emphasises the need to carefully consider how experiments of this type are designed. While athletes did not differ from non-athletes in the amount of cognitive load during the decision-making task, we did find that the level of cognitive load increased as each trial progressed (irrespective of expertise). This increase throughout trials is indicated by an increase in pupil dilation across the phases of each trial. Besides further highlighting how pupillometry can be used as a proxy for cognitive load in video-based decision-making tasks, the current study provides insight into how decision making can be measured within expert (athlete) populations which has considerations for designing future experiments. For example, it is possible that participants with the ability to select “when” and also “what” decision they wanted to make as the video is playing, will show expertise differences in response accuracy and cognitive load. There is an opportunity for future research to consider how to overcome this design challenge. One such solution could be to utilise a similar design to Bennett et al. (2019) who had the key decision maker (player who is pivotal to the situation and who was in possession of the ball at the occlusion point) wearing a yellow training bib to identify them. Finding an appropriate paradigm will help in the quest to test pupillometry for the ability to differentiate expert and novice performers and support this method for measuring cognitive load. Doing so will advance the area and the pursuit to understand how elites are able to deal with complex environments while displaying their skill.

Chapter 6: General Discussion

The primary focus of this thesis was to enhance our understanding of how intuitive decisions in sport are utilised and how they can be measured objectively through cognitive load. The work had two specific aims:

1. To determine and test a measurement tool sensitive to detect cognitive load differences between intuitive and deliberative decisions
2. To compare the difference in cognitive load of athletes and non-athletes in a sport-based decision-making task.

This chapter provides a general discussion of the thesis and summarises the key findings of the presented studies. Details of the major contributions to theory and methodology as well as the contributions to applied practice are also presented. Finally, this chapter discusses the strengths of the thesis, limitations of the studies presented, and outlines steps for future work to investigate and further develop the groundwork laid out by the studies in this PhD program.

6.1 SUMMARY OF FINDINGS

In addressing the aims of this thesis to enhance our understanding of intuitive decision making in sport and contribute to the literature, a series of studies were presented that provide insight and novel findings into the underlying processes associated with decision making in elite athletes. In particular, the findings of these studies provide evidence that pupillometry is an appropriate methodology to examine cognitive load within the context of intuitive decision making. The findings presented also show that the amount of cognitive load exerted by individuals is influenced by the design of video-based experiments. This latter point has implications for future research designs.

6.1.1 Chapter 3: Systematic review of the tools used to measure cognitive workload in athletes

As identified in the introductory literature review of this thesis, measuring intuitive decisions in athletes poses some significant challenges. Possibly the most significant of these challenges is finding a way to measure cognitive load as a psychophysiological phenomenon that is sensitive to the task loads experienced in sport. Although there appears to be an array of feasible technologies and tools that purport to achieve the goal of measuring cognitive load in sport, no consistent approach has yet been adopted. Additionally, some technologies that have been heavily used in domains outside of sport (e.g., economics, behavioural psychology) have potential application and have been underutilised thus far.

A systematic review of the extant literature was conducted to investigate the technologies utilised to measure cognitive load in athletes within perceptual-cognitive tasks. The aims of this review were to synthesise the literature that has measured cognitive load in sport in perceptual-cognitive tasks and discuss the variability in tools chosen and specific analysis techniques.

The systematic review revealed that the most commonly used technology is electroencephalography (EEG), however, no consistent analysis technique to establish cognitive load has been applied. In addition to the lack of consistent analysis techniques adopted to establish cognitive load, the review also revealed that EEG has some barriers for application in sport. While this technology has developed (and continues to develop), EEG requires extensive calibration and is generally expensive. An additional finding was that very few studies have utilised pupillometry to measure cognitive load. This is despite eye tracking technology being used regularly in sport science research and especially in perceptual-cognitive studies in sport. With pupillometry being very portable, relatively easy to use, and generally cheaper than neurophysiological measurements, it was suggested as a key method for adoption in sport science research. Particularly given the number of published studies that have recorded gaze measures in athletes, it is possible that researchers could conduct additional analyses on existing datasets to gain further insight into the underlying mechanisms that explain perceptual-cognitive expertise. Based on this apparent gap in the literature, a series of follow up experimental studies were conducted in which pupillometry was adopted.

6.1.2 Chapter 4: Measuring intuitive decision-making strategies using pupillometry

Based on the position from the systematic review, a study was designed to test whether pupillometry is a method sensitive enough to detect the subtle differences between intuitive and deliberative decisions. The aim of the study was to measure cognitive load in two distinct domain-generic tasks. In this way, the study targeted one of Kahneman's (1973) arguments that any physiological marker of cognitive processing, such as cognitive load, should reflect differences between tasks with qualitatively different cognitive needs.

Thus, the tasks utilised were designed to elicit qualitatively different processes, with an intuitive task (face perception) contrasted with a deliberative task (using the Tower of London).

The results of this study indicate that pupillometry can distinguish between intuitive and deliberative based processes. The findings revealed that cognitive load (as measured through pupil dilation) was greater in the deliberative-based task compared to the intuitive-based tasked, supporting the hypothesis that intuitions are categorised by less cognitive load (a cornerstone of intuition decisions). Although alternative interpretations of the results are possible (e.g., arousal differences between the tasks), we presented arguments to support this interpretation. Based on this finding, we concluded that pupillometry is an appropriate measure of cognitive load in the context of intuitive and deliberative decision-making tasks.

Another significant finding from this study was that the order in which participants completed the prescribed tasks influenced the cognitive load experienced. More specifically, the participants who began with the intuitive task (lower cognitive load) subsequently demonstrated a much larger pupil dilation during the deliberative task (higher cognitive load). The results of the study in Chapter 4, therefore, suggested that after completing an intuitive (lower cognitive load, relatively easier) task, future deliberative tasks were more effortful.

6.1.3 Chapter 5: Using pupillometry to measure the cognitive load and decision-making strategies of elite field hockey athletes

Chapter 5 measured cognitive load and decision-making performance of athletes (experts) and non-athletes (novices) during a hockey-specific decision-making task, to examine the assumption that experts operate more intuitively in their domain of expertise. It was hypothesised that athletes would demonstrate lower cognitive load (as evidenced through less pupil dilation) compared to non-athletes which would also be linked to making more correct decisions.

The purpose of this study was to address the final point presented by Kahneman (1973) that any physiological marker of cognitive processing should be sensitive enough to detect differences between individuals with different abilities on the same cognitive operations. To test this, elite hockey athletes and individuals with no formal hockey experience/training performed the same video-based decision-making task. Contrary to the hypothesis, the study found no significant effect of group (expertise) on pupil dilation suggesting that cognitive load was similar between groups. The results of this study did, however, uncover a significant main effect of 'phase' during the task. Pupil dilation during the Decision Phase (when the stimulus video was paused, and the participants indicated their decision) significantly increased from baseline values and then further increased significantly during the Post-response Phase (the time after the participant's decision was made until the next trial began).

A surprising finding in this study was that there was no significant increase in pupil dilation during the Video Phase (the section of the trial where the stimulus video was playing) compared to baseline values in either group. This suggests that cognitive load did not increase while participants were simply watching the video stimuli. An explanation for this finding is that removing the requirement for experts to decide "when" to make a decision influences the amount of cognitive load participants experience. That is, because the point at which a decision was needed was not determined by the participants themselves, it is possible that they did not need (or see the need to) engage in meaningful cognition until that point was made clear to them. This feature of the task design, in which it is unclear when a decision is needed, potentially makes processing information extremely challenging while participants orient themselves appropriately to the stimuli. Indeed, many video-based decision making research studies in team-based field sports show accuracy levels in experts that can vary between 50% and 70% (Lorains et al., 2013b; Spitz et al., 2018), even in elite decision makers, showing that this approach does not fully capture elite skill. Research that has adopted perception-action coupled designs as an alternative to more static, laboratory, video-based approaches is certainly grounded in strong theoretical and practical arguments about the greater ability to capture skill through representative design (Araújo et al., 2006). There are, however, also several practical benefits of video-based tasks (Lorains et al., 2011), such as, in this case, their use to examine decision processes of intuition and deliberation. This discussion is influential, nonetheless, in remaining mindful of the influence that paradigm features have on the decision process, with implications for the design of video-based decision-making tasks.

6.2 MAJOR CONTRIBUTIONS

6.2.1 Contributions to theory

This work was focused on exploring the nature of cognitive processing for decision making in sport, with a focus on intuition. As an underexplored area, particularly in sport, and a difficult process to capture, the theoretical contributions of using sport as a domain contribute to not only understanding intuitive decision making itself, but also to the conceptual framework that describes types of decisions and their processes. Finally, this work also contributes theoretically as it highlights a paradigm to build on the relatively small volume of work in sport expertise examining mechanisms underlying expert-novice differences in perceptual-cognitive skills.

Decision types

The idea that humans arrive at decisions through the interaction of two systems, System 1 (intuition) and System 2 (deliberative) has become a popular perspective in recent years (Kahneman, 2011). Research adopting this perspective suggests that System 1 arrives at a possible solution quickly while System 2 monitors System 1 and "steps in" to help solve problems when an apparent answer is not clearly available (Moxley et al., 2012). In general, the most efficient path to make decisions is to rely on System 1 (intuitions), which is generally what occurs in humans. Within this context, this view suggests a dichotomy of decision-making processes that are either intuitive or deliberative.

While the focus in this thesis was on the popular System 1 and System 2 approach from Kahneman (2011), there are other similar dual-system approaches that exist. One such framework is implicit vs. explicit learning. Implicit learning is defined as "the process by which knowledge about the rule-governed complexities of the stimulus environment is acquired independently of conscious attempts to do so" (Reber, 1989, p. 219). Intuition and implicit learning are undoubtably linked and share many of the same features e.g., they are both unconscious (Shirley & Langan-Fox, 1996). It has also been suggested that the ability to make intuitive decisions is a result of knowledge gained through an implicit learning process (Reber, 1989). So, it may well be the case that the ability to utilise intuitive decision-making strategies, is linked to an individual's level of tactic knowledge.

What is evident through understanding the difficulty of capturing the intuitive decision-making process is that a dichotomous or dual-system view of decision-making processing (i.e., intuitive or deliberative) is overly simplistic and does not truly encapsulate the highly dynamic nature of human cognition. An alternative viewpoint suggested by Hamm (2007) and Raab and Johnson (2007b) is to instead view decision making strategies on a continuum. The argument against a dichotomous view of decision types, is that in order to categorise decisions as either intuitive or deliberative, researchers must identify a certain threshold or specific criteria (Raab & Johnson, 2007b). This raises questions such as, exactly how fast does a decision need to be to be classified as intuition? At what level of cognitive load does a decision become deliberative? As highlighted by Raab and Johnson (2007b, p. 121) without these thresholds for intuitive and deliberative decisions, research is only able to discuss decisions as being either "more or less intuitive", making a continuum view more appropriate.

Further supporting the continuum view of intuition and deliberation is work by Schelling and Robertson (2020), that addresses the range of different decisions in sport made by individuals in different roles e.g., players, coaches, and medical staff. The decisions these individuals make are governed by a range of contextual factors that shape the decision-making process adopted. A key question that Hamm (2007, p. 56) poses is "should the analytical-intuitive space be based on two dimensions rather than one?" In their paper, Schelling and Robertson (2020), present an adaptation of Hamm's Cognitive Continuum (1988) which positions different decision making situations across two axes (see Figure 6.1). The vertical axis represents the decision-making time required/afforded (from less to more) while the horizontal axis represents the predominant cognitive mode of the decision-making process, from intuitive to analytical (where analytical is another term used in place of deliberative).

In Figure 6.1, Schelling and Robertson (2020), define different 'types' of decision making situations and link these with the type of decision making process. For example, on one end of this continuum are 'in-game decisions' e.g., to pass or shoot. These types of decisions are categorised as intuitive, with less time afforded, in other words faster (System 1). On the other end of their framework is 'technology validation' (e.g., if a sport science team is deciding on what technology to purchase) which is categorised as analytical and requiring/afforded more time (System 2). In between these two extremes, however, they identify several other decisions. This is where questions are raised with the dual-process approach to decision making. For example, 'in-game live coach instructions' are identified by Schelling and Robertson (2020) as closer to the intuitive end of the continuum but not as intuitive as in-game decisions to pass or shoot, which are also more time-pressured.

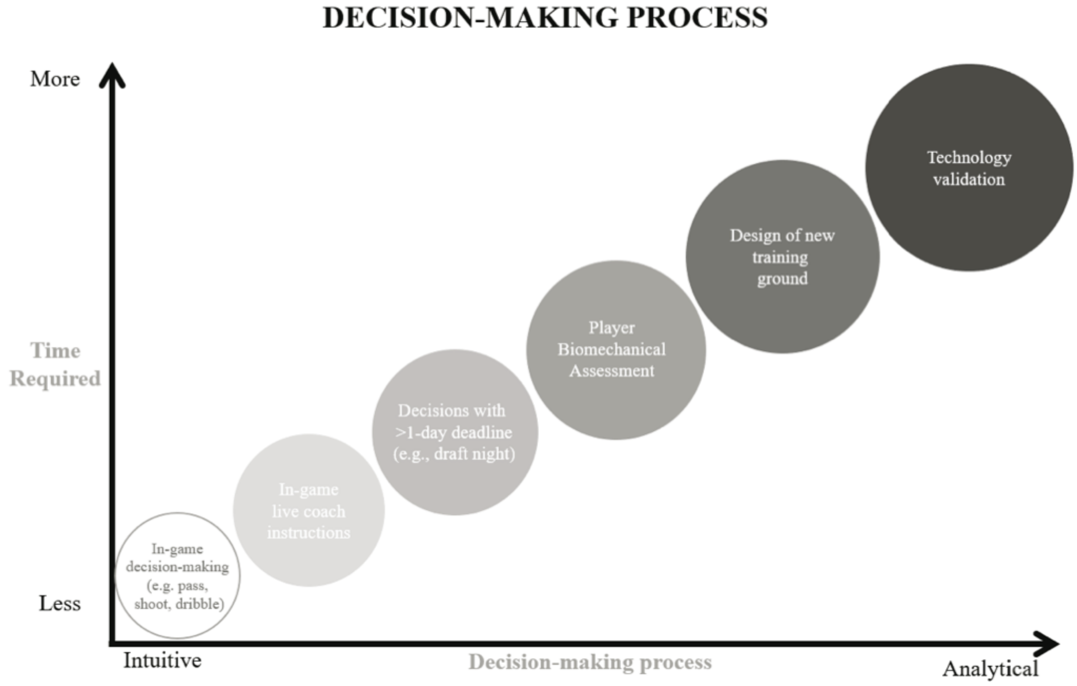

Figure 6.1: Examples of different decision-making situations. From "A development framework for decision support systems in high-performance sport," by Schelling and Robertson, 2020, International Journal of Computer Science in Sport, 19 (1).

The adaption presented by Schelling and Robertson (2020) provides a succinct conceptualisation of how a dual-process view cannot fully explain the myriad of decisions that occur within broader sporting situations. Considering the vertical axis, the amount of time required/afforded is one of the cornerstones of intuition we have identified in this thesis and supports the notion that intuitive-based decisions (like in-game decision making) would sit lower on this axis. On the other hand, the horizontal axis which indicates the predominant cognitive mode ranging from intuitive to analytical does not map as well onto the cornerstones identified in this thesis. In other words, it would be relatively easy to place a particular decision-making situation on the vertical axis (time can be easily measured) but deciding where that decision making situation should sit along the horizontal axis is challenging without a more defined measurement of intuitive decision making.

Without a more defined measurement to assist placing decision making situations along this axis, conceptually several questions arise. Are there in-game decisions that can be analytical or more deliberative? Are all in-game intuitive decisions equally intuitive? While answers to these questions are beyond the scope of this thesis, it has nonetheless provided support for a measurement tool to assist identifying the decision process (intuitive or analytical/deliberative) and where along the horizontal axis particular types of decision-making situations should be placed, through the measurement of cognitive load. Much like the vertical axis which aligns with the intuition cornerstone of *decision speed* below we propose a model that aligns the horizontal axis with *cognitive load* (Figure 6.2).

The results presented in this thesis highlight that pupillometry can be used as a proxy measure of cognitive load as a key characteristic. The model in Figure 6.2 therefore proposes the possibility of intuitive and deliberative decisions along two intersecting continua. The vertical continuum, as in the example provided by Schelling and Robertson (2020), is the amount of time afforded for decisions. The horizontal continuum in this proposed model is the amount of cognitive load decisions require. Viewing decisions in this way provides a potential framework to study and address the issues that Hamm (2007, p. 56) presents: "should the analytics-intuitive space be based on two dimensions rather than one?" and "are there two distinct types of intuition?" (in the suggestion below the second type of intuition would be decisions that are afforded more time but are still categorised by less cognitive effort).

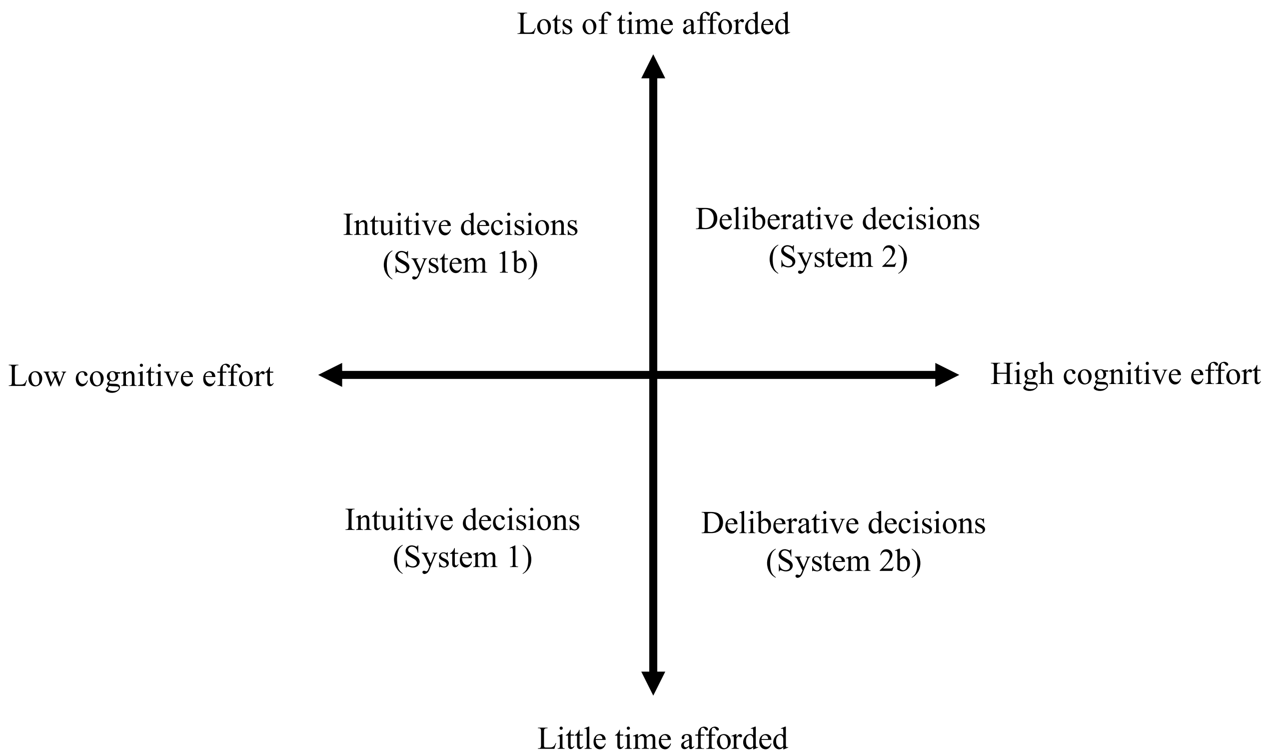

Figure 6.2: A proposed model of how decisions sit along two concurrent continua

Expert performance approach

Not only does this thesis contribute to theory and understanding intuition in general, intuition in sport, and types of decisions in sport, it also contributes to understanding sport expertise, more specifically. As highlighted in this thesis, the expert performance approach proposed by Ericsson and Smith (1991) is one of the most well-known and utilised frameworks for studying expertise. It provides three stages for empirically testing and understanding the nature of expertise. As emphasised in Chapter 2, there have been several studies within sport that have examined expertise from the perspective of the first stage of this model, capturing the performance. Indeed, research that has captured expertise, has identified that differences exist between experts and lesser skilled individuals on tasks like decision making, but research that has identified the underlying mechanisms is still emerging (stage two of this framework). Regarding the second stage of the expert performance approach, research seeks to identify the underlying mechanism of experts through process tracing measures. Typically, process measures include video occlusion (Lorains et al., 2013b; Müller & Abernethy, 2014), verbal reports (McPherson, 1999), and (particularly in sport science research) eye tracking (Kredel et al., 2017; Savelsbergh et al., 2002). To the best of our knowledge, the use of pupillometry has only been used in one other study to measure cognitive load with a specific focus on decision making. The study by Cardoso et al. (2019) found that football players with higher levels of tactical knowledge demonstrated lower cognitive effort during a video-based soccer decision making task. The lower cognitive effort measured in players with higher tactical knowledge was captured using pupillometry from a mobile eye tracking device. This provides support for the adoption of pupillometry to measure cognitive load in the studies presented in this thesis. Because Cardoso et al. (2019) only included experienced soccer players in their study, however, it is not clear if pupillometry is sensitive enough to detect differences in cognitive load between experts and novices. In addition, the focus of their study was to examine differences in cognitive load between players with higher and lower levels of tactical knowledge, not specifically on decisions that are intuitive. In contrast, this thesis did focus on intuitive decisions. It extends the use of cognitive load captured by pupillometry into intuitive decision making. Through a series of experimental studies, this thesis demonstrated that tasks that require different decision-making strategies (i.e., intuitive, and deliberative) are linked to the level of cognitive load exerted and that pupil dilation can detect these subtle differences. The findings in this thesis also highlight that different phases of decision-making tasks exhibit varying amounts of cognitive load, also detectable by pupillometry. Overall, the findings provide support for the potential use of pupillometry as a measure to understand the processes that underlie successful decision making and progress our understanding of the expert athlete's perceptual-cognitive advantage.

6.2.2 Contributions to methodology

A common methodological approach in research examining decision making in sport is the video-based occlusion paradigm. This paradigm presents individuals with video clips that have key pieces of information missing (either spatially or temporally) and has been shown to demonstrate differences in performance according to level of expertise. The occlusion paradigm is also adopted in Chapter 5, however, the thesis makes an additional important contribution to how performance is measured by going beyond the typical use of simple *outcome measures.* To illustrate, several studies have demonstrated that experts make more accurate (and better) decisions in a range of sports (Lorains et al., 2013b; Raab & Laborde, 2011). Demonstrating that differences exist between experts and novices in video-based occlusion tasks fulfills the first phase of the expert performance approach proposed by Ericsson and Smith (1991). Studies that seek to understand the underpinning reasons for these differences or processes (as in this thesis) aligns with the second stage.

As mentioned, the emerging body of literature that has examined expert performance in the second stage of the expert performance approach, to understand why experts differ, uses *process measures* such as verbal reports (McPherson, 1999), event-related potentials (Vecchio et al., 2012; M. Wright & Jackson, 2019), and eye movements (Panchuk et al., 2017; Vaeyens et al., 2007). Typically, studies using eye movements to identify the underlying mechanisms of expert decision making have focused on analysis of fixations and saccades. For example, Vaeyens et al. (2007) showed that successful decision makers spent longer fixating on the player in possession of the ball in video-based tests. Traditional eye tracking variables (e.g., fixations and saccades) can provide insight into the underlying visual processing of decision making. However, because visual search variables essentially track the regions of interest (either in video or in-situ) that experts focus on and how that differs from novices, they do not necessarily provide insight into intuitive processes, which is the specific process of concern in this work.

As highlighted in this thesis, the main cornerstones of intuitive decisions are speed and cognitive effort. In research outside of sport, speed might well be suited as a measure of intuitive decisions. This is especially the case for situations where the action choice e.g., pressing a button or a verbal response, more accurately reflects the moment a decision is made. In sport, action choices do not lend themselves as well to using decision making speed to characterise a more intuitive decision from a less intuitive one or for determining differences between experts and novices. For example, an athlete might make an intuitive (i.e., fast) decision to pass the ball to a particular player, but the actual behaviour occurs after a delay as the player waits for the right moment in time (which might be a couple of seconds). There is thus a distinction between the speed of "decision making" and the speed of which an action or response is made (e.g., to pass or to shoot), which makes measurement difficult.

An alternative measure and characteristic of intuitive decisions that was the focus of this thesis is cognitive effort. The literature shows that intuitive decision-making strategies are easier, with less effort required. The notion that intuition requires less cognitive effort was supported in this thesis. Moreover, and of key impact, is that this thesis contributes a specific method to use in understanding decision making in sport; specifically, measurement of cognitive load for sporting decisions using pupillometry.

An important contribution this thesis makes to methodology, is demonstrating that pupillometry can be used to distinguish decision processes, as a proxy for cognitive effort. While pupillometry has been utilised in fields outside of sport (e.g., Piquado et al., 2010; G. Porter et al., 2007), there is little work using pupillometry to measure sport-based decisions. In the systematic review undertaken (Chapter 3), we identified only one study that utilised pupillometry to measure cognitive load of decision making in sport. This is despite eye tracking being used extensively in sport science research for the past 40 years.

The evidence provided in this thesis contributes to the extant literature by introducing a new process measure of perceptual-cognitive skill. Specifically, we show that pupillometry can provide useful insights into decision making processes in sport. Given the variability in findings of eye tracking studies i.e., some studies show experts exhibit more fixations (Bertrand & Thullier, 2009; Roca et al., 2011) and others show experts use fewer fixations (Cañal-Bruland et al., 2011) or no difference (Savelsbergh et al., 2006), it might be the case that cognitive load (via pupil diameter) can provide additional measures and analyses. Another consideration is whether group-based analyses are best suited for studies adopting eye tracking or whether adopting an individual differences approach might be more appropriate. These considerations present the possibility for researchers to re-examine data from these studies (as pupil diameter is often also recorded, even if not analysed).

In Chapter 5, it was found that participants did not demonstrate a significant increase in cognitive load during the phase of the trial in which they were watching the video stimuli. We referred to this phase as the Video Phase, and we anticipated that participants would be searching for available options and processing key information, in preparation to make a response as quickly and accurately as possible once the video was occluded. The results suggest that cognitive load did not increase above baseline until after the video stopped. This finding was indeed unexpected, but we suggest that this might be due to the specific design of the task. We suggest that participants waited until the trial ended to engage in significant cognitive processing. Support for this view is provided as pupil diameter increased in the phase following the video being occluded, before returning to baseline levels again before the next trial.

The finding that participants did not spend time processing during the video clip, but rather at occlusion has implications for how researchers design video-based tasks, and methodology going forward. In many of the studies that have found expert-novice differences in decision making, more details are provided (or are available naturally) to the participant about the developing situation. For example, in studies examining anticipation in cricket batting, participants are aware of the specific response they need to make ahead of time (e.g., type of delivery and ball length) and have a general idea of when the video will be occluded (participants know it will occur at or around ball release) (Müller et al., 2006). Similarly, in studies in racquet sports (Farrow et al., 2005; Singer et al., 1996) participants make decisions about the location and type of serve, knowing roughly when a decision is required. This is not the case for less-structured, open sports like hockey.

A further important contribution this thesis makes to methodology is highlighting that task order relative to task type can influence the level of cognitive load experienced. In Chapter 4, the results suggest that the decision making during the deliberative task (Tower of London) was more effortful when it was preceded by an intuitive task (or relatively easier). Previous research has similarly demonstrated that cognitive task performance can influence the effort, manner, or order in which a subsequent task is selected by individuals (VonderHaar et al., 2019) and can negatively influence subsequent physical task performance (MacMahon et al., 2019). What is important to note, however, is that athletes during match play (particularly team sports) have multiple demands in terms of load – not just physical but also cognitive, and that cognitive load is underexamined but potentially influential. So, if in matches players are doing both aerobic and perceptual-cognitive tasks (decision making), researchers and practitioners should be aware of this in designing studies and interventions. This is an area that future work should investigate, and the methodologies presented in this thesis can serve as a design for such studies. Overall, the findings presented here have important implications for future work adopting a similar methodology to measure cognitive load in decision making contexts.

6.2.3 Contributions to applied practice

The findings of the work presented in this thesis make important contributions to applied practice in a range of ways. Primarily, the use of pupillometry as a measurement of cognitive load within the context of intuitive decision making presents an opportunity to enhance a) how we can test decision making in practice, and b) possible training methods for decision making.

How we can test decision making in practice

As highlighted throughout this thesis, measuring decision making in athletes is a particularly challenging task due to the myriad of factors that contribute and influence performance. Intuitive decisions present additional challenges to researchers and applied practitioners to understand not only if an individual uses intuition but also when. The studies presented in this thesis provide some early evidence on a method that may assist practitioners and researchers in understanding the situations when athletes rely on intuitive decisions. In several studies that test decision making in athletes, it is common to adopt an approach whereby participants provide verbal reports of the options generated (e.g., Raab & Laborde, 2011; Roca et al., 2011; Ward et al., 2011). For example, Raab and Johnson (2007a) suggested that when an expert selects the first option they think of, it is often the best and correct decision. This suggests that experts adopt a "take the first" heuristic and is supported by the finding that the handball experts in their study indicated that their final decision matched with their initial decision 60% of the time. A study by Buszard et al. (2013) extended this work by examining the influence of instructions on decision making accuracy in Australian football players. In their study, participants were instructed to either "take the first option (TTF)", "keep the ball away from the loose defender (LOOSE)" or were not provided with any specific instructions (NI). A particularly novel approach adopted in this study was to confirm, through eye tracking analysis, that participants had indeed adhered to the instructions. The authors confirmed that the participants in the TTF condition fixated on their final decision early in the fixations

The analysis of visual search behaviour to provide evidence that the athletes followed the instructions provided was novel, but it alone does not suggest that the athletes actually adopted the take the first heuristic as an intuitive strategy, or indeed if athletes adopt other intuitive decision-making strategies. Considering that heuristics are basic “rules of thumb”, it is possible that the group in the LOOSE condition also acted intuitively, albeit with a different heuristic. The results of the studies presented in this thesis, however, provide a potential analysis technique that may give further insight into the use of intuitive decision-making strategies. By including objective measures of cognitive load e.g., pupillometry, future research would be able to categorise decision making strategies, such as those in the Buszard et al. (2013) study, as more or less intuitive. Knowing that intuitive processing is less effortful, saving resources that can potentially be allocated to other tasks (e.g., skill execution), and assessing the degree to which an athlete is processing intuitively allows for the identification of those who may benefit from intervention and training.

Possible training methods for decision making

The ability to improve the decision making ability of individuals through training programs is an area of interest in applied sport science (Lorains et al., 2013a). Building on the knowledge of the characteristics that distinguish the elite from the sub-elite, researchers can design training methods to provide performance enhancements. While it is acknowledged that in-game performances are an important form of practice to enhance decision making, given there are often limited number of matches possible and athletes spend more time in their week in targeted training activities, research has investigated the potential for video-based training methods (Kittel et al., 2019). Despite an emergence of research investigating intuitive decision making in sport, there is still limited research that has examined training methods, particularly with regards to intuitive decisions.

6.3 RESEARCH STRENGTHS

The main strengths of the work presented in this thesis are highlighted below. This thesis identifies key areas that the research to date has been lacking and presents studies that have extended on previous research in several ways.

1. The work presented is grounded in well-founded and theoretically supported underpinnings, drawing on research from relevant fields beyond sport.
2. The work presents a strong understanding of the existing literature through a systematic review of the existing literature (Chapter 3) that is also mindful of the unique challenges of sport.
3. The research adopts an underutilised, but well-founded and objective, measurement approach by using pupillometry to measure cognitive load.
4. Presents studies in a controlled environment and with carefully designed tasks that allow for measurement in tasks with distinctively different processes required (i.e., intuitive, and deliberative).
5. Utilises a sample of elite athletes currently playing at the highest level, which adds to the strength of the studies.

6.4 RESEARCH LIMITATIONS

The research presented in this thesis presents novel approaches that provide substantial theoretical, methodological, and practical contributions. However, there are some limitations which are important to consider when interpreting and evaluating the findings. Outlined below are the limitations of this thesis, which future research can seek to address and further develop.

- The use of a video-based decision-making task that was decoupled from action is a potential limitation of the studies presented. Striking a balance between examining decision making in natural environments and approaches that allow for greater experimental control (which is a strength of the research presented) is an area that has been an issue in sport science research for some time (Farrow & Abernethy, 2003). Despite the benefits of video-based decision making testing and training, such as removing the need for any physical loading and allowing injured players to partake (Lorains et al., 2013a), some research has suggested that reducing the specificity of an action response (i.e., touch-screen vs. actual movement) potentially limits the applicability of these approaches (Bennett et al., 2019). While the studies presented in this thesis utilised a decoupled action (i.e., touch-screen response), this level of control allowed for a comparison between the generic decision-making tasks and the hockey decision making task. Additionally, given the need to account for external factors that could influence pupil size and the preliminary nature of this work, the use of video-based approaches was warranted. Nonetheless it does present a limitation to the findings discussed in this thesis and therefore the results should be considered from that context.

- The chosen domain-generic decision-making tasks in Chapter 4 (i.e., face perception and Tower of London) makes the findings of this study more generic in nature. The purpose of selecting these tasks was two-fold. First, to compare tasks that would prompt different processing strategies. Second, to focus on task differences, and limit a potential expertise effect. In doing so, however, while the results provide support for pupillometry as a measure of cognitive load, the general nature of the tasks potentially limits the applicability into decision making tasks more broadly.
- In the studies presented in this thesis, we did not measure individual preferences for intuition or deliberation (using for example the Preference for Intuition/Deliberation (PID; or the Rationality-Experientiality Inventory-(REI)). Research suggests that athletes who have a preference for intuitive decisions make faster and better decisions compared to athletes classified as deliberative (Raab & Laborde, 2011). As each individual's preference for intuition and deliberation was not recorded in the studies presented in the thesis, we are unable to make inferences about how preferences may play a role in the utilisation of intuitive decision-making strategies and consequently the underlying cognitive load that was experienced.
- While the use of pupillometry has many years of evidence supporting its use to measure cognitive load in fields outside of sport science (e.g., psychology, driving, and medicine), its use in sport science research is still limited. We present one of the first studies to utilise pupillometry in measuring underlying mechanisms of decision making in sport, and one of the only studies

specifically focused on pupillometry for intuitive decisions in sport. Although there is strong evidence that supports the sensitivity of pupillometry in measuring cognitive load, there are several other factors that can also influence pupil size, such as ambient light. While research (including the studies presented in this thesis) can account for these factors, this still poses a potential limitation. Additionally, using pupillometry as a proxy measure for cognitive load poses a possible limitation because it is not a direct measure of cortical activity. While the challenges of more direct measures of cortical activity (e.g., EEG, fMRI) are highlighted in this thesis, these are nonetheless alternative or additional options that researchers have utilised. Given the early stages of the work using pupillometry for cognitive load measures in sport, the findings presented in this thesis should be considered with caution.

6.5 FUTURE RESEARCH

This thesis has advanced the research investigating intuitive decision making in sport and provides a platform for future work to continue developing. Given the relative infancy of this body of work, there is scope for future work to further develop the theoretical underpinnings presented in this thesis. It is recommended that future work seeks to build upon the work completed in this thesis to allow new knowledge to be gained and increase the practical applications of this research. The ideas that follow, while not an exhaustive list, provide some considerations for future research to consider that will advance our understanding of intuitive decision making within the sporting domain as well as fields more broadly.

6.5.1 Sport research

In Chapter 5 of this thesis, we did not find any expertise differences (decision accuracy or cognitive load) in the hockey decision making task. This was surprising but may be due to the task using stimuli that were too easy. It is also possible that the video-based nature (completed on a touch screen device) and viewing perspective limited the expert hockey athletes' advantage. Future research should address these limitations by introducing more difficult video clips and including a coupled motor response. Adopting these suggestions may tease out more expertise differences which can then be further supported through pupillometry measures of cognitive load.

Beyond examining intuitive decision making in athletes and examining other sports with similar time pressures (e.g., football, handball, basketball) to expand the research base, two other specialist roles within sport also provide an opportunity for future research, namely coaches and referees. Sports officials also make decisions that are time-pressured, performed under physical fatigue, and often highly scrutinised by athletes, fans, and the media. Different types or categories of sports officials also range in their level of interaction with the environment and the number of cues that need to be monitored (e.g., gymnastics judge versus football referee) which leads to different categories of officials (Plessner & MacMahon, 2013) who may have different intuitive decision making requirements. For example, future work could examine the difference between a basketball referee who needs to make quick decisions as situations occur while simultaneously considering elements of "game management" compared to scenarios where they use video-based replays to assist in decision-making.

Finally, as there is an abundance of eye tracking research in sport science that had utilised eye tracking devices, there is potential for future research to re-examine this data from the context of cognitive load via pupillometry. While it is acknowledged that not all experimental designs used in eye tracking research to date are conducive to pupillometry analysis, nonetheless this presents a possible opportunity. In particular, given there have been mixed results with regards to simple gaze metrics (e.g., number of fixations), pupillometry may provide additional insight into the underpinnings of decision-making performance in scenarios were expert-novice differences are found.

6.5.2 Other domains

The primary field of interest in this thesis was elite athletes, however, the presented methods and results provide an opportunity to expand into fields outside of sport. For example, in any field where decisions are made under extreme time pressures, with missing or incomplete information, intuitive decision-making strategies may provide a framework to understand expertise. Such examples could include clinical decision making i.e., doctors, nurses, paramedics, or indeed other healthcare professions. While these fields are beyond the scope of this thesis, these areas present as additional opportunities for future research.

6.6 CONCLUSION

This thesis details a series of studies conducted as part of a PhD program that investigated the underlying psychophysiology of intuitive decision making in elite athletes. The studies presented represent a substantial contribution to the extant literature and advances our understanding of the delicate mechanisms that underpin expert decision making. This thesis has contributed to the theoretical understanding of the types of decisions that experts make and highlights that dual-process models of intuition are perhaps too simplistic to capture the complexity of decision making in sport. As suggested by Hamm (2007) and Raab and Johnson (2007b), it is useful to view intuition as sitting along two continua rather than as dichotomous. While to our knowledge no model currently exists to categorise the intuitive or deliberative nature of different sport decisions in a way similar to Kahneman's System 1 and system 2, Figure 6.2 suggests how such a model might look and acknowledges that there are many types of decisions that might be investigated in this context. While this thesis does not provide insight into how intuitive decision-making strategies are *developed* in experts, it presents a methodology that is capable of measuring cognitive load as a proxy for intuitive decisions. This is an important step, as understanding if experts are making intuitive decisions opens the opportunity to design and implement training programs that seek to improve this ability. Finally, the findings presented in this thesis build an evidence base that supports pupillometry as a measurement tool for intuitive decision making that can inform future research in this area.

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