PERCEPTUAL-COGNITIVE EXPERTISE IN CRICKET UMPIRES DURING LEG BEFORE WICKET DECISION MAKING

PRAVINATH RAMACHANDRAN

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Contents

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Abstract

Perceptual-cognitive skills have been shown to contribute towards elite performance in multiple domains and sports, including cricket. However, research examining these skills in cricket has predominantly focused on batters, with little attention devoted to extensively exploring the factors that contribute towards expert cricket umpiring. In this thesis the 'expert performance approach' proposed by Ericsson & Smith (1991) was used to develop a series of studies that examined the influence of perceptual-cognitive skills in leg before wicket (LBW) decisions made by cricket umpires. In Chapter 2, eye movement data was collected from expert and novice cricket umpires whilst they performed a simulated LBW decision making task. In addition to making more accurate decisions, the expert umpires demonstrated a tendency to anchor their gaze on the stumps, whereas the novices showcased a preference to fixate on the pitch. In Chapter 3 a different sample of expert umpires were required in one condition to make a 'no-ball' verdict prior to an LBW decision and in another condition to exclusively make the LBW decision with no preceding task. The 'no-ball' task aimed to engage the shifting function of the umpire's working memory, to better mirror match demands. The purpose of this Chapter was to examine whether switching from the 'no-ball' task to the LBW task would negatively affect the umpire's decision-making performance in line with the 'switch cost' evidenced in cognitive psychology literature. In corroboration with the switch-cost, umpires were less accurate at determining where the ball bounced on the pitch when required to task-switch. Also, in line with previous research, following the task-switch the umpires were more likely to allocate their gaze towards 'other locations' compared to when performing the LBW task exclusively on its own. Despite this, umpires still displayed a tendency to anchor their gaze on the stumps in both conditions. Chapter 4 utilised

findings from Chapters 2 and 3, and involved the implementation of a Quiet Eye training intervention in novice umpires with the aim of augmenting LBW decision making. To compare the effectiveness of this intervention, novice umpires were allocated to either a Quiet Eye Training, Technical Training or Control group. The Quiet Eye intervention led to improved LBW performance across all components of the task immediately following training, and these effects persisted in a one-week retention test. Immediately after the intervention, the Technical Training group reported improvements on determining where the ball would have travelled post ball-pad impact however these effects were lost in a one-week retention test. The Control group reported no changes in accuracy across all three experimental phases. With all the experimental chapters considered, this thesis provides insights into the perceptual-cognitive skills cricket umpires use to cope with the unique demands on LBW decision making, and how these skills can be transferred to novice performers to expedite more accurate decisions. These data have implications for improving decision making throughout the cricketing pyramid, as well as theoretical implications for understanding the role of visual attention in complex decision making tasks.

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Chapter 1:

Review of Expertise, Perceptual-Cognitive Skill, and Sports Officiating

"The umpire at cricket is like the geyser in the bathroom; we cannot do without it, yet we notice it only when it is out of order. The solemn truth is that the umpire is the most important man on the field; he is like the conductor of an orchestra."

(Neville Cardus, May 1934)

1.1 Umpiring

The abovementioned words were penned by Neville Cardus in the 1930's, however some 90 years later, the statement remains accurate. Whilst a number of regulations within cricket have been amended and innovated over this period (Vamplew, 2007), for over a century the umpire who stands at the non-striker's end (Figure 1.1) has held the responsibility of adjudicating decisions regarding batter dismissals that consequently determine match outcomes (Sacheti et al. 2015).

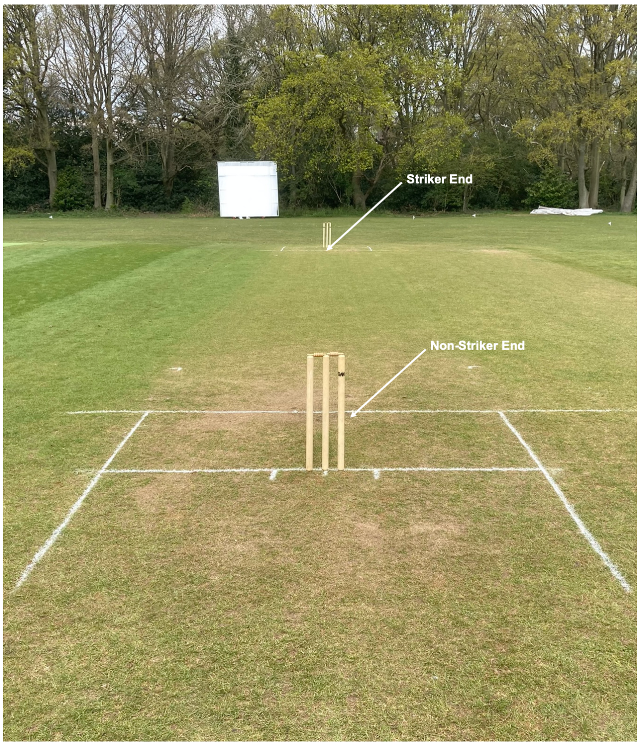

Figure: 1.1: Umpire viewpoint of the pitch. The bowler delivers from the 'Non-Striker End' towards the batter at the 'Striker End'**.**

Currently an appeal to dismiss a batter can be made via ten methods; caught, bowled, leg before wicket, stumped, run out, timed out, hit wicket, obstructing the field during play, handling the ball, and double hitting of the ball. Of these modes of dismissals, none has consistently led to as much controversy and dispute as the leg before wicket (LBW) (Chedzoy, 1997; Sancheti et al. 2015; Southgate et al. 2008). LBW appeals occur when the ball impacts the batter on any part of their body (usually leg pads) apart from the bat and hand(s) holding it (Craven, 1998). For a bowler to dismiss a batter via LBW, the umpire must consider whether the delivery meets a number of technicalities before reaching an out/not out decision (Crowe & Middeldorp, 1996). However, Law 36 of the 2017 Marylebone Cricket Club (MCC) laws of cricket states that before even considering an LBW appeal, an umpire must determine the legality of the delivery, whereby part of the bowler's shoe must land behind the popping crease upon releasing the ball. Following this, for an LBW appeal to be considered out, the ball must firstly pitch (bounce) in line or on the offside of the stumps (Figure 1.2). If the ball pitches on the legside of the stumps then an umpire must not deem the batter out under any circumstances (Figure 1.2). Law 36 provides further technicalities surrounding where the ball strikes the batter in relation to the stumps. Should the batter make a genuine attempt to hit the ball with the bat, then for an umpire to consider giving them out the ball must strike them in front of one of the stumps. Conversely, should the batter not attempt to hit the delivery, the umpire can consider making an out decision even if they are struck by the ball outside the line of off stump. Following the deliberation of these technicalities, the umpire must finally arbitrate whether they believe the ball would have continued on its flight path to hit the stumps had the obstruction with the batter not occurred (Southgate et al. 2008). With this final rule considered, the LBW decision appears to be unique amongst sports in that the official must determine what might have happened (would the ball have hit the stumps?) if other events did not occur (ball flight path being obstructed). Consequently, the subjectivity of each appeal contributes to the dispute amongst players, the media and followers of cricket (Crowe & Middeldorp, 1996). Further complexity to the task is added as an umpire must also account for a number of contextual determinants of an LBW appeal, such as the batter stance (Southgate et al. 2008), deviation of the delivery away from typical trajectory (spin and swing) and the ball's surface degradation (Chalkley et al. 2013).

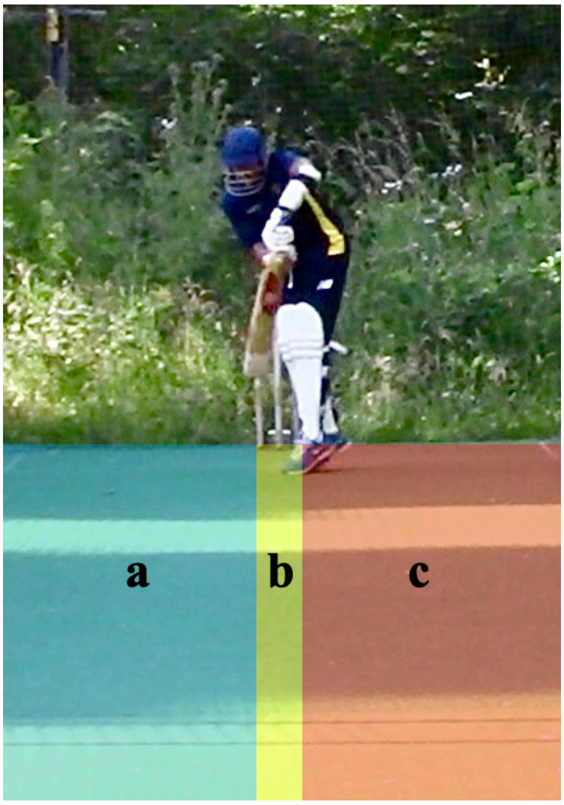

Figure: 1.2 a) off side of the stumps to a right-handed batter b) in-line with the stumps c) leg side of the stumps to a right-handed batter

Prior to 2008 the umpire would simply adjudicate LBW appeals by providing an out/not out decision which would be accepted by both teams irrespective of their own opinions. However, the landscape of umpiring was to change forever in 2008 as the International Cricket Council (ICC) introduced the Decision Review System (DRS) into International Cricket. The DRS enables captains of either team to refer the decisions made by the on-field umpires to the third umpire who has an array of replays and technologies at their disposal to assess the accuracy of the original decision (Borooah et al. 2016). Should there be sufficient evidence, the third umpire can overturn the on-field umpire's original decision in favour of the team who requested the review (Borooah et al. 2016). Utilising statistics between the inception of DRS (July 2008) and March 2017, ESPN Cricinfo analysed the reviews made in Test Cricket (http://www.espn.co.uk/cricket/story/_/id/19835497/charles-davis-analyses-use-drs-players-teams). It was found that approximately 74% of the reviews made by players were for LBW appeals, with the overturn rate being at 22%. One such technology at the third umpire's disposal to assess LBW reviews is Hawk-Eye, a Reconstructed Track Device which provides a 3D simulation of the ball's flight path had the obstruction not occurred (Collins, 2010). Hawk-Eye technology employs 6 cameras that feed images into a computer which enables the ball's location to be coordinated into a data point at every frame (Borooah, 2016). Based on the theory of triangulation, Hawk-Eye then measures the angle between each data point to ultimately create a 3D trajectory of the ball flight, whilst additionally helping determine the deliveries' speed, angle and deviation of the flight path (Duggal, 2014). Whilst the benefits of Hawk-Eye are plentiful, Hawk-Eye is subject to statistical error due to 'gaps' between each data point of each frame (Collins, 2010). Currently it is estimated that the inaccuracy of Hawk-Eye is 55mm wide and thus, if any review comes within this zone of the stumps and the on-field umpire's call remains (Collins, 2010). Technology such as Hawk-Eye has inadvertently placed on-field umpires under increasing scrutiny (Collins & Evans 2012).

As Neville Cardus highlighted, umpire's decisions often garner attention only at times of inaccurate judgement as opposed to the numerous instances where successful verdicts are made. The increased use of technology which aimed to aid umpire decision making has inadvertently led to poor decisions being further scrutinised (Collins & Evans, 2012). In some instances, these inaccurate decisions have led to umpires being labelled as inept and in extreme cases corrupt (Heffer, 2016). Whilst it would be easy to leap conclusions of unprofessionalism and ineptness of umpires at the first sighting of an error in judgement, it must be emphasised that these officials are often placed under acute time constraints in which to make these decisions (Chalkley et al. 2013; Southgate et al. 2008). In some instances, the ball (7.29cm) can travel at velocities up to 150kmh/93mph over 20m which serves them approximately 543ms to process the visual information necessary to generate a decision (Southgate et al. 2008). Despite these constraint's, Adie et al. (2020) found that elite cricket umpires are extremely accurate when making LBW decisions. Examining 5578 LBW decisions in elite cricket between 2009-2016, umpires were correct 98.08% of the time. Despite the overarching limitation that appeals were retrospectively reviewed by the match referee subjectively without use of ball tracking technology, it was clear that umpires are exceedingly accurate at making decisions in response to LBW appeals. To help combat the enormous time constraints they are faced with in order to make accurate decisions, it has been proposed expert umpires employ specific visual behaviours to increase the likelihood of generating correct decisions (Southgate et al. 2008). Whilst these visual skills have not been specifically evidenced in expert cricket umpires, such behaviours have been evidenced to increase decision making accuracy in a number of fast ball sports (Broadbent et al. 2015). Any specialised visual skills that can be used to facilitate umpire decision making under these immense time constraints must be explored in order to ensure justice prevails at every level of the game, and that incorrect decisions which can affect player's careers and the outcome of matches (Craven, 1998) are minimised.

1.2 Visual System

It has been suggested that the primary purpose of the visual system is to enable the construction of an 'internal model' of the external environment in order to guide visually based thought and action (Milner & Goodale, 1995). Perhaps then, the principal sensory system required for cricket umpiring is the visual system. Unlike most sporting tasks, cricket umpiring has perceptual and cognitive elements, but not a specific action outcome. Therefore, it is important to outline some of the background theory relating to the differences between 'vision for perception' and 'vision for action'.

The visual system is responsible for converting electromagnetic waves from the external environment into a series of synapses that carry visual information to various regions of the brain for processing (Remington, 2011). The first cells found in the visual pathway, known as photoreceptors, are responsible for the initial conversion of light into a neuronal signal. Photoreceptors comprise of cones and rods; cones being essential for high visual acuity and colour vision, whilst rods are responsible for peripheral vision (Hubel, 1988). Around 4.6 million cones occupy the retina which accounts for approximately 5% of the photoreceptors in both eyes (Lamb 2016). The remaining 95% is comprised by over 85 million rods (Lamb 2016). The neuronal signals in the photoreceptors are then transferred to the bipolar cell, then to the amacrine cell and finally the ganglion cell before it leaves the retina (Remington, 2011). Upon exiting the retina, the signal travels via the optic nerve, to the optic chiasm where information from each eye crosses to the alternate side of the brain, before travelling into the lateral geniculate nucleus (LGN). From the LGN, the visual information travels to the primary visual cortex located in the occipital lobe of the brain, specifically in Brodmann area 17. From here, it has been suggested that visual information is projected via two separate visual streams that can be distinguished on both anatomical and functional grounds (Milner & Goodale, 1995).

In a series of lesion experiments on rhesus monkeys, results from Mishkin and Ungerleider (1982) first established somewhat distinct cortical streams for processing object features and their spatial positioning. Since then, a series of human studies have found that like in rhesus monkeys, humans also possess two separate visual streams, one for perceptual feature-based discrimination and the other for determining the spatial positioning of objects within the environment to help guide visuo-motor behaviours. Firstly, the ventral stream, which is projected from the visual cortex to the inferior temporal cortex reportedly performs a critical role in providing an individual with a comprehensive representation of the external world by enabling cognitive operations such as identification and recognition of objects (Lee & Donkelaar, 2002; Milner & Goodale, 2005; Valyear et al. 2006). Transformation of visual inputs into these representations permit individuals to deliberate and contemplate about objects and events in the real world (Milner & Goodale, 2008a). Conversely, the dorsal stream, which is projected from the visual cortex to the posterior parietal cortex, is reported to process spatial characteristics such as size, shape, disposition and coordinates of objects to guide motor actions (Lee & Donkelaar, 2002; Milner & Goodale, 2008a; Valyear et al. 2006). Therefore, the dorsal stream holds a critical role in mediating actions such as reaching and grasping by constantly processing and updating spatial information of an object in relation to other objects and the effector(s) being used in the action (Milner & Goodale, 2008a). Evidence for the separate visual streams has been evidenced in patients suffering from visual form agnosia and optic ataxia (Milner & Goodale, 1995). Perhaps the most frequently studied patient with visual form agnosia was patient D.F, a lady who was brain damaged due to accidental carbon monoxide intoxication (James et al. 2003; Milner et al. 1991). In a number of experiments, Milner et al. (1991) found that patient D.F maintained the ability to anticipate and coordinate visually guided motor behaviours. Specifically, she was able to insert both her hand and a card, into a 12.5cm x 3.8cm disk slot that was orientated at 0°, 45°, 90° or 135°. However, patient D.F was incapable of making an accurate perceptual judgement on the same task when required to express how she would orientate her hand or the card verbally, nor by using tactile or visual feedback. Similar findings were made by James et al. (2003) who additionally showed patient D.F exhibited the expected neural activation in areas associated with the dorsal stream, however a lack of activation of the lateral occipital cortex, a region attributed to the ventral stream. Such results suggested patient D.F had lost visual form perception due to a damaged ventral stream, whilst her visuomotor control remained due to an intact dorsal stream.

Contrary to visual form agnosia, patients suffering from optic ataxia have been shown to display impaired visuomotor control whereas their feature based discrimination processes remain intact (Milner & Goodale, 1995). For example, patients with optic ataxia who had parietal lesions in Perenin and Vighetto (1988) performed a similar hand reaching task to that in Milner et al. (1991). Unlike patient

D.F, optic ataxia patients made several errors on this task suggesting damage to the dorsal stream impaired their visuomotor ability.

Whilst the evidence is compelling for a dissociation between ‘vision for action’ and ‘vision for perception’ processing streams, Milner and Goodale (2008a) admitted that lesion studies are somewhat imperfect due to damage very rarely being uniformly localized in a specific region. Eysenck & Keane (2010) also further state that it is difficult to make concrete predictions when testing this theory due to most visual tasks requiring both visual streams to some degree. Nevertheless, they also stated that at the time of writing the two-stream model remains the most influential theory to explain visual processing and that no existing alternate theory was superior. (Milner & Goodale, 2008a; Van Der Kamp et al. 2008; Abernethy & Mann, 2008).

Considering the dorsal stream functions primarily as a visuo-spatial processor, numerous researchers have speculated on and studied its role in sporting activities. For example, Sasada et al. (2015) found that college baseball players were less capable of identifying the colour of a ball thrown at them than novice baseball players. The authors suggested the expert’s utilised the dorsal stream to intercept the projectile at the critical time point, and therefore were unable to report on its colour change effectively due to reduced activation of the ventral stream. Milner & Goodale (2008b) further suggest that the dorsal stream performs a critical role in sporting activities such as fielding in cricket whereby it provides the performer with an unconscious processing of visual information so that they can control the mechanics of their movement in response to the trajectory of the ball. Based on the current evidence within sport and additionally a commentary from Milner & Goodale themselves, the dorsal stream has been offered as the principal visual system responsible for online control of a motor action when intercepting a projectile. Whilst a motor component is not a requisite of cricket umpiring, findings from Zachariou et al. (2014) highlight that the dorsal stream also performs a role in identifying and differentiating the spatial position of an object in relation to other objects (Zachariou et al. 2014). In the first experiment of this study, using fMRI the researchers aimed to identify the contribution of both visual streams in two distinct tasks. In one task, for each trial participants were presented with two objects on either side of a screen, and were required to detect whether they were identical or differed in shape. This task aimed to identify cortical activity associated with detecting shape features. In the second task, participants were presented the same objects on either side of a screen, but this time were required to determine whether their spatial positionings were congruent or incongruent with each other in relation to a central line. This task aimed to identify the cortical activity associated with detecting object spatial characteristics in relation to other objects. In line with the two streams theory, shape feature detection resulted in primary blood oxygenation level dependent (BOLD) levels in the lateral occipital cortex located in the occipital lobe and fusiform gyrus located in the temporal lobe, with both of these regions forming parts of the ventral stream. Also in correspondence with the two streams theory, detecting the spatial positioning of objects led to primary BOLD levels in most anterior and posterior portions of the intraparietal sulcus located in the parietal lobe, this region being part of the dorsal stream. However, shape detection also led to non-primary, but significant, activity in regions associated with the dorsal stream suggesting spatial processing also occurs during shape feature detection. However, object spatial task performance did not result in increased BOLD levels in any ventral stream regions. This asymmetry suggests that whilst some forms of feature detection also rely on dorsal stream processes, the dorsal stream is solely responsible for processing object locations with relation to other objects. Whilst most studies examining the dorsal stream have focused on vision for action (usually grasping movements) from an egocentric perspective, Zachariou et al. (2014) appeared to be the first study to highlight that this visual system also contributes to identifying object locations with relation to other objects from an allocentric perspective. This in turn highlighted the dorsal stream's function irrespective of whether the stimulus required a coupled motor action or not. Despite these findings being novel, they correspond with findings from animal studies where specific cells in the dorsal stream activate when a monkey is required to either follow a moving object with their eyes or when they are required to fixate on a stationary stimulus (Milner & Goodale, 1995). The exclusivity of spatial discrimination in the dorsal stream likely suggests that cricket umpiring relies predominantly on this visual system. Umpires decisions usually rely on the umpire detecting the spatial positioning of the ball in relation to other objects such as the stumps and the batter's legs at critical moments including when it pitches and where it strikes the bat and/or the batter's body. This, in addition to other tasks, such as determining the landing positioning of the bowler's shoe in relation to the crease, assessing whether the ball was caught by a fielder without it touching the ground, and whether the fielders are positioned in placings that are in accordance with the rules, all suggest the dorsal stream performs a principal role within cricket umpiring decision making.

1.3 Working Memory

Throughout the history of cognitive psychology, it has been assumed that there is a distinction between 'short-term memory' and 'long term memory' (Eysenck & Keane, 2010). For example, in the context of cricket umpiring it would be assumed there is a difference in the cognitive mechanisms involved in briefly remembering specific events relating to an impending LBW appeal, and the longer-term recall of the rules that must be applied to this appeal. Originally, one of the widely accepted models of memory was a multi-store model proposed by Atkinson and Shiffrin (1968). This model proposed memory comprising of separate stores; the sensory register, short-term store and long-term store. The sensory register was described as the store in which a stimulus is immediately registered via detection of the sensory organs (Atkinson & Shiffrin, 1968). The information held in this sensory store was reported to be extremely transient, and via a 'selective scan', overt attentional processes would choose information to be fed into the short term-store (Atkinson & Shiffrin, 1968). The 'short-term store' was reported to also hold information temporarily before complete decay, with a capacity of $7_{\pm 2}$ chunks of information (Miller, 1956). Whilst residing in the short-term store, it was assumed that information would be transferred to the long-term store via cognitive control processes (Atkinson & Shiffrin, 1968; Jacoby & Bartz, 1972). Finally, information held in the long-term store was reported to not face the same decay effects as the previous two components, and therefore remained relatively permanent (Atkinson & Shiffrin, 1968).

Whilst the Atkinson & Shiffrin model was extremely dominant during the period that it was proposed, limitations especially relating to the proposed short-term store were exposed (Baddeley, 2012). Firstly, the model suggested that as long as information reached the short-term store, it would eventually be transferred to the long-term store, an assumption which has been refuted (Baddeley, 2012). The oversimplified nature of the model perhaps also unreasonably implied both short and long-term stores operate in a uniform way (Eysenck & Keane, 2010). Thirdly, should the short-term store exist as a gateway to the long-term store, then it would be expected that any impairments to short-term memory would also debilitate long-term memory processes. However, lesion studies have since rejected this possibility as well (Baddeley, 2012). Finally, it was suggested that the short-term store played an imperative role in cognition, thus suggesting impairments to this store would lead to intellectual deficits, however again evidence contradicted this idea (Baddeley, 2012).

To address the issues of the multi-store model, Baddeley & Hitch (1974) proposed the ground-breaking model of 'working memory' which surpassed all other ideas, and to date remains the dominant theory of attention, cognition and temporary storage of information. This model is comprised of 4 components, with the 'phonological loop', 'visuo-spatial sketchpad', 'central executive' appearing in the original model (Baddeley & Hitch, 1974), before a further component termed the 'episodic buffer' was added 26 years later (Baddeley, 2000) (see Figure 1.3). Importantly, this model was perhaps the first to split attentional control processes from temporary information storage.

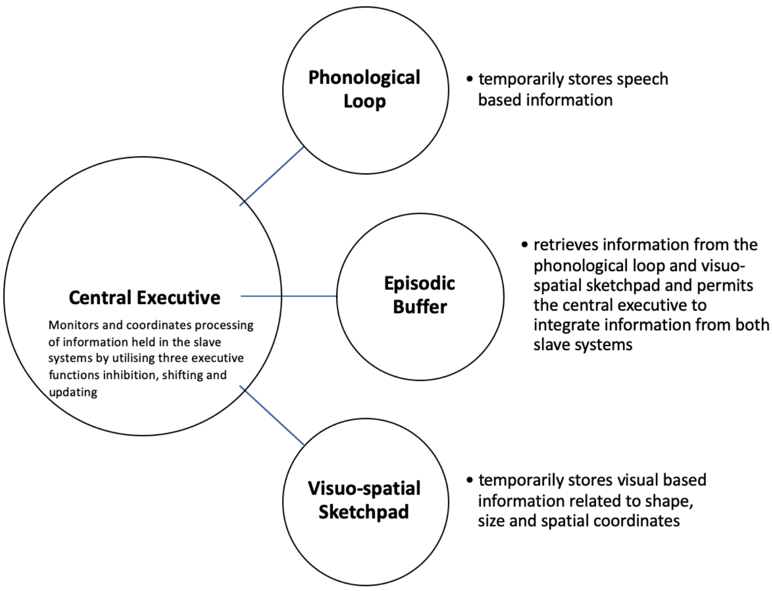

Figure 1.3: Model of working memory adapted from Baddeley (2000)

The phonological loop has been proposed as the component which temporarily holds information in a speech-based form via vocal or subvocal rehearsal (Baddeley, 2012; Eysenck & Keane, 2010). Two phenomena gave support to the phonological loop; the ‘phonological similarity effect’ and the ‘word length effect’ (Baddeley, 2012). The phonological similarity effect is where serial recall performance of a list of words is poorer when they are phonologically similar (Baddeley, 1998). The word length effect is where longer words result in a lower memory span due to increased time for decay, therefore rehearsal of each word is essential to revive and maintain temporary verbal storage in the phonological loop. The visuo-spatial sketchpad is where visual information, such as visual appearance of an object, and spatial information, such as the location of an object, is temporarily maintained (Baddeley, 1998). Whilst less is known about this component compared to the phonological loop, it was apparent that separate processes within the visuo-spatial sketchpad exist for the processing of visual and spatial information. However, Baddeley (1998) pointed out further research must examine possible components involved in temporary motor and kinaesthetic informational storage too. Nevertheless, neuroimaging studies have provided support for the distinction between transient phonological information storage and spatial information storage (see Smith et al. 1996).

Whilst the two slave systems, the phonological loop and visuo-spatial sketchpad, store separate information from one another, they are controlled simultaneously by the central executive, perhaps the most important component of the Baddeley & Hitch (1974) model. The central executive’s principal role is to determine the attentional control of action. Whilst it is assumed to possess no storage capacity in itself, it is capable of dictating attentional focus and storage within the two slave-systems (Baddeley, 2012). Therefore, in each instance an individual engages in complex cognitive activity the central executive is called upon. Whilst there has been lengthy debate as to the specific roles of the central executive, Miyake et al. (2000) found three widely accepted ‘executive functions’; inhibition, shifting and updating. Firstly, the inhibition function refers to an individual being able, when required, to prevent an automatic response to a stimulus. Evidence for this function has been seen using the Stroop test (Eysecnk & Keane, 2010) and antisaccade task (Nieuwenhuis et al. (2004). The shifting function enables the ability to shift attention between multiple tasks, a process called ‘task-switching’. This executive function is utilised in human behaviour frequently on a daily basis, and has been tested using ‘task-switching paradigms’ (Vandierendonck et al. 2010) (this executive function will be discussed in further detail in the ‘Task-switching’ section). Finally, the updating function involves, as Morris & Jones (1990) quotes, ‘the act of modifying the current status of a representation of schema in memory to accommodate new input’. The importance of this function is that as opposed to simply permitting temporary storage of new information, it allows manipulation and cognitive processing of it so an individual can keep track of no longer relevant information (Miyake, 2000).

At the start of the century, it was argued that a further component was required to account for instances where phonological and visuo-spatial information originate from a single source (Baddeley, 2012). Therefore, Baddeley (2000) included the ‘episodic buffer’ which can be considered a fractionation of the central executive (Furley & Memmert, 2010). The principal role of the episodic buffer is to retrieve information from both slave systems which differentiate in code, and create cognitive representations in the form of conscious awareness that permits the central executive to reflect, manipulate and modify it (Baddeley, 2000). This enables an individual to comprehend a coherent and complex structure that resembles a ‘scene’ or ‘episode’ (Eysenck & Keane, 2010).

Perhaps the biggest development of the working memory model created by Baddeley & Hitch (1974) was not related simply to transient storage, but that it provided an explanation as to how individuals were capable of allocating attention to different sources of information and how they cognitively process and manipulate it. With respect to the Baddeley and Hitch’s model, it is possible working memory performs a principal role in umpire decision making. For example, the umpire must temporarily hold spatial information surrounding the ball and its relative position to the batter, pitch, stumps, boundary and ground, as these variables are essential in decisions being generated such as out/not out, boundary/no boundary and runs/byes. With this considered, the visuo-spatial sketchpad appears to be the most suitable slave-system for storing such information (Baars & Gage, 2010). Baddeley (1997) further highlights the visuo-spatial sketchpad is essential in helping an individual hold spatial information of an object from an ego-centric perspective, this perhaps being useful when one considers that umpire’s position themselves centrally to the batter’s middle stump. Whilst important information related to umpiring might be held in the visuo-spatial sketchpad, there is a possibility that the central executive is required in the processing of the information. Firstly, it has been proposed that working memory is important in attentional allocation. Should a target be pre-activated in working memory, then this object will receive prioritised focus of attention should it appear in the visual field (Furley & Memmert, 2013; Furley & Wood, 2016). In the context of cricket, should the appearance of the ball be activated by the central executive prior to the delivery, then this in turn might promote covert and overt attention being directed towards critical cues related to the projectile. In addition to attention, the executive functions might also hold a role in cricket umpiring. Whilst such statements remain speculative until tested, the inhibition function might help prevent attention being directed towards stimuli that are unrelated to the delivery, whereas the updating function might be necessary when umpires are officiating on a match held in variable environmental conditions. With respect to switching attention from adjudicating the legality of the delivery to processing spatial information related to the delivery, it is perhaps logical to speculate use of the shifting function (refer to task-switching section for a more extensive examination of this function and its role in umpiring). Whilst assessments of expertise advantages in central executive functioning have provided mixed results (Furley & Memmert, 2015; Vestberg et al. 2012), it has been suggested that superior performance in certain tasks might be predicted by the way in which working memory and long-term memory interact with one another. Several years after the introduction of the original working memory, it was proposed by Ericsson and Kintsch (1995) that individuals with expertise within a specific domain are capable of rapidly encoding task-relevant information and circumventing the limited capacity of the working memory. This ability was attributed to the development of long-term working memory (LT-WM). Due to extensive deliberate practice, it has been suggested LT-WM provides experts with the ability to rapidly store task-relevant information within their long-term memory. Additionally, LT-WM reportedly enables the individual to directly retrieve task-relevant information temporarily into their working memory once they encounter a specific retrieval cue (Ericsson & Kintsch, 1995; Gobet, 2000). Storage of domain specific information in the LT-WM provides experts with the benefit of being able to retrieve unlimited amounts of information upon stimulation from the retrieval cue, whereas normal information held in the working memory is irretrievable once lost (Ericsson & Kintsch, 1995). Therefore, experts hold direct access to domain-relevant information, this seemingly accounting for the perception that they possess increased capacity for working memory functions (Gobet, 2000).

It has been proposed that LT-WM offers experts an advantage over lesser skilled contemporaries in complex domains, where they are capable of generating faster and more accurate decisions due to rapid encoding of task relevant sensory information via their developed retrieval structures. As a consequence, this reportedly enables circumvention of the typical limitations of working memory and long-term memory, therefore leading to faster decisions of higher quality (Gredin et al. (2020). For example, in Experiment 1A of Belling et al. (2015), skilled and lesser skilled football players were required to view footage of 24 temporally occluded match simulations and in one condition assume the role of the attacking player (intervention phase) and in the other condition to assume the role of the defender. In both conditions, participants were required to generate as many options that the attacking player might and should take. Findings from this experiment showed the skilled players generated more task-relevant options in both assessment and intervention phases, suggesting with significantly more practice they had more elaborate task relevant retrieval structures which they could all upon into their working memory. Recent corroboration of this finding can be seen in Roca et al (2021) who examined the verbal reports of creative and less creative footballers who viewed 20 trials of professional German football matches. Participants were required to perform a similar task to that of the intervention phase in Belling et al. (2015), however at the point of occlusion the participants physically executed the action they deemed most appropriate by playing a ball situated in front of them. Following this they offered a verbal report of their thoughts that led to this response. Finally, for each trial the participant was shown the final frame of the video and were required to generate as many creative solutions as possible for the scenario in 45 seconds. Compared to less creative players, the more creative players generated a greater number of possible decisions whilst they executed their selected action. Further, they were also able to offer more substantial retrospective explanations as to the options the attacking player could have taken, suggesting a greater repertoire of solutions being stored in their LT-WM.

These findings also appear to extend to golf, as Shaw et al. (2021) examined the thought processes of skilled and lesser skilled golfers as they walked to the green and as they 'read' the putt. Whilst walking to the green, the lesser skilled participants verbalized more planning statements related to the putt than the skilled participants. The authors of this study suggested that the skilled players likely deemed this information less relevant to task outcome due to the distance from the putting green. However, in support of the idea that LT-WM contributes to expertise, the skilled golfers verbally reported more statements related to the trajectory they would aim to hit the putt, whereas the lesser skilled players more often verbalised information related to the mechanics of striking the ball. Taken together, these studies provide an insight into the utility of LT-WM in sporting domains, and how it might contribute to better and more efficient performance. These findings further correspond with Ericsson & Kitsch (1995) who suggest skilled performers must be able to anticipate future demands by refining the cues which enable retrieval of the desired information into the working memory. Whilst Baddeley (2012) agreed with the notion of LT-WM, he suggested that it should be regarded as an interaction between the working memory and long-term memory stores as opposed to LT-WM being treated as a separate entity. Nevertheless, working memory and specifically the executive functions of the central executive as well as potential developed LT-WM structures, might possess a principal role in the performance of cricket umpiring, a task in which the officials must hold and process numerous information sources simultaneously.

1.4 Task Switching

In human behaviour, there is a demand for individuals to attend to multiple tasks over a short period of time (Kiesel et al. 2010; Monsell, 2003), for example switching between reading a newspaper and answering a telephone call (Vandierendonck et al. 2010). Switching between tasks is also an essential part of cricket umpiring, in which during a delivery the official must switch from determining the spatial positioning of the bowler's landing shoe, to perceptual judgments about the ball flight trajectory and subsequent impact with the bat or pad (Chedzoy, 1997). Human behaviour is reportedly largely able to cope with the demands of 'task switching' due to the shifting function of the central executive described in Baddeley's working memory model (Eysenck et al. 2007). This shifting function permits individuals to switch back and forth between distinct *task sets*. Task-sets are deemed distinct from one another when they possess exclusive task-specific properties such as perceptual encoding, memory retrieval, response selection or response execution (Schneider & Logan 2007). Whilst the shifting function of the central executive enables the cognitive processing of a succession of various task sets, laboratory studies within the field of cognitive psychology have established that there are limitations to the flexibility of this (Elchlepp et al. 2017). Specifically, research has shown that upon switching to a second task set, an individual is prone to making more errors coupled with a slower response time (RT) (Monsell, 2003; Vandierendock et al. 2010). This effect has been termed the *switch cost*. Interestingly, the switch cost is not exhibited when a task is performed in isolation or when an individual switches between task sets that possess similar configurations (Monsell, 2003).

To examine the functions of the switch cost, Jersild (1927) was the first to develop what is now termed the ‘switch cost paradigm’ which involves performing a series of task-sets that either alternate or remain the same within a testing block. Usually when performing in a task-switch block, both tasks are executed one after another in quick succession (Pashler, 2000). The purpose of the methodology is to examine behavioural and sometimes neurological correlates of task switching compared to non-switching (Monsell, 2003). Generally within studies that employ such methodology, the participants display ‘switch cost’ effects in task-switching blocks where they often perform the second task slower and with more errors (Arrington & Logan, 2004; Elchlepp et al. 2017; Rubinstein et al. 2001). To examine the effect that preparation for a task-switch has on the switch cost, these methodologies often manipulate the duration between offset of the first task-set and onset of the second task-set, this being termed the ‘response-stimulus-interval’ (RSI). Another method to examine preparatory effects of the switch cost involves manipulation of the ‘cue-stimulus-interval’ (CSI). This is specifically the interval between the participant being instructed as to what the secondary task will be and the commencement of this task. It has been consistently found that increasing either RSI and/or CSI periods leads to a reduction in switch cost errors and RT, but fails to completely eliminate them (Monsell, 2003). The switch cost in this instance has been termed the ‘*residual switch cost’*.

To explain the mechanisms underlying the switch cost, two principal theories have been proposed; the *interference view* and the *reconfiguration view*.

The interference view, proposed by Allport et al. (1994), suggests '*task-set inertia'* occurs where activation of the previous task-set interferes with the activation of the task-set required for the second task. Therefore to overcome the activation of the first task-set, the inhibition function of the central executive is required, and this has been suggested to account for the switch-cost (Allport et al. 1994). This theory also provides an explanation for preparation reducing the switch-cost, as it suggests an increased RSI and CSI period provides an individual with sufficient time to partially inhibit activation of the first task-set. In support of this theory, Allport et al. (1994) found that in contrast to task-switching from easy to a difficult tasks, the switch cost was significantly greater when individuals switched from a harder task to an easier one. It was suggested that this asymmetric switch cost was caused by individuals being required to use additional inhibitory processes to overcome the interference of the more complex task-set prior to activation of the easier task-set. Some neurological evidence also exists for this theory (Evans et al. 2015). The two tasks in this study both involved presenting participants with a word, and required them to either recall the word (memory task) or to discriminate the location that it appeared on the display (perceptual task). Upon switching to the perceptual task, event-related potentials (ERPs) that were active during the memory task initially remained active after switching to the perceptual task. These task-irrelevant ERPs also correlated with the switch cost. Carryover of the ERPs upon the task-switch were deemed a result of executive processes inhibiting the memory task-set before enabling the switch to the perceptual task-set.

The commonly cited alternative theory, the *reconfiguration view,* suggests that upon switching task-sets, executive processes are required to reconfigure the new task-set and/or retrieve it from the long term-memory (Monsell, 2003; Vandierendonck et al. 2010). This theory proposes the switch cost reflects the time required to reconfigure the new-task set, hence why preparation reduces the RT and error. Further, when an individual performs the same task repeatedly there is supposedly no necessity for reconfiguration of a new task-set and consequently, switch costs are not exhibited. Task-set reconfiguration/retrieval processes reportedly take place in two separate processes (Kiesel et al. 2010). Upon completion of the initial task, an *endogenous component* of reconfiguration occurs prior to the onset of the second task. This involves goal shifting where declarative memory deletes the previous goal and replaces it with the goal of completing the second task. Upon commencement of the second task, the *exogeneous component* reconfiguration takes place. During this stage, rule activation of the second task activates via procedural memory. As the *exogenous component* can only occur upon commencement of the second task, it is suggested the residual switch cost occurs as no period of preparation can fully enable reconfiguration. Whilst this theory is widely accepted as a possible mechanism, research which has supported its predictions might also be explained by the interference view (Vandierendonck et al. 2010). This is because the studies which appear to support the reconfiguration view, come from results which find that increased preparatory periods (Arrington & Logan, 2004) result in reduced switch costs. However, whilst in theory increased preparatory periods could provide time for endogenous reconfiguration processes to take place, it could also result in increased periods of inhibition and decay of the previous task-set in support the interreference view (Vandierendonck et al. 2010). Nevertheless, both theories find support from both behavioural studies (see Vandierendonck et al. 2010), and neurological studies (see Sakai, 2008).

Over the last 7 years, another potential but neglected contributor towards the switch cost has garnered increased interest. Evidence has highlighted that concurrently during task-set interference and/or reconfiguration, the task-switch might also cause an impairment in visual attention re-allocation towards the critical cue(s) on the second task (Longman et al. 2013; Longman et al. 2014; Longman et al. 2017). In Longman et al. (2013), whilst wearing eye tracking glasses, participants were subjected to a task-switching paradigm where they either had to recognise one of four different faces presented on the display OR determine which of four letters (G, C, O, Q) were located on the forehead of the face. Two CSI preparation periods were included (200ms and 800ms), and the RSI was kept constant at 1650ms between the initial task's offset and secondary task's onset. On the task-switch trials, attention was less well oriented towards the task-relevant stimulus from the onset of the secondary task. This attention misorientation lasted around 400-500ms. The authors therefore suggested that task-switching causes an 'attentional inertia' where attentional settings also require reactivation towards the second task in a similar manner to task-set reconfiguration. As a consequence, they suggested individuals were more likely to allocate attention towards the previous task. In line with the residual switch-cost, when the CSI period was increased, the likelihood of misorientation of visual attention towards irrelevant cues was diminished but not completely eliminated. However, the researchers conceded that with only two tasks, they were unable to confidently conclude that attentional settings were not fully reconfigured to the second task from the first task, and that distraction was also a possibility.

To address this, in two experiments the researchers used a task-switching paradigm but with three distinct tasks (Longman et al. 2014). In experiment one, participants were presented with three numbers (between 2 and 9) located on each point of an equilateral triangle. The three tasks involved determining if the number they were instructed to fixate on was; odd/even, higher than 5/less than 6, or whether it was an inner (4, 5, 6, 7) or outer (2, 3, 8, 9) number. Employing three tasks allowed a task-switch sequence of ABCABC compared to the 2013 study which only used an ABAB sequence. This enabled the researchers to examine whether task-switching would cause attention to be directed towards the previously relevant but now irrelevant task in support of attentional inertia, or whether attention would be directed to both irrelevant tasks equally. A lettered cue signalled to participants in the task-switching group which number to attend to and which task, whilst a control group were cued on the location of the number they should attend to. CSI preparation times were 120ms, 620ms, 1020ms and 1420ms and were kept constant between blocks of 72 trials. In addition to the widely reported switch-costs, in line with attentional inertia the task-switching participants were more likely to allocate their visual attention to the previously relevant but now irrelevant task. Like the 2013 study, preparation helped reduce but not eliminate attentional inertia. These results supported the idea that in addition to task-related components, attentional parameters must also be reset from the perceptual attributes of the initial task to that of the next task. Interestingly, the control group who only shifted attention between different locations also appeared to show a tendency to allocate attention towards the irrelevant tasks. This interesting result led to the conclusion that in addition to attentional parameters, the oculomotor system is also required to reset when attention is shifted between various locations. However, this effect was eliminated when preparation times afforded between the cue and the task were over a second.

In 2017, the same research group aimed to examine whether the attentional inertia could be eliminated when participants self-paced the task-switch (Longman et al. 2017). This methodology contrasted traditional task-switching paradigms where experimenters typically manipulate the CSI time period. Utilising the same task as Longman et al. (2014), it was found that with self-paced long preparation times between the task-switch, attentional inertia was eliminated, however switch costs remained. Whilst the attentional inertia was not evident, preparation did not eradicate the tendency to fixate on task irrelevant cues during the task-switch. Importantly, the researchers suggested that the task-switch might lead to an initial weak reconfiguration of attentional settings towards the second task regardless of the previous task set's influence. With respect to the reconfiguration view then, this attentional impairment might occur due to similar processes occurring like in the *exogenous component* of task-set reconfiguration.

Whilst laboratory-based task-switching experiments provide an elegant methodology of examining the cognitive processes that occur during task-switching, they do not indicate whether switch costs and attentional impairments debilitate performance of tasks performed in the real world. Whilst it can be expected that the switch cost and attentional misallocation would not noticeably affect most behaviours, cricket umpiring might prove to be different. Cricket umpires are successively required to perform a number of perceptual tasks which can be considered to hold distinct task-sets. When considering the definition of a 'task-set' outlined by Schneider & Logan (2007), the front-foot no ball and LBW task likely possess a number of separate processes that equate to them forming separate task-sets. For example, both tasks possess separate perceptual-encoding processes as the no ball-task's primary stimulus is the bowler's shoe, whereas the LBW appeal's primary stimulus is perhaps the ball itself. With regards to response selection, the front-foot no ball requires a decision as to the bowler's vertical foot placement in relation to the crease, whereas the LBW task requires a response related to the ball's radial spatial positioning in relation to multiple environmental sources such as the pitch, stumps and batter. As these two tasks must be performed whilst under extreme time constraints, it is a possibility that the switch-cost might lead to consequences in their decision making. In the instance of an LBW appeal, an umpire is required to perform a series of tasks in rapid time (Chedzoy, 1997). According to Law 36 of the 2017 Marylebone Cricket Club (MCC) laws of cricket, an umpire is required to determine the legality of the delivery by determining if any part of the bowler's shoe is grounded behind the popping crease and inside the return crease (Figure 1.4ab). Next, they must determine whether the ball 'pitched' in line, offside or legside of the stumps (Figure 1.2) before determining the location it struck the batter's pad in relation to the stumps, before finally being required to extrapolate where the ball would have travelled had the batter's pad not obstructed the ball. These decisions must be made whilst the ball travels around 20 metres at sometimes speeds over 90mph, thus, providing the umpire with approximately 0.5s of visual information to decide (Chalkley et al. 2013). Whilst it is unlikely that task-switching would see an umpire re-fixating on the crease like that of attentional inertia, following initial adjudication of the front foot no ball, it is possible that any attentional impairments like those seen in Longman et al. (2017) might prove to be costly to LBW decision accuracy.

To date, only one study has examined whether the front foot no ball task affects LBW decision making (Southgate et al. 2008). In this study, cricket umpires were required to determine where a series of deliveries pitched with respect to the stumps. However, prior to this, one condition required umpires to perform the front foot no ball in task and in a second condition they were required to perform a back foot no ball task (similar to the front foot no ball but examination of the position of the nonstriding leg). In the final condition umpires only determined where the ball pitched. Interestingly when required to switch from making a no ball decision, umpires made significantly more errors when assessing where the ball pitched compared to when they performed this task in isolation. These results might provide some evidence that a switch-cost occurs during cricket umpiring. However due to lack of eye tracking technology the researchers were unable to examine whether task-switching also rendered attentional misallocation. Results from Southgate et al. (2008) provide some interesting questions related to the task-switching domain. Firstly, it would be of interest to understand whether task-switching leads to a switch-cost across all three LBW components or whether it solely affects the 'pitch' decision. Further, as Southgate et al. (2008) highlight, umpires require a quick and accurate re-fixation from the crease to areas related to the batter. Consequently, it would be of worth to examine whether task-switching effects the attentional allocation of umpires (Longman et al. 2017).

Figure 1.4a: Legal delivery

Figure 1.4b: Illegal delivery (no ball)

1.5 Gaze Strategies: Foveal Spot, Visual Pivot, Gaze Anchor

In recent times, research has highlighted the importance of both foveal and peripheral vision in sport, and how they complement one another to detect and process visual information from multiple sources in quick succession (Klostermann et al. 2020; Vater et al. 2019). It has come to light that both overt attentional processes, where the locus of attention is directed towards foveal vision, alternates with covert attentional processes where the locus of attention is directed towards the periphery of the retina, to enhance information pickup from the whole field of view (Klostermann et al. 2020). Use of peripheral vision at the expense of excessive eye saccades has been proposed as an efficient strategy to prevent informational suppression (Klostermann et al. 2020; Vater et al. 2017; Vater et al. 2019). In a review, Vater et al. (2019) outlined 3 visual strategies which utilise a combination of foveal and peripheral vision to prevent these excessive saccades. These 3 strategies were: the *foveal spot, gaze anchor* and *visual pivot* (see Appendix 1).

Firstly, the *foveal spot* was proposed as a stable gaze strategy by which the individual fixates their central vision towards an information source that requires a high level of spatial acuity. Use of what appears to be a *foveal spot* has been exhibited in elite football referees when making foul assessments (Spitz et al. 2016). Spitz et al. (2016) compared the visual behaviours of 20 elite and 19 sub-elite referees during open play and corner foul situations. Whilst no performance differences were exhibited, during open play fouls the elite referees fixated significantly more on the contact zones of the attacking player compared to the sub-elite referees. During corner situations, both groups fixated significantly more on contact zones, however the elite referees made more accurate foul assessments. The *foveal spot* was perhaps utilised to process the highly important spatial information relating to regions on the attacking player where infringements might take place. Use of the foveal spot in officiating appears to be of use where a decision is made in response to a single information source as foveal vision is highly attuned to processing spatial information with a high visual acuity. Conversely, peripheral regions of the retina hold a higher level of motion sensitivity due to greater eccentricity and consequently processes information with lower acuity (Klostermann et al. 2020).

The second stable gaze behaviour described by Vater et al. (2019) termed, the *gaze anchor*, involves an individual directing their central vision between multiple information sources so that they can all be processed via covert attentional processes simultaneously. Often, this strategy will involve stabilizing gaze in a free space proximal to a number of cues that require processing in order to prevent information suppression that would occur should the individual saccade to these multiple sources. Therefore, unlike the *foveal spot* which relies on use of a single attentional spotlight, the *gaze anchor* predominantly employs peripheral vision to deploy several attentional spotlights on regions surrounding central vision. Evidence for this strategy has been displayed in elite officials such as rugby union referees (Moore et al. 2019), assistant football referees (Schnyder et al. 2017) and gymnastics judges (Pizzera et al. 2018), as well as elite athletes from combat sports (Hausegger et al. 2019; Piras et al. 2014). For example, Moore et al. (2019) examined the gaze behaviours of 9 elite rugby referees, 9 trainee rugby referees and 9 rugby players (no refereeing experience). Participants were required to view 10 video projected scrum situations, and make one of four decisions. In addition to making more accurate decisions, the elite and trainee referees fixated on central pack regions significantly more than the player group during the critical moment of the scrum. Conversely, the non-referees directed their visual attention more towards outer and non-pack locations. Whilst at the point of writing the authors described this expert gaze behaviour as a *visual* pivot, it actually appears to fall under the criteria of a *gaze anchor.* It was suggested this strategy was an effective way of the referees processing cues related to the front rows, binds and contact points concurrently. Schnyder et al. (2017) found that expert and near-expert assistant referees in football were more likely to anchor their gaze on the 'offside line', perhaps so peripheral vision could be used to monitor critical information surrounding the passer and attacker simultaneously. Interestingly, both groups in this study were more successful at calling offsides when implementing this strategy as opposed to directing foveal vision towards the attacker, defender, passer or the ball, thus endorsing use of the *gaze anchor* in such tasks. Despite use of a similar strategy, the expert assistant referees still made significantly more accurate decisions than the near-experts, suggesting an enhanced ability to utilise peripheral information. The gaze anchor also appears to be of use to some elite athletes, as Piras et al. (2014) showed that expert judo fighters fixated significantly more on the lapel of their opponent compared to areas such as the jacket skirt, sleeve and hands. Interestingly, the region where a performer orientates their gaze anchor also depends on the task relevant information that requires processing. Hausegger et al. (2019) found that Qwan Ki Do fighters, who can be struck by both fist and foot strikes, anchor their gaze towards their opponent's head whereas Korean Tae Kwon Do fighters, who can be struck solely by foot strikes, anchor their gaze on the opponent's upper torso. This suggests whilst the gaze anchor is an effective method of processing various streams of information concurrently, task context dictates the location it must be positioned to enable optimal cue pickup.

The final visual strategy described by Vater et al. (2019) is termed, the *visual pivot*. Similarly, to the *gaze anchor*, the *visual pivot* involves a performer anchoring their gaze on a central cue, and using peripheral vision covertly to monitor various streams of information. However, this strategy differs from the *gaze anchor* in that once salient information is detected covertly via the periphery, an overt saccade transfers gaze to its source so that it can be processed with high visual acuity via foveal vision. Following this, a saccade back to the pivot point occurs so that peripheral vision can be used to detect the next optimal target to fixate on. As gaze is only transferred towards salient cues, unnecessary saccades to search for areas of interest are therefore prevented. Klostermann et al. (2020) suggests that this strategy is necessary when spatially distributed cues all require accurate visual processing of high acuity. Use of this strategy might explain as to why sporting expertise is commonly typified by fewer fixations of longer durations (Williams et al. 2011). Perhaps the first study to have identified use of the *visual pivot* was conducted by Ripoll et al. (1995) who used a video based French boxing task in a sample of 6 expert boxers, 6 intermediate boxers and 6 novices. As well as making significantly more accurate decisions in complex conditions, the experts appeared to utilise an organised visual search strategy around their opponent's head where saccades were used to transfer gaze to and from various regions of the opponent's body. Whilst intermediate fighters also looked at their opponent's head, they also fixated more on other regions more than the experts, whereas the novices fixated more on their opponent's arm/fists. Use of the *visual pivot* has since been reported in expert karate fighters (Milazzo et al. 2016) and skilled basketball players (Ryu et al. 2013). Milazzo et al. (2016) found that compared to novices, international level karate fighters were not only significantly faster to block opponent attacks and more accurate in executing attacks, but also fixated significantly more on the head and upper torso of their opponent whilst using 'short visual excursions' towards peripheral regions. Using an interesting 'gaze contingent paradigm' in a basketball video-based decision-making task, Ryu et al. (2013) found expert basketballers made saccadic transitions from the ball-carrier to various locations and back to the ball-carrier. This was evident when foveal and peripheral vision were occluded separately in two different conditions as well as when the basketballers were presented the full visual field. The skilled basketballers also performed above chance level in all 3 conditions whereas the lesser skilled basketballers only performed above chance level when the whole visual field was presented. This further highlights an expertise-based ability to utilise both central and peripheral information. However, the *visual pivot* remains to be a gaze strategy seen in sports officiating, this is perhaps due to most studies in such populations focussing on a single temporal point during decision making as opposed to a dynamic scenario where officials might hold an opportunity to pivot between multiple cues.

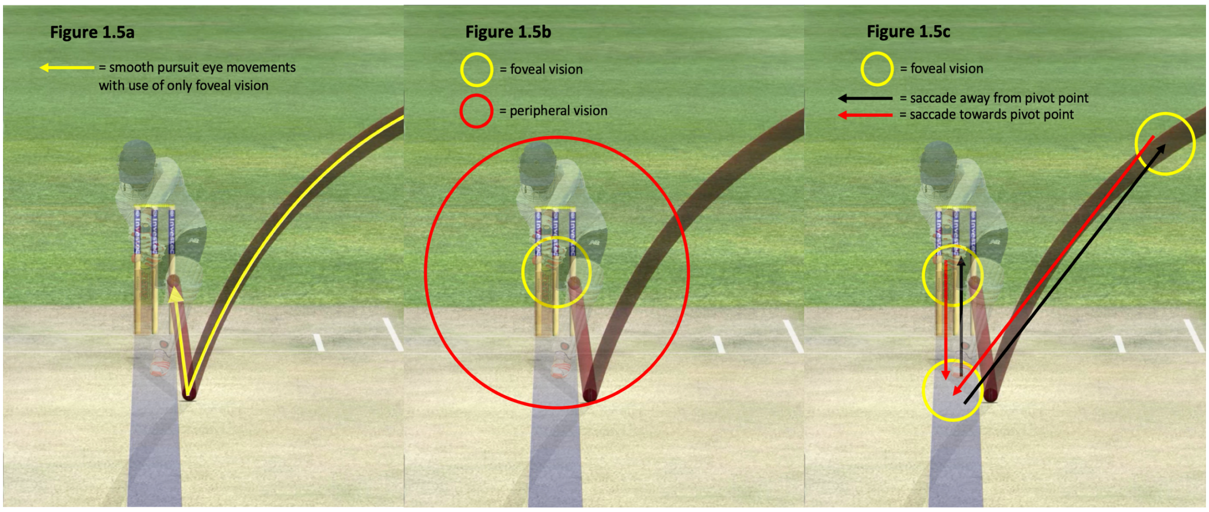

Figure 1.5: Depiction of an umpire's potential use of a: a) foveal spot; b) gaze anchor; c) visual pivot

Whilst these three gaze strategies differ from one another in their function, they can be interchanged with one another throughout a task (Klostermann et al. 2020). For example, research in baseball has shown that batters might initially use a visual pivot as the pitcher prepares to throw the ball, and at the point of release utilise either a *gaze anchor* (Kato & Fukuda, 2002) or *foveal spot* (Takeuchi et al. 2009). Initial use of the *visual pivot* is seen in Kato & Fukuda (2002) where expert batters initially organised their visual search around the pitcher's shoulder/trunk whilst Takeuchi et al. (2000) similarly found experts initially organised their visual search around the proximal region of the pitcher, including their head, chest and trunk. However, at the point of ball release, batter's in Kato & Fukuda (2002) appeared to fixate on the pitcher's elbow suggesting use of a *gaze anchor* between the ball and the pitcher's shoulder, whilst the batter's in Takeuchi et al. (2009) fixated on the pitching arm and release point of the ball, suggesting use of the *foveal spot*. The evidence of these three stable gaze strategies in both sport officials and athletes highlight the integral role peripheral vision holds within expert performance. In figure 1.5abc, a diagram can be seen that outlines how cricket umpires might utilise these 3 gaze strategies to enable processing of the multiple cues associated with making an LBW decision.

In addition to the strategy utilised, research examining automobile driving suggests that expertise can result in an individual possessing a wider 'functional field of view' (FFoV), this being the area of the retina which can process information (Crundall et al. 1999). The principal finding of this study was that experienced drivers were more likely to detect cues located in the periphery of the visual field than less experienced and non-drivers. Interestingly, the ability to detect these cues decreased in all groups when driving task complexity increased. This suggests that both cognitive demands of a task and an individual's task experience determines the width of the FFoV. A theory, termed the 'tunnel-vision model' proposed that an individual's attention is narrower when there is a high cognitive load during information processing of foveal information (Williams, 1989). Such a theory would explain why despite using a similar gaze behaviour, expert assistant football referees in Schnyder et al (2017) and basketballers (Ryu et al. 2013) were better able to utilise peripheral vision to outperform their lesser skilled counterparts. Should the cognitive demands of the tasks from both of these studies be reduced in the skilled participants due to extensive deliberate practice, then in theory they might possess a broader FFoV. This would permit the processing of more cues than lesser skilled counterparts who might require additional cognitive resources to process a central cue's information, consequently resulting in a narrower field of vision to extract information.

1.6 Quiet Eye

Whilst visuo-spatial positioning of the fovea appears to be of high importance, the duration that it remains fixated on the location has been also shown to dictate performance outcomes (Gonzalez et al. 2017a). The Quiet Eye (QE) is defined as the final fixation held within 1-3° of the visual angle for a duration of at least 100ms (Gonzalez et al. 2017a; Moran et al. 2019; Nagano et al. 2006; Vickers, 2016). An extended QE duration has been shown to enhance performance in a variety of sports (Causer et al. 2010; Vickers & Williams 2007; Vickers et al. 2000), so it is of little surprise that many elite sportspeople employ a longer QE period than lesser skilled counterparts in fields such as; golf (Mann et al. 2011) ballet dancing (Panchuk & Vickers, 2011), archery (Gonzalez et al. 2017b), rifle shooting (Janelle et al. 2000) and surgery (Vickers et al. 2015; Wilson et al. 2011). Longer QE durations also appear a predictor of motor coordination abilities in children (Wilson et al. 2013).

The first study that identified a prolonged final fixation can enhance performance was conducted by Vickers (1992), who found that compared with high handicap golfers, low handicap golfers fixated significantly more on the ball when putting. Since this seminal study, extensive research into QE, a term coined in 1996, has been conducted in a variety of fields. Whilst some studies have shown that QE durations do not differ between populations of varying expertise, these studies remain few and far between (refer to Klostermann & Moeinrad 2020). Therefore, it is fair to suggest the performance benefits associated with a prolonged QE are fairly robust.

Whilst the descriptive studies examining performance and skill-based differences generally yield similar results, the mechanisms that underlie the QE remain somewhat unclear 29 years on from its discovery. Three principal theories exist which aim to expound these mechanisms; the *pre-programming, inhibition hypothesis*, and *attentional focus hypothesis.*

The pre-programming hypothesis postulates the QE enhances information processing, and that its duration reflects the time period necessary to optimally organise cortical resources. This supposedly enables synthesis of sensory information that is essential to programme the final parameters of a motor action (Gonzalez et al. 2017a; Rodrigues & Navarro, 2016). Essentially this theory propounds that an extended QE period is crucial for the fine tuning of motor responses which consequently improves task performance. Initial evidence for this hypothesis was seen in Williams et al (2002), who manipulated the complexity of billiards shots taken by skilled and lesser skilled players. Results corroborated previous research as participants employed longer QE periods compared to when their shots were unsuccessful. In support of the pre-programming hypothesis, this study also found that the QE of participants increased in relation to an increase in task complexity. It was suggested that this increased QE duration arose as a result of increased response programming being necessary to fine tune the movement on the more complex trials. Some neurological evidence for this theory also presents itself in Mann et al. (2011), who established that a prolonged QE duration in low and high handicap golfers was associated with increased Bereitschaftspotential (BP), this being a slow rising of negative electrocortical activity that precedes a motor action (Shibasaki & Hallett, 2006). Whilst association does not prove causality, this provides some support that the QE might provide a function in effective pre-programming of a motor task.

Despite this evidence, the validity of the pre-programming theory has been disputed by some due to the ‘efficiency paradox’, whereby its predictions contradict the speed and efficiency of behaviour often associated with elite performance

(Klostermann & Hossner, 2018). Consequently, the inhibition hypothesis was posited by Klostermann et al. (2014). This theory postulates that due to significantly more experience, elite performers possess a greater number of movement options to respond to a given stimulus/situation (Moran et al. 2019). Therefore, to select the appropriate movement response, the prolonged QE duration supposedly inhibits alternative and less optimal options from being executed. Further, Klostermann et al. (2014) suggested inhibitory processes do not solely operate during pre-movement periods, but are also active during movement execution in more complex tasks. Like the pre-programming hypothesis, this also provides an explanation to why QE increases with task complexity (Williams et al. 2002). To test this theory, Klostermann (2019) examined whether increased movement variants would result in an extended QE period. Participants were presented 16 discs, and were required to throw an object towards them. In one group, 4 target discs were highlighted during the pre-movement phase for the participants to throw the object at. In another group, just 1 disc was highlighted, therefore removing three alternate movement variants. In line with the inhibition hypothesis, participants who were presented with more target discs exhibited a longer QE duration than those who were presented a single disc. It was suggested that the longer QE period exhibited was a consequence of participants inhibiting alternate movement variants that would have been necessary should they have chosen to throw at the other three discs. In a follow up study, Klostermann (2020) employed a similar procedure but manipulated the space between each of the discs. Interestingly, the closer the target discs were together, the longer their QE period was. It was suggested that when targets were close together, due to the spatial similarity between targets, further cognitive resources were required to inhibit less optimal movement variants that were similar to the optimal ones.

Whilst most theories have focused on motor-action related functions of the QE, it has been also proposed that it might increase attentional focus optimally towards task related properties (Gonzalez et al. 2017a). Vickers (2009) and Vickers (2016b) suggest the QE might increase activation of the dorsal visual stream (refer to visual systems section) so that attention is predominantly directed towards specific locations in space, which in turn also helps prevent distractive stimuli from entering the working memory via the ventral stream. Attentional Control Theory (ACT) postulates that anxiety renders task performance decline as a direct consequence of attention being allocated towards the source of stress via the ventral visual stream at the expense of dorsal stream processing (Eysenck & Derakshan 2011). Behan and Wilson (2008) found in a computer simulated archery task that when participants were faced with anxiety not only did they perform worse, but their QE duration also significantly reduced. A similar study by Wilson et al. (2009) examining 10 basketball players replicated findings from Behan and Wilson's study where both performance and QE duration reduced in an anxiety condition. This provides some indication that anxiety significantly reduces the duration of the QE. However, a line of research has provided some support for the attentional benefits of the QE, as they have displayed that by training participants to utilise an extended QE period, they can prevent the commonly reported performance decline often associated with anxiety (Causer et al. 2014; Moore et al. 2012; Vickers et al. 2017; Vine & Wilson, 2010; Vine et al. 2011). Further support for QE enabling the increased activation of the of dorsal stream processing comes from Harris et al. (2017), who examined the role of QE in states of flow in basketball players. A small effect was found where QE enhanced states of flow during basketball free throws, this according to the authors providing some evidence that QE enhances task related attentional processes. Mann et al. (2011) also found in comparison to high handicap golfers, low handicap golfers displayed longer QE durations in addition to greater activation in the right parietal lobe, this being one of the primary regions that the dorsal visual stream navigates through. The abovementioned studies highlight a potential link between an extended QE duration and enhanced attentional allocation that would potentially enable performers to ensure all salient cues within the visual field are picked up before and during the sporting action. However, at the time of writing no research has examined whether an increased QE duration holds any utility in improving performance on an attentional task which does not require movement pre-programming and/or inhibition. Research surrounding umpiring decision making provides the perfect base to examine the attentional benefits of QE. Whilst there is a necessity to process information from numerous sources in little over half a second, should the QE prove to be a beneficial strategy when providing verdicts on LBW appeals that require accurate spatial processing of the ball, it could further support the notion that it increases visual processing via the dorsal stream (Vickers, 2016a; Zachariou et al. 2014).

1.7 Quiet Eye Training

As well as trying to establish the mechanisms involved in the QE, as briefly alluded to in the above section, researchers have dedicated much effort in aiming to understand whether this gaze strategy can be translated into elucidating an acceleration of skill learning via training techniques (Farrow & Panchuk, 2016). As Vickers (2016a) highlights, the human brain is a slow visual processor and is therefore reliant on a performer to uncover novel methods of accessing complex spatial information earlier and more efficiently. Consequently, for just over a decade, researchers have examined what visual skills can be trained to expedite expert performance. As the QE appears to mediate expertise in a wide array of tasks (Vine et al. 2014), QE training interventions have been developed and implemented in both novice and expert populations in various sporting and non-sporting tasks (Vickers, 2016a).

Vickers (2016a) suggests a QE training programme should aim to abide by the following 7 step model. Firstly, researchers should establish an 'expert QE prototype'. This involves identifying the optimal QE fixation location, onset, final critical moment, offset and overall duration used by experts when performing a specific task. These five prototype characteristics are fundamental to the intervention as they are ultimately used to visually guide novice attentional allocation. To do this, skilled performers are required to wear eye tracking technology whilst executing the task of their expertise. The five QE characteristics can be further developed by comparing the successful and unsuccessful trials of the skilled performers (Farrow & Panchuk, 2016). The second step involves repeating methodologies from step one, but this time in the novice group to establish how their QE behaviours differ from the experts. Results from this step usually provide initial QE and performance outcomes that form the novice baseline 'pre-test'. The third step initiates the training intervention. Here, video footage of gaze behaviours displayed by the experts in the first step is displayed to the novices, with extra emphasis being placed on the five QE characteristics in a frame-by-frame analysis. Next, video feedback of the participant's QE behaviours from step 2 is presented visually and compared side-by-side to the expert's footage. Vickers (2016a) highlights the importance of this stage in examining the participant's understanding of their attentional focus during performance. The fifth stage involves participants deciding which of the five QE characteristics they would prefer to work on, however this view is contended by Farrow and Panchuk (2016), who suggest that information minimization might be a more optimal solution. Further, they suggest an implicit instruction would be more appropriate so that attentional control is subtly learnt as opposed to use of explicit teaching methods that might be considered detrimental to learning the task. Next, participants engage in blocked and random training drills where they perform a series of trials similar to the pre-test with the aim of practicing methods learnt in step three and four. Finally, in the seventh step, participants perform a retention test to establish if the intervention augments better task performance and whether it yields optimal QE behaviours. Whilst not mentioned in the 7 step-model, a plethora of studies have also included a 'transfer test' whereby participants perform the same task whilst under stressful conditions. This allows researchers to assess whether they are able to maintain their attentional control when anxious or they revert to a shorter QE duration in line with ACT. A number of these interventions have been implemented in both expert and novice populations, and have generally provided positive results. Such findings validate the use of QE interventions as well as further supporting the consensus that the QE forms an imperative part of elite performance (see Appendix 2).

The first pilot QE intervention study was conducted by Adolphe et al. (1997) in 3 expert and 6 near-expert volleyball players. Over a 6-week training period, participants were instructed to track small objects on a display and identify numbers written on them (implicit learning technique). This instruction was based on findings which highlighted tracking the ball for longer durations predicted higher service reception. Following training, participants improved their tracking onset and offset times as well as their overall QE durations. Importantly, improvements were evident in serve reception accuracy over the next 3 seasons of international competition. Despite the lack of control group in this pilot, a plethora of studies have since included control groups and/or technical training groups and found QE training interventions are effective at improving performance in tasks such as Olympic skeet shooting (Causer et al. 2011), surgery (Causer et al. 2014a; Causer et al. 2014b), golf putting (Vine et al. 2011) and soccer penalties (Wood & Wilson, 2011; Wood & Wilson 2012). Not only do such interventions improve attentional control of experts, but in some instances also movement kinematics. For example, Causer et al. (2011) implemented a QE training intervention in a sample of 10 international skeet shooters. Participants initially made 30 shots which formed the pre-test as 5 hits and 5 misses were chosen. Following this, participants completed an 8 week training programme. In the retention-test, the training group significantly improved performance coupled with significantly longer QE durations. Interestingly, the QE group also showed more efficient gun movements by displaying smaller gun displacement and lower peak velocities in the retention test. The QE group also improved their shooting accuracy in an in-situ competition setting further providing evidence of the usefulness of such interventions. This study also included a control group who in line with expectations showed no gaze or performance differences across the pre-test and retention test. In addition to highlighting the overall effectiveness of such interventions from a performance standpoint, this study also provided further evidence that the QE is mechanistically involved at a visuo-motor level by pre-programming the upcoming movement and/or inhibiting less optimal movement variants. Studies following similar intervention protocols have yielded performance increments for novice participants in tasks such as golf putting (Moore et al. 2012; Moore et al. 2013; Vine & Wilson, 2010; Vine et al. 2013), basketball free throws (Vine & Wilson, 2011), marksman shooting (Moore et al. 2014) and throwing and catching (Miles et al. 2014; Miles et al. 2015, Miles et al. 2017) (see Appendix 2). Interestingly, Vine & Wilson (2011), Vine et al. (2013), Moore et al. (2012) and Moore et al. (2013) found that in addition to improving performance of various tasks, the QE intervention shielded novices from a decline in performance when they were subjected to performing under stressful conditions. These findings again reiterate the potential attentional benefits of such training.

As Wilson et al. (2016) summarises, QE training provides an easily accessible method of accelerating skill learning in numerous domains and potentially via a variety of mechanisms. Considering these mechanistic explanations target different aspects of task execution, application of such programmes should be tested in as many self-paced domains to examine their utility beyond typical laboratory settings.

1.8 The Expert Performance Approach

In order to examine expertise in any domain with rigour, Ericsson & Smith (1991) drew upon their research in chess and extracted three steps for researchers to follow. These three steps comprise 'the expert performance approach' (Figure 1.6).

The first step in this framework is, 'capturing superior performance'. Here, researchers are encouraged to identify or design a task in standardized laboratory conditions that is representative of in-situ activity, so that the stable mechanisms of expertise are displayed (Ericsson & Smith, 1991). Such tasks should also permit experts to reproduce superior performance compared to novices in a similar manner to the differences seen during real life performance (Starkes & Ericsson, 2003). Consequently, the procedure should hold the capacity to be administered to both beginners and experts so that measurements can be taken using a longitudinal design.

With use of a similar representative task, the second step, termed 'analysing expert performance' can be considered (Ericsson & Smith, 1991). This stage of inquiry involves extensive analysis of the mechanisms that underlie superior performance using a variety of methods. It is the researcher's role to isolate the complex cognitive mechanisms such as perception, attention and memory processes that are required during expert performance (Starkes & Ericsson, 2003). For example, in the Gaze Strategies and Quiet Eye sections, a plethora of research has examined expert gaze behaviours using eye tracking technology in various sporting activities to establish which cognitive mechanisms contribute to their seemingly enhanced ability to process task-relevant information (Causer et al. 2012).

Finally, once mechanisms for expert performance are identified, the third and final stage of the expert performance approach, namely 'acquisition of expert performance and its mechanisms' can be followed (Starkes & Ericsson, 2003). In this stage, researchers examine whether practice activities related to the mechanisms found in stage two can expedite superior performance across all levels of performers. It is the assumption that expertise is developed gradually via means of cognitive refinement. Therefore in theory, implementation of deliberate practice activities related to the underlying mechanisms associated with expert performance might improve specific aspects of performance without debilitating other aspects (Starkes & Ericsson, 2003).

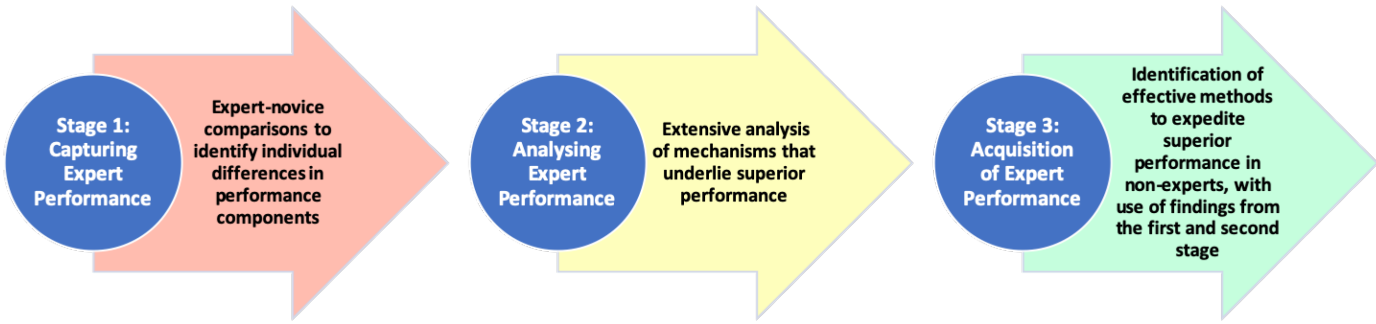

Figure 1.6: Visual representation of the expert performance approach (Ericsson & Smith, 1991)

To examine whether perceptual-cognitive skills contribute towards umpiring expertise, the three steps from the abovementioned ‘expert performance approach’ developed by Ericsson & Smith (1991) were used as a framework to guide this research programme (Starkes & Ericsson, 2003). As a consequence of there being limited prior research surrounding the use of perceptual-cognitive skills and umpiring, this theoretical framework provided a template to help development of the overall methodologies and testing procedures utilised.

1.9 Aims of the thesis and theoretical justification

The principal aims of this thesis were to examine whether perceptual-cognitive skills contribute to expert performance within cricket umpiring and whether these skills could be developed in novices to enhance decision making.

As mentioned, the first step of the expert performance approach involves designing an appropriate task to ‘capture superior performance’ that will provide researchers with a method of testing various processes of elite performers (Ericsson & Smith, 1991; Starkes & Ericsson, 2003). An LBW decision making test was designed with the help of Hawk-Eye technology. Two right-handed batters faced a number of deliveries delivered by a BOLA Bowling Machine at speeds between 65-80mph. Video footage of every delivery was recorded from an umpire’s perspective. Deliveries which struck the batter’s pad were reviewed via ‘Hawk-Eye’, which reconstructed and plotted the ball’s flight path should the obstruction not have occurred. The importance of obtaining Hawk-eye data was that, unlike in previous methodologies examining umpiring and officiating (Chalkley et al. 2013), it provided objective measures as to where the ball pitched, impacted the batter’s pad and where it would have travelled post impact, which could be used to judge performance of the umpires.

Once the general task was designed, the second step, 'identifying mechanisms that mediate expert performance' (Starkes & Ericsson, 2003), was used to guide Chapter 2 and to a greater extent Chapter 3. In this step Starkes & Ericsson (2003) suggest researchers should try and identify specific processes that account for expert performance over lesser skilled individuals, for example, cognitive or anatomical differences. With this in mind, the principal aims of Chapter 2 were to examine whether expert cricket umpires use perceptual-cognitive skills to enhance their decision making of LBW appeals, whether there would be a skill-based difference between expert and novice umpires, and finally whether a representative task could be developed to differentiate these skills between groups. Umpires were defined as experts using Swann et al. (2015) as a framework. The umpires performed either at National Level or developmental level, with over 8 years of umpiring experience at these respective levels. To do this, expert umpires and novice umpires viewed a number of the video-based LBW appeals, and were required to mark a location on an 'empty' Hawk-Eye image where they thought the ball pitched, impacted the batter's pad and where it would have travelled post obstruction. These decisions were compared against Hawk-Eye data for each trial so that the researchers could measure how accurate decisions were on each LBW component. Whilst they performed this task, eye trackers were worn to enable the researchers to establish whether any perceptual-cognitive skills were used. Novices were included in the first study for two reasons: firstly to provide clarification on the representability of the task in line with step 1, and also to provide a comparison of the attentional behaviours of the two groups in line with step 2. If novices and experts performed at similar levels, then it might have been the result of the task not meeting the first criteria of the expert performance approach of mirroring in-situ cricket umpiring. It was hypothesised that expert umpires would outperform novice umpires in decision accuracy on the ‘pitch’, ‘pad’ and ‘wickets’ aspects of the LBW (Chalkley et al. 2013). It was also hypothesised that expert umpires would use a more efficient visual strategy consisting of fewer fixations of longer durations that would be directed to more informative locations (Moore et al. 2019). It was also expected that a longer QE duration would lead to more successful decision making (Schnyder et al. 2017). The final hypothesis was that expert umpires would use a gaze anchor at the critical moments of ball pitching and impacting the batter’s pad in a similar way to previous sporting officials (Vater et al. 2019; Schnyder et al. 2017).

It was decided in Chapter 3 that further examination into the mechanisms of expert umpiring performance would be of interest. Chapter 3 examined how the front foot no ball rule affects umpire’s decision making. There has been a lot of controversy in high level cricket surrounding the front foot no ball (D’Souza, 2019, March 29) with several elite players weighing in on the debate, suggesting technology should be used to make this decision whilst umpires concentrate on other aspects of the game. Within the field of cognitive psychology, it has been found that switching between different tasks can lead to an increased amount of errors on the second task as well as slower response times (Monsell, 2003). Further, it has been found that upon task-switching, individuals sometimes mis-orientate their visual attention towards irrelevant cues (Longman et al. 2017).

Therefore, the aim of this study was to examine whether umpires would make less accurate LBW decisions when required to switch to this task from calling the front foot no ball. Umpires performed an adapted version of the task used in Chapter 2.

However, an experimental condition in this study required umpires to task-switch whilst a 'control' other condition replicated the procedure from Chapter 2. First, it was hypothesised that task switching from the front foot no ball decision task to the LBW decision making task, would lead to increased decision-making error on the pitch aspect (Southgate et al. 2008) and additionally the 'pad' and 'wickets' components. It was also expected that irrespective of the condition, a longer QE duration on the stumps would lead to more successful decision making (Vickers, 2016a). It was lastly expected that when task-switching, umpires would direct their attention significantly more to task-irrelevant locations (Longman et al. 2017).

Finally, Chapter 4 adhered to the third step of the expert performance approach, where it aimed to examine whether expertise in cricket umpiring could be acquired by non-experts by using expert eye movement behaviours (Starkes & Ericsson, 2003). A plethora of research has found that 'QE training' can mediate improved sporting performance (Farrow & Panchuk, 2016). A sample of novice-umpires were split into a QE, technical training (TT) and control (CTRL) group. A similar task to Chapter 3's experimental condition formed trials across all phases of this chapter. All participants made 8 pre-test LBW decisions before the intervention was implemented. Within the intervention, the QE group was provided information as to where they should fixate their gaze and the duration they should hold it in a certain position for, the TT group were provided information surrounding LBW decision making thought process, whilst the control group were provided no information. Following this, participants took part in the acquisition phase where they practiced the information they had been provided before taking part in the post-test where they viewed a further 8 LBW appeals. It was firstly hypothesised that the QE and TT groups would improve their LBW decision making accuracy significantly across all three components (Vickers, 2017). However, it was predicted that only the QE group would maintain learning effects in a one-week retention test (Miles et al. 2017). Finally, it was expected that the control group would exhibit no significant changes in decision making accuracy across all three phases.

Chapter 2:

Expertise Differences in LBW Decision Making and Perceptual-Cognitive Skills

Abstract

Cricket umpires are required to make high-pressure, match-changing decisions based on multiple complex information sources under severe temporal constraints. The aim of this study was to examine the decision-making and perceptual-cognitive differences between expert and novice cricket umpires when judging leg before wicket (LBW) decisions. Twelve expert umpires and nineteen novice umpires were fitted with an eye-tracker before viewing video-based LBW appeals. Dependent variables were radial error (cm), number of fixations, average fixation duration (ms), final fixation duration (ms), and final fixation location (%). Expert umpires were significantly more accurate at adjudicating on all aspects of the LBW law, compared to the novice umpires ($p < .05$). The expert umpires' final fixation prior to ball-pad contact was directed significantly more towards the stumps ($p < .05$), whereas the novice umpires directed their final fixation significantly more towards a good length ($p < .05$). These data suggest that expert umpires utilise specialised perceptual-cognitive skills, consisting of a gaze anchor on the stumps in order to overcome the processing demands of the task. These data have implications for the training of current and aspiring umpires in order to enhance the accuracy of LBW decision making across all levels of the cricketing pyramid.

Cricket umpires make decisions regarding batter dismissals that consequently determine match outcomes (Sacheti, et al. 2015). Of the modes of dismissals within cricket (see Marylebone Cricket Club, 2017), none has led to as much controversy and dispute as the leg before wicket (LBW) (Chedzoy, 1997; Sacheti et al., 2015; Southgate et al. 2008). LBW appeals occur when the ball strikes the batter on any part of their body (usually leg pads) apart from the bat and hands (Craven, 1998). For a bowler to dismiss a batter via LBW, the umpire must consider whether the delivery met a number of specific criteria (Crowe & Middeldorp, 1996). For every delivery, the umpire must initially determine whether the bowler's front foot grounds behind a line termed the crease (Adie et al. 2020). Subsequently, the umpire must consider where the ball bounced (pitched), where the ball impacted the batter in relation to the stumps, and the more challenging judgement of whether the ball would have continued on its flight path to hit the stumps had the obstruction with the batter not occurred (Southgate et al., 2008). Therefore, the LBW rule appears to be one of the few regulations in sport where an official must determine what might have happened (would the ball have hit the stumps?) if other events did not occur (ball flight path being obstructed by the leg), which contributes to the dispute amongst players, media and followers of cricket (Crowe & Middeldorp, 1996). A number of contextual factors further add to the difficulty of the umpire's LBW verdict, such as the batter's stance (Southgate et al., 2008), dynamics of the delivery (spin and swing) and the ball's surface degradation (Chalkley et al. 2013). In spite of these challenges, it has been shown that professional umpires are highly accurate at making LBW decisions. Adie et al. (2020) examined 5578 decisions made in elite level cricket in Australia between 2009-2016 and found that umpires were correct 98.08% of the time. Further, when they broke down the match format, 96.20% of 'out' decisions were correct in first class cricket, 96.29% in One Day cricket and 86.15% in T20 cricket.

In 2008 the International Cricket Council (ICC) introduced the Decision Review System (DRS) into international cricket. This permits the captains of either team to refer a limited number of decisions made by the on-field umpires to the third umpire who is able to utilise an array of replays and technologies to assess the accuracy of the original decision (Borooah, 2013). Utilising statistics from the DRS in international test cricket (July 2008 to March 2017) ESPN Cricinfo estimated that 74% of the reviews involved LBW appeals, with the overturn rate being at 22% (Davis, 2017, June 1). Whilst initially this proportion seems high, it must be stressed that these officials are often placed under severe constraints when making these decisions (Chalkley et al., 2013; Southgate et al., 2008). More specifically, in certain scenarios, umpires must process information related to the ball's (7.29 cm) flight that can travel at velocities up to 95 mph over 20 m. These constraints offer umpires approximately 543 ms to process the multitude of visual and auditory information required to make a single decision (Southgate et al., 2008). To help combat these processing demands, it has been suggested that umpires utilise specific perceptual-cognitive behaviours that contribute to the increased likelihood of correct decisions (Southgate et al., 2008).

Cricket batters face similar temporal constraints, and researchers have highlighted differing gaze behaviours to attempt to overcome these demands (Croft et al. 2010; Land & McLeod, 2000; Mann et al. 2013). Upon ball release from the bowler, expert batters generally make an anticipatory saccade to it its pitching point (Croft et al., 2010). However, following the ball pitching, two distinct strategies have been identified. Land and McLeod (2000) reported that batters made a saccade towards the ball about 200 ms after its bounce before attempting to pursuit track the remainder of its flight, whereas batters from Mann et al. (2013) made a saccade towards the bat at the point it contacted the ball. The variability in ball tracking techniques utilised within cricket batting was highlighted by Croft et al. (2010), who reported that whilst individual batters displayed a consistent gaze strategy, these strategies varied greatly between participants with a mixture of saccades and pursuit tracking being used at different time points before and after the ball bounced. To date, just one study has examined whether expert umpires possess decision making advantages over lesser skilled counterparts (Chalkley et al. 2013). Using a temporal occlusion design, Chalkley et al. (2013) found expert and near-expert umpires were better able to determine where the ball would travel compared to non-umpires. However, no eye tracking technology was used to examine whether expert umpires employed specialised visual strategies to increase their decision making accuracy.

When tracking a projectile, such as a cricket ball, it has been suggested that use of a series of fixations or saccades limits the amount of information that can be efficiently processed (Ludwig, 2011). Therefore, in these scenarios a single stable fixation can enable more accurate performance (Wilson et al. 2015). In a recent review, Vater et al. (2019) identified 3 unique stable gaze strategies utilised by athletes that have similar characteristics but have a functional difference: 1) foveal spot; 2) gaze anchor; and 3) visual pivot. First, the ‘foveal spot’, is a strategy that involves an individual processing information by directing their visual attention towards a central cue with the aim of accurate information processing via the fovea (Vaeyens et al. 2007). Second, the ‘gaze anchor’ is a location in the centre of several critical cues in order to distribute attention to several cues using peripheral vision. Importantly, the actual fixation location may not contain any task-specific information that is being process by the fovea, but is equidistant to the pertinent cues (Vansteenkiste et al.

2014). Third, the 'visual pivot' acts as a centre point for a series of fixations to important locations to minimise the retinal distance between critical cues. Similar to the gaze anchor, it is possible that there is no task-specific information located at the visual pivot, but it is the most efficient central position for subsequent visual scanning (Ryu et al. 2013). Given the spatial-temporal constraints that cricket umpires are under, making numerous judgements and predictions in less than 550 ms (Southgate et al., 2008), a stable fixation, such as a gaze anchor, may be the most efficient and effective strategy to process the relevant information. In addition to the location of the anchor, a wide array of studies have showcased that the duration of this fixation can influence task performance (Farrow & Panchuk, 2016). A prolonged Quiet Eye (QE), defined as a final fixation within 1-3° of the visual angle, has been reported to enhance performance in athletes via multiple mechanisms (Gonzalez et al. 2017a). The benefit of the QE has been showcased in both expert and novice counterparts alike, and common mechanistic explanations relate to the prolonged final fixation enabling comprehensive pre-programming and online control of the required motor action (Causer et al. 2017). However, it has been suggested the QE also increases activation of the dorsal visual stream (Vickers, 2012), and therefore this strategy might also be of major benefit to tasks which do not require a motor component. This was somewhat evident in Schnyder et al. (2017) who observed a trend in prolonged QE durations being associated with correct offside decisions in assistant football referees. However, this phenomenon has rarely been tested in tasks that do not couple perception with action.

With the abovementioned research in mind, the aim of the current study was to establish whether skill-based differences exist between expert and novice cricket umpires when making judgments that are crucial for LBW decisions. Furthermore, this study aimed to elucidate whether expert umpires possess specialised visual strategies that enhance LBW decision making. It was predicted that: 1) expert umpires would outperform novice umpires on adjudicating of all three components of LBW appeals; 2) expert umpires would utilise a specialised visual strategy consisting of fewer fixations of longer durations to more informative locations (Williams, 2009); 3) a longer QE duration would lead to more successful decisions in both groups; and 4) expert umpires' final fixation before the ball struck the batter's pad would be a gaze anchor between a good length and the middle of the stumps.

Methods

Participants

Participants were 12 expert umpires (M = 58 years of age, SD = 10) and 19 novice umpires (M = 42 years of age, SD = 7). The expert umpires had officiated in organised cricket at elite club (n = 9), minor counties (n = 2) and first-class cricket (n = 1). The expert umpires had a mean of 11 years (SD = 5) umpiring experience, accumulated over a mean of 100 matches (SD = 12). Additionally, the expert umpires had accumulated a mean of 279 (SD = 390) matches of playing experience in competitive club cricket. The novice participants had not umpired in any form of organised cricket. In a later analysis, sub-samples were created between the novice group for further examination of the data. They were split into experienced cricketers (M = 20 years of age, SD = 2) and non-experienced cricketers (M = 22.55 years of age, SE = 2.70). The experienced novices had accumulated a mean of 20 (SD = 8) matches playing experience in school level cricket. Participants gave their informed consent prior to taking part in the study and the study was approved by the Research Ethics Committee of the lead institution.

Task & Apparatus

Visual search behaviours were recorded using the TobiiGlasses2 corneal reflection eye movement system (Tobii Technology AB; Danderyd, Sweden). The test film was recorded at the Marylebone Cricket Club Cricket Academy. Video footage from an umpire's perspective was recorded using a Canon VIXIA HFR706 camera (Tokyo, Japan). The camera was positioned in line with middle stump 1.00 m away from the non-strikers popping crease. A right-handed batter who competes in the Worcestershire Premier League faced a number of deliveries delivered by a BOLA Bowling Machine (Bola Manufacturing Ltd.; Bristol, UK), from both around and over the wicket, at speeds between 65-80 mph. The batter was encouraged to play their 'natural game' whilst facing these deliveries. Deliveries that struck the batter's pad were termed 'appeals' and were reviewed via 'Hawk-Eye' (Basingstoke, UK), which reconstructed the ball flight characteristics should the obstruction not have occurred (Collins, 2010). Hawk-Eye technology utilises a theory of triangulation, which helps predict post ball-pad impact by measuring angles from the known points of the delivery's pre-impact flight (Duggal, 2014). In total, 20 appeals were used for the study with 11 being delivered from around the wicket, and 9 being delivered from over the wicket. A total of 16 appeals were deemed 'out' and 4 deemed 'not out' by Hawk-Eye. Based on the surface, 10 trials were deemed to have pitched on a 'good length' and 10 trials were deemed to have pitched on a 'full length'. According to hawk-eye's predictions, 6 trials would have struck off stump, 6 trials would have struck middle stump, 6 trials would have struck leg stump and 2 trials would have missed the stumps. Based on pilot testing, trials that were deemed too easy (85% and above in accuracy), were omitted from the final test film.

The footage was edited using Windows Movie Maker 2016 (Washington, USA). Each appeal formed one trial. For each trial the trial number and position of the delivery (over or around the wicket) were each shown for 3.0 seconds and were followed by a 3.0 second countdown. The video clip started 3.0 seconds before ball release, to represent the time for a bowler's run-up in a match scenario. The video clip continued for a further 3.0 seconds after ball-pad impact, and was followed by a black screen, which signalled the end of the trial. The position of delivery for each trial was randomised to avoid any order effects. Additionally, 5 catch trials were randomly included in the test film, in which the batter successfully hit the ball so that participants were not always presented successive LBW appeals, and thus increased task realism.

Procedure

Participants were fitted with the TobiiGlasses2 eye tracker which was calibrated using a one-point calibration card held by the researcher 1.00 m away. The test film was projected by an Epson EB-7000 projector (Suwa; Japan) onto a large Cinefold Projection Sheet (Draper Inc; Spiceland, IN; 2.74 m x 3.66 m). Participants stood 3.20 m away from this display to ensure it subtended a visual angle of 12.8 °, thereby replicating the height of the batter in situ. To cross-check calibration, participants viewed a still image of the pitch and were asked to direct their visual attention towards the stumps. This was repeated throughout the data collection period to ensure participant gaze remained calibrated with the eye trackers.

Initially, the researchers provided the participants with an overview of the LBW rule as per Marylebone Cricket Club guidelines, using standardised diagrams and text. To familiarise participants with the experiment protocol and response requirements, participants observed two familiarisation trials, which showed LBW appeals similar to those in the test. Participants verbally predicted the three components of LBW adjudication and then were given a handout that revealed the Hawk-Eye ball flight path. This familiarised participants with the scale of the Hawk-Eye slides they would be adjudicating on for each trial. Following this the testing period began. During the testing period, the participant viewed each trial and was then asked on a computer to position 3 balls (circles scaled to the Hawk-Eye image) on a pitch image, once the display had gone black. Specifically, the balls were positioned on Hawk-Eye slides corresponding to where they perceived the ball to; have pitched, impacted the batter's front pad, and where it would have hit/passed the stumps had its flight not been obstructed (see Figure 2.1). Participants were asked to adjudicate the three variables in any order they saw fit and in a time frame similar to how they would generally make decisions in a match. Once participants had made a judgement for one of the LBW variables, they could not alter this decision. This procedure was repeated for all 20 trials. The whole collection process took approximately 40 minutes.

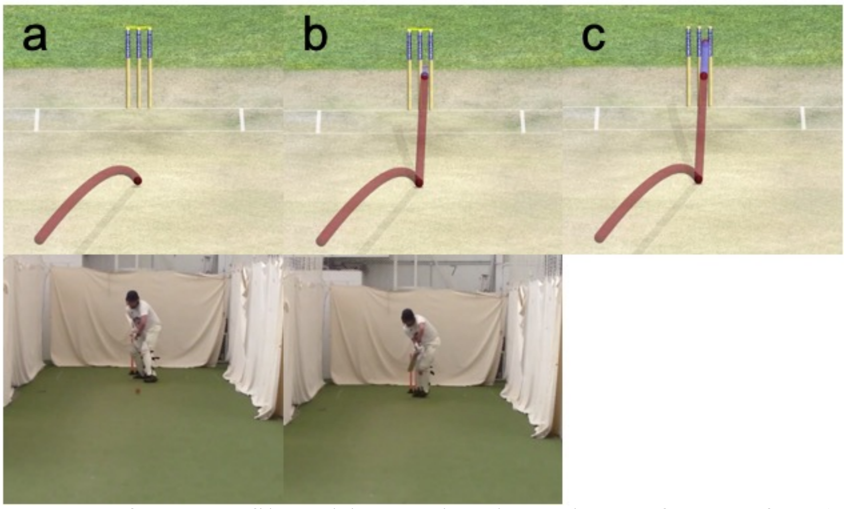

Figure 2.1: Frames from test film with associated Hawk-Eye footage for: a) pitch, b) pad, and c) stumps.

Measures

Response accuracy was determined by radial error (cm), which was defined as the Euclidean distance of the participant's judgment of ball impact with the pitch, pad, and stumps compared to the Hawk-Eye data. To represent this distance to a real-life setting, radial error was upscaled in a similar manner to Runswick et al. (2019), who examined anticipation of cricket batter's when facing congruent and incongruent deliveries. This distance was scaled to quantify accuracy at a game scale (see Runswick et al. 2019). Fixations were defined as gaze being directed towards a location within 3 ° of the visual angle for a minimum of 100ms (Vickers et al. 2019). Number of fixations were measured from the onset of the trial until the offset of the trial. Average fixation duration (ms) was calculated by dividing the total fixation duration by the number of fixations of each trial. Final fixation duration (ms) was the duration of the last fixation prior to ball-pad impact until conclusion of post-impact dwell time. Post impact dwell time was defined as the fixation duration from ball-pad impact until offset of the fixation. Final fixation location (%) was defined as the percentage of trials participant's final fixation was located on a specific area. Five fixation locations were coded: good length, full length, short length, stumps, other location (see Figure 2.2). The front pad of the batter occludes a large proportion of the stumps during a standard delivery. Therefore, when umpires directed their vision towards the batter's front pad, this was coded as 'stumps' as the umpires typically maintained their gaze on the stumps after the batter had moved away, suggesting they were anchoring their gaze on the stumps as opposed to following the batter's pad.

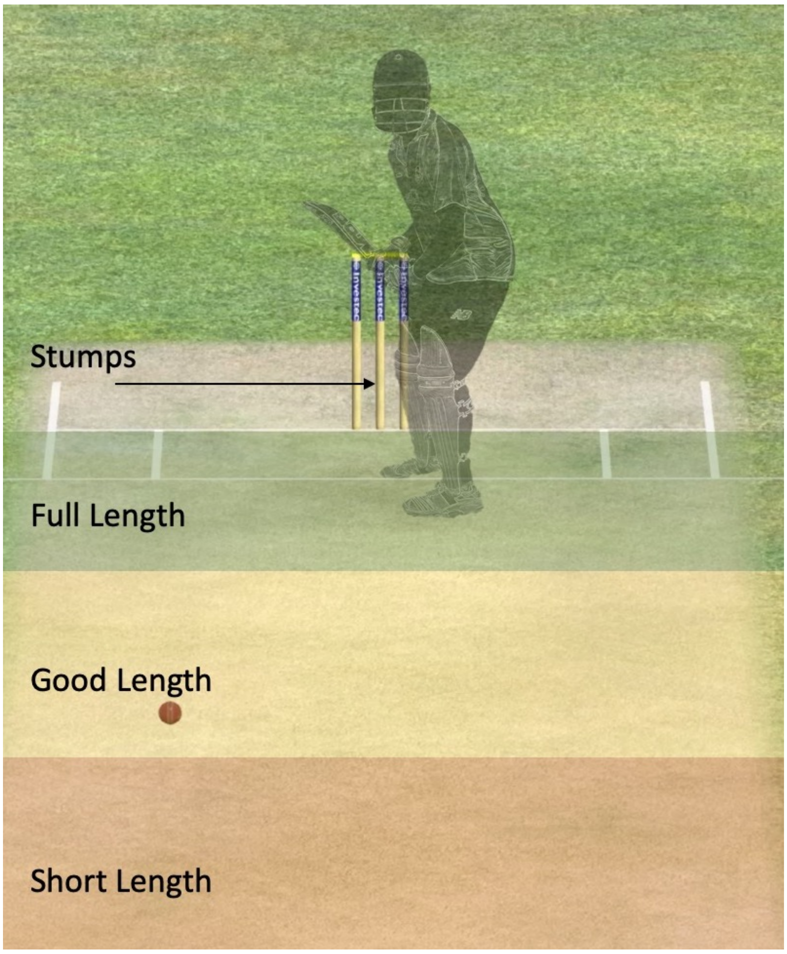

Figure 2.2: Final fixation locations: *good length, full length, short length, stumps*.

Statistical analysis

Radial error data were analysed by a 2 (Expertise: expert, novice) x 3 (Decision: pitch, pad, stumps) mixed-factor analysis of variance (ANOVA). Number of fixations, average fixation duration (ms) and final fixation duration (ms) were analysed using separate 2 (Expertise: expert, novice) x 2 (Outcome: correct, incorrect) mixed-factor ANOVAs. Final fixation location was analysed using a 2 (Expertise: expert, novice) x 2 (Outcome: correct, incorrect) x 5 (Location: good, full, short, stumps, other) mixed-factor ANOVA. In later analyses, the final fixation duration was split into pre-impact duration and dwell duration before two separate 2 (Expertise:

expert, novice) x 2 (Outcome: correct, incorrect) mixed-factor ANOVAs were used. Separate analyses on the novice sample between experienced cricketers and non-cricketers were also later conducted. Specifically, a 2 (Experience: experienced cricketers, non-experienced cricketers) x 2 (Decision: pitch, pad, wickets) mixed-factor ANOVA was used to analyse radial error. To analyse final fixation location, a 2 (Experience: experienced crickets, non-experienced cricketers) x 5 (Location: good, full, short, stumps, other) mixed-factor ANOVA was used. Effect sizes were calculated using partial eta squared values (ηp2). Greenhouse-Geisser epsilon was used to control for violations of sphericity and the alpha level for significance was set at .05 with Bonferroni adjustment to control for Type 1 errors.

A priori power analysis using G*Power (Faul et al. 2007) for a 3 x 2 within-between ANOVA indicated a total sample size of 28 was needed to detect a medium effect (f = 0.25) for the within-participant and interaction effects. The pool of expert umpire participants was limited so it is important to note that statistical power for tests of between-participant effects was only sufficient to detect larger effects (f > 0.42).

Results

Radial error (cm)

There was a large main effect of expertise, $F_{1,29} = 8.88$, p = .01, $\eta p^2 = .23$ (see Figure 2.3). Novice umpires had significantly higher error (M = 25.87 cm, SE = 1.31) than the expert umpires (M = 19.61 cm, SE = 1.64). The novice group were less accurate at determining the ball's impact with the pitch (M = 24.60 cm, SE = 2.29), pad (M = 22.65 cm, SE = 1.83) and stumps (M = 30.35 cm, SE = 2.02), compared to the expert group (pitch: M = 20.57 cm, SE = 2.88; p < .05; pad: M = 16.15 cm, SE =

2.30; $p < .05$; stumps: M = 22.11 cm, SE = 2.55; $p < .05$). There was also a large main effect of decision, $F_{2,58} = 4.80$, $p = .01$, $\eta p^2 = .14$. Radial error was significantly higher for stumps (M = 26.23 cm, SE = 1.63) compared to pad (M = 19.40 cm, SE = 1.47; $p < .05$). There was no significant Group x Decision interaction $F_{2,58} = .46$, $p = .63$, ηp2= .02. There were no main effects for experience, $F_{1,17} = .26$, $p = .61$, $\eta p^2 = .02$. There was a small main effect of decision, $F_{2,34} = .3.27$, $p = .05$, $\eta p^2 = .16$. Radial error was significantly higher for stumps (M = 30.56 cm, SE = 2.36) compared to pad (M = 22.86 cm, SE = 2.26; $p < .05$).

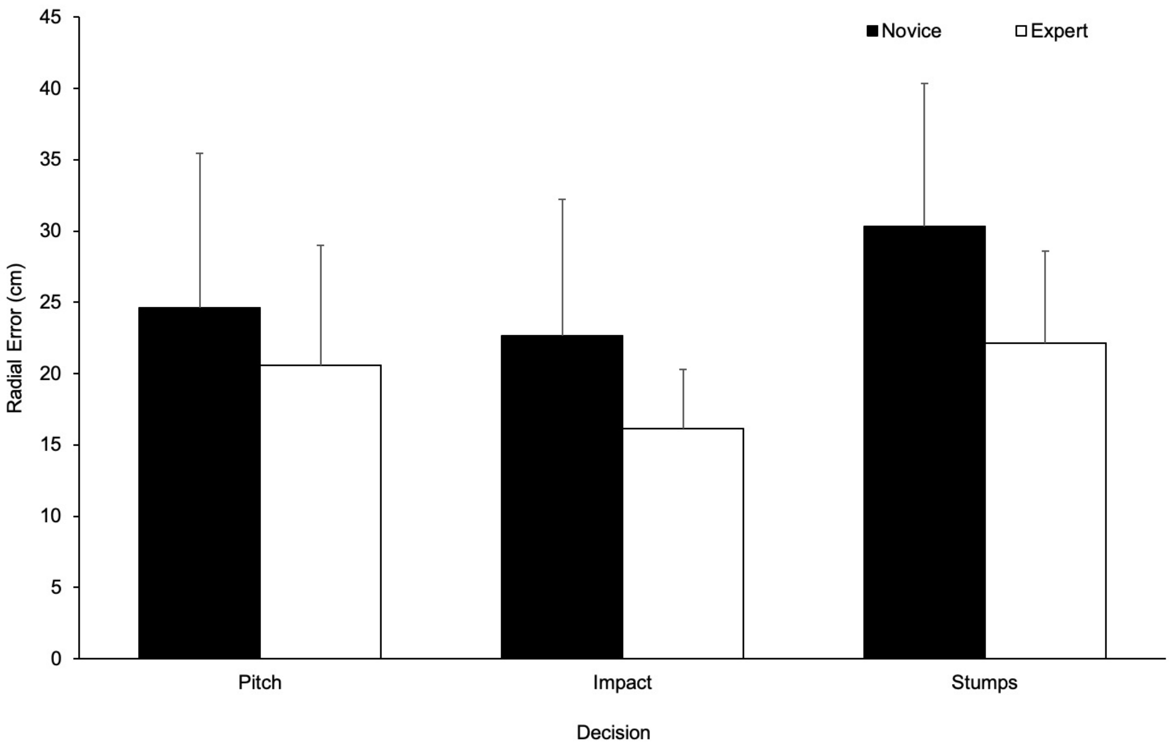

Figure 2.3: Radial error (cm) for expert and novice umpires, *for pitch, impact* and *stumps*.

Number of fixations

The main effects of expertise, $F_{1,27} = 1.536$, $p = .23$, $\eta p^2 = .05$, and outcome, $F_{1,27} = 2.183$, $p = .15$, $\eta p^2 = .08$, were small to moderate hence were statistically non-significant. This reflected a similar number of fixations for correct trials ($M = 4.4$, $SE = .32$) and incorrect trials ($M = 4.7$, $SE = .33$); and between expert ($M = 5.0$, $SE = .47$) and novice umpires ($M = 4.2$, $SE = .39$). The Expertise x Outcome interaction was non-significant, $F_{1,27} = 1.082$, $p = .31$, $\eta p^2 = .04$.

Average fixation duration (ms)

There was a large effect of expertise, $F_{1,27} = 5.347$, $p = .03$, $\eta p^2 = .17$. The average fixation duration for novice umpires ($M = 1520.42$ ms, $SE = 152.31$) was significantly longer than for expert umpires ($M = 972.91$ ms, $SE = 181.29$). The main effect of outcome was small and non-significant, $F_{1,27} = 1.318$, $p = .26$, $\eta p^2 = .05$, which reflected the similar average fixation duration for correct ($M = 1361.06$ ms, $SE = 143.85$) and incorrect ($M = 1226.67$ ms, $SE = 125.22$) trials. The Expertise x Outcome interaction was non-significant, $F_{1,27} = .389$, $p = .54$, $\eta p^2 = .01$.

Final fixation duration (ms)

There was a large effect of expertise, $F_{1,27} = 7.787$, $p = .01$, $\eta p^2 = .22$. The final fixation duration was significantly longer in the novice group ($M = 2906.14$ ms, $SE = 235.27$) than the expert group ($M = 1885.56$ ms, $SE = 280.02$). There was also a large main effect of outcome, $F_{1,27} = 5.500$, $p = .03$, $\eta p^2 = .17$. Final fixation duration was significantly longer for correct ($M = 2612.58$ ms, $SD = 1083.65$) compared to incorrect trials ($M = 2355.08$ ms, $SD = 1173.60$). The Expertise x Outcome interaction was non-significant, $F_{1,27} = 1.743$, $p = .20$, $\eta p^2 = .06$.

Pre-Impact duration (ms)

There was no expertise main effect for pre-impact duration, $F_{1,27} = 2.36$, $p = .14$, $\eta p^2 = .08$. There was also no main effect of outcome, $F_{1,27} = 3.06$, $p = .09$, $\eta p^2 = .10$.

Dwell duration (ms)

There was a moderate effect of expertise for dwell duration, $F_{1,27} = 10.30$, $p < .01$, $\eta p^2 = .28$. The dwell duration was significantly longer in the novice group (M = 1567.27 ms, SE = 144.26) than the expert group (M = 847.58 ms, SE = 144.26). There was no main effect for outcome, $F_{1,27} = 1.51$, $p = .23$, $\eta p^2 = .05$.

Final fixation locations (%)

There was a very large main effect of location, $F_{2.04,\ 53.09} = 17.80$, $p < .001$, $\eta p^2 = .41$. (see Figure 2.4). A higher percentage of final fixations were directed towards the *stumps* (M = 41.95%, SE = 4.97) than towards a *good length* (M = 21.51 %, SE = 4.01), a *full length* (M = 27.47 %, SE = 3.14) (p < .05), a *short length* (M = 2.54 %, SE = 1.09) and *other locations* (M = 7.68 %, SE = 2.14) (all p < .01). A significantly higher percentage of fixations were directed towards a *good length* and a *full length* than towards a *short length* and *other locations* (all $p < .01$). There was also a large interaction effect between expertise and location, $F_{2.04,\ 53.09} = 7.04$, $p < .001$, $\eta p^2 = .21$. This reflected that the percentage of final fixations directed towards a *good length* was higher in the novice group (M = 35.85 %, SE = 5.02) than the expert group (M = 7.17 %, SE = 6.24; p < .05), whereas the percentage of final fixations directed towards the *stumps* was lower in the novice group (M = 28.89 %, SE = 6.24; $p < .05$) than in the expert group (M = 55.51 %, SE = 7.75). When comparing experienced and non-experienced cricketers within the novices, the group x location interaction was small and statistically non-significant, $F_{4,60}$= .75, p = .56, ηp^2= .05. All other main effects and interactions were non-significant (all p > .05).

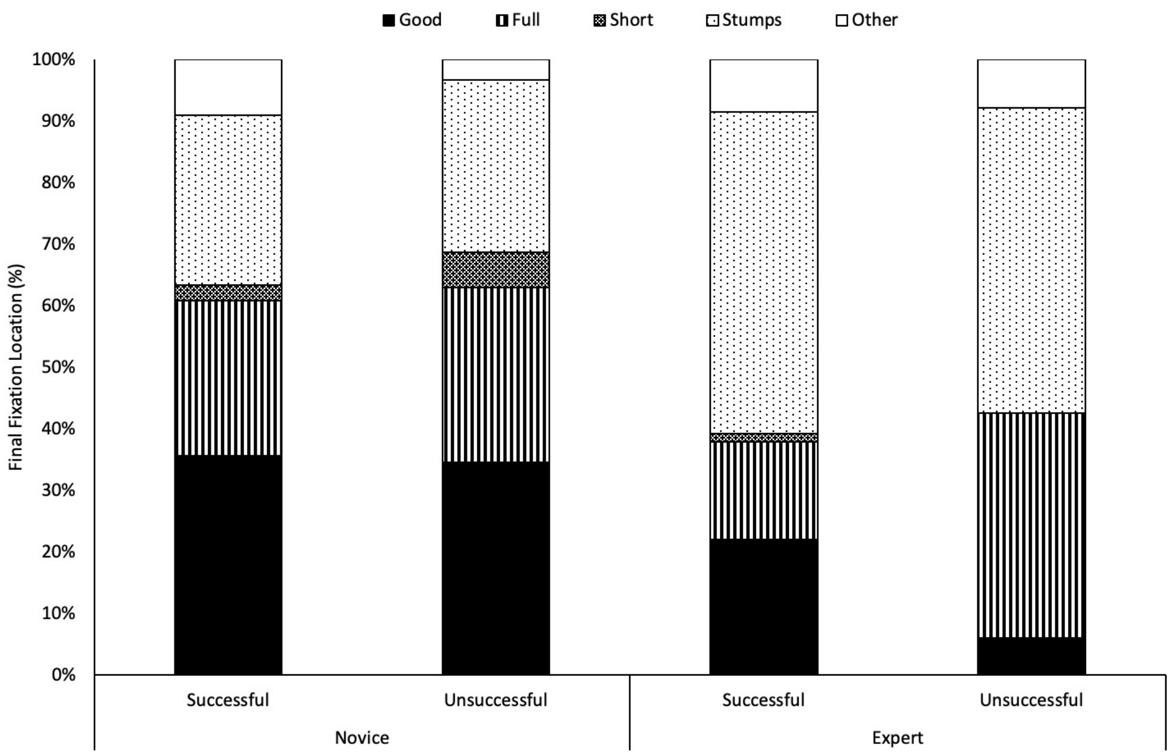

Figure 2.4: Final fixation locations (%) for experts and novices on correct and incorrect trials for *good, full length, short length, stumps* and *other* locations.

Discussion

In line with hypothesis 1, expert umpires were much more accurate on all aspects of the decision-making task, compared to the novice group. Experts demonstrated lower radial error when judging the location of the ball's pitch and impact with the batter's pad, and when predicting the location the ball would have passed the wickets had it not been obstructed. As well as providing predictive validity for the task, these data demonstrate that umpires possess domain-specific expertise in this complex decision making task similarly to Chalkley et al. (2013). Further to Chalkley's findings, this study highlights expert umpires possess domain specific advantages on all three components of the LBW task as opposed to solely the wickets aspect. These data also corroborate previous literature that has shown that expert sports officials are able to make more accurate decisions, by developing refined perceptual-cognitive strategies through deliberate practice activities, specifically competitive match exposure (MacMahon et al. 2007). As performers become more expert, they have been shown to use working memory more efficiently (Ericsson, 2008). In the current task, determination of pitch and pad primarily required the umpires to accurately recall the ball's spatial location, which might rely on the use of working memory (Furley & Wood, 2016). Researchers have proposed that when performing the task in which they are an expert in, performers are capable of circumventing the limits of working memory by directly accessing domain-specific information from long-term memory through retrieval cues in short-term working memory (Ericsson & Kintsch, 1995). This may explain the more accurate decisions of the experts in the pitch and pad judgements. Such an explanation would be in line with the assumption that whilst elite officials do not have a greater working memory capacity for general tasks, they acquire strategies that enable a more efficient use of working memory in domain-specific activities (Spitz et al. 2016).

Despite their differences, both groups were less accurate when predicting stumps compared to pad. This can be explained by the fact that judging ball flight path after ball-pad contact requires a perceptual judgement based on a variety of factors such as batter stance (Southgate et al., 2008), dynamics of the delivery (spin and swing) and the ball's surface degradation (Chalkley et al., 2013). Conversely, when judging ball-pad impact, all visual information was present so the umpire did not need to consider these contextual factors.

As well as accuracy differences, previous studies of expertise in sport have consistently reported differences in the number of fixations and average fixation duration between skill levels in a variety of tasks (Mann et al. 2007). It is generally accepted that in a temporally constrained decision-making task, such as the current study, a more efficient strategy consists of fewer fixations of longer duration (Mann et al. 2019). This is predominantly to reduce suppression of information during saccadic eye movements in order to maximise the information that can be gathered (Ludwig, 2011). However, there was no significant difference in the number of fixations between the groups. Furthermore, the average fixation duration for the novice group was significantly longer than that of the expert umpires, although this was not associated with more accurate decision making.

The finding that final fixation duration was significantly longer for the novices compared to the experts, conflicts with hypothesis 2. Previous studies (Raab & Laborde, 2011) have shown that experts are better able to generate the first and best option, produce fewer overall options and are quicker to generate the first option than near-experts and novices, therefore requiring a shorter final fixation. Conversely, novices sometimes require a longer final fixation in order to extract the information needed to make a judgement as they have less refined perceptual-cognitive strategies (Mann et al., 2019). This is supported by reports that experts favour intuitive decision-making, compared to novices, who tend to be more deliberative (Raab & Laborde, 2011). Novices have been shown to generate more options (Raab & Laborde, 2011) and take longer to generate an initial response (Raab & Johnson, 2007). Conversely, experts have been shown to generate fewer options and pick the first option more often

(Raab & Laborde, 2011), a strategy that has been shown to result in better and more consistent decisions (Johnson & Raab, 2003). This take-the-first heuristic allows the experts to make quick decisions under limitations of time, processing resources, or information. Whilst these decisions are usually accurate, they can sometimes be affected by biases (Raab & Johnson, 2007). Whilst cricket umpiring generally allows some time for deliberation, it could be argued that the speed at which critical visual information becomes available dictates that intuitive decision making plays a key role. Whilst this argument corresponds with these unexpected findings and additionally the expertise differences seen in hypothesis 1, an alternative explanation can be found in Chirico et al. (2019). In the shooting section of the pentathlon laser run, experts similarly adopted a shorter QE duration than the novices. It was proposed that this atypical finding was a result of the experts being conditioned to perform under time constraints where a compromise between the speed and accuracy of the task is required. Similarly, it is possible that umpires select their decisions intuitively with the intention of not slowing the match down. Despite this possibility, there is no official ruling on the timeframe in which an umpire should select a decision, and therefore comparisons with Chirico et al. (2018) remain unconvincing.

However, in support of hypothesis 3 and similarly to Chirico et al. (2018), a longer QE duration in both groups led to more successful decisions. This finding further supports the idea that the QE provides functional benefits in tasks which do not require a motor component, perhaps due to increased dorsal visual stream activation (Vickers, 2012) which is essential in determining an object's location in the environment (Zachariou et al. 2014). Further, this finding is in support of Schnyder et al. (2017) who found preliminary evidence that the QE is of use in sporting officials who are required to process multiple sources of information concurrently.

In hypothesis 4, it was predicted that expert umpires would use a perceptual-cognitive strategy that consisted of a final fixation point (gaze anchor) in a location central to the critical information sites. In support of this, the more accurate decisions made by the expert group across all of the conditions could be explained by their allocation of attention to the stumps significantly more than their novice counterparts, who tended to allocate their final fixation towards a good length on the pitch. Such differences also corroborate previous research within fast-ball sports (Broadbent et al. 2015), which have shown specialised perceptual-cognitive skills utilised by expert performers enhance their ability to locate and identify salient cues which ultimately aid decision making success. A gaze anchor is located in the centre of several critical cues (pitch, pad, stumps) in order to distribute attention towards several information points using peripheral vision. Use of the gaze anchor has been seen to enhance decision making of football officials in expert and near-expert assistant football referees, who anchored their gaze on the offside line as opposed directing foveal vision on either the passer, the ball or the attacker (Schnyder et al. 2017). Such a strategy might have held utility for this task and assistant football refereeing as both tasks do not offer the official an abundance of time in which to make their decision, and therefore peripheral vision acts as an additional attentional spotlight. Notably, the actual fixation location (stumps) from the present study may not contain any task-specific information that is being processed by the fovea, but is equidistant to the pertinent cues (Vansteenkiste et al., 2014). Therefore, by anchoring their gaze toward to stumps, the expert umpires are capable of utilising their peripheral vision to ascertain the position the ball pitched as well as the initial angle of delivery using the relative motion around the central point. Consequently, information processing via foveal vision directed towards the stumps might have enhanced their ability to perceive the height and line of impact with the pad and thus provided them with an increased accuracy when judging the trajectory of the ball towards the stumps. The expert's ability to deploy a visual anchor might be a consequence of them possessing a broader functional field of view (FFoV). In a driving task, Crundall (1999) found experienced drivers identified more stimuli on the periphery of the display than lesser experienced counterparts. Further, when cognitive demands were increased, both samples suffered from a decrease in ability to pick up the peripheral stimuli. It has been argued that domain specific experience enables a wider FFoV due to optimal performance requiring lower processing demands being placed on the central task. Such a view might also correspond with the capability of expert's utilising the aforementioned LT-WM, where some of the limitations of working memory are reportedly circumvented. With this is translated to cricket umpiring, perhaps the central LBW decision making requires lower cognitive effort on the cricket umpires and as result they can employ the gaze anchor to process peripheral cues due to possession of a broader FFoV.

Conversely, with a shrunken FFoV, the novice umpires might not have been capable of utilising both foveal and peripheral vision to make the judgements, and therefore might have fixated on a good length due to the pitch aspect being the first consideration when applying the LBW law. In addition to a possible reduced FFoV, the demands of processing multiple trajectories and impact points may have overwhelmed the working memory capacity of the novices leading to less accurate decisions on the later variables. The information reduction hypothesis (Haider & Frensch, 1999) postulates that when individuals practice a task, they selectively allocate attentional processes towards task-relevant information at the expense of task-redundant information which limits the load on working memory processes, and as a consequence enhances performance. In the current study, the expert's anchoring their vision on the stumps may have permitted them to selectively process critical information related to pad and wickets and thus reduce task-redundant processing. Consequently, load on the working memory will have been reduced and recall of all three components of the LBW law may have been enhanced.

Summary

Taken together these data show that expert umpires have developed a systematic perceptual-cognitive strategy, comprising a gaze anchor, that enables them to overcome the processing demands and maximise accuracy in a complex decision making task. These data provide an important first step toward the design of training interventions to help less-skilled umpires develop a more refined and systematic visual strategy to enhance decision making. However, further research is required to determine the processing demands in umpires during a delivery, which includes other elements, such as the front foot no ball call, and other external factors influencing attentional control. For example, the use of a real-life bowler, and the front foot no ball decision, would increase the representativeness of both the batter's biomechanics (Pinder et al. 2009) and the overall match demands of an umpire, which may alter the umpires' visual strategy. It is possible that the limited time between the front foot grounding and the ball-pad impact might impair the use of the gaze anchor and require umpires to implement an alternative gaze strategy. Understanding the development of these domain-specific perceptual-cognitive skills and the effect of other attentional and contextual factors will be critical in designing any future training interventions.

Chapter 3:

Task-Switching, Attentional Allocation and LBW decision making

Abstract

Cognitive psychologists have consistently shown that switching between consecutive tasks can result in the misallocation of attention and poorer performance. Cricket umpires are required to determine the legality of each delivery by considering the landing position of the bowler's front foot in relation to the crease, before reallocating their attention to events related to the ball and batter. The aim of this study was to examine whether this attentional switch would modulate performance when adjudicating leg before wicket (LBW) decisions. Fifteen expert cricket umpires wore an eye tracker as they performed a series of LBW decision tasks in two conditions (task-switching, control), with and without the requirement to adjudicate the front foot no ball'. Dependant variables were: radial error (cm), final fixation duration (ms), pre-impact duration (ms), post-impact dwell time (ms), number of fixations, average fixation duration (ms) and final fixation location (%). Overall radial error was not significantly different between the 'task-switching' and 'control' conditions; however, radial error was higher on the initial 'pitch' judgement in the task-switching, compared to control condition. In successful trials, umpires employed a longer final fixation duration and post-impact dwell time on the stumps. Task-switching led to shorter final fixation and pre-impact durations as well as an increase number of final fixations to less-relevant locations. These data suggest that expert umpires use adaptive gaze strategies to maintain decision accuracy despite increases in processing demands and the constraints of reallocating attention. These data have implications for understanding expert perceptual-cognitive skill in complex decision-making tasks and may have implications for the development of training protocols for sub-elite umpires.

Every day there is a demand for individuals to attend to multiple tasks successively over a short period of time (Vandierendonck et al. 2010). Researchers have highlighted the debilitative effect that task-switching can have on response time and overall performance accuracy (Monsell, 2003). When switching between tasks individuals can experience ‘attentional inertia’, where they require a longer period to re-orientate their visual attention towards a secondary task, as well as being more likely to orientate attention towards task-irrelevant cues (Longman et al. 2013). In sport, athletes, coaches and officials are often placed under severe temporal constraints, with high processing demands, whilst trying to navigate a complex and transient environment (Mann et al. 2019). Therefore, individuals are required to switch between multiple sources of information in order to achieve an optimal outcome.

In cricket, umpires must switch from determining the location of the bowler’s landing foot at one end of the pitch, to monitoring the trajectory of a ball travelling up to 95 mph towards the batter, before making a series of perceptual-cognitive judgements approximately 22 yards away from the release point, all in under a second (Chedzoy, 1997). The most complex decision for an umpire is the leg before wicket (LBW) judgement (Craven, 1998). Firstly, according to Law 36 of the Marylebone Cricket Club (2017) laws of cricket, an umpire is required to determine the legality of the delivery by observing if any part of the bowler’s shoe is grounded behind the popping crease and inside the return crease (see Figure 3.1). Next, umpires must perform an accurate refixation towards the batter (Southgate et al. 2008) to determine whether the ball: 1) ‘pitched’ (bounced) in line, offside or legside of the stumps (see Figure 3.2); 2) impacted the batter’s pad in line with the stumps; and 3) would have hit the wickets if the batter’s pad had not obstructed the ball. Umpires are required to process all of this information, as well as account for environmental information, such as ball condition and pitch degradation, with little over 500 ms of visual information (Chalkley et al. 2013). In order to alleviate some of these constraints, it was suggested in Chapter 2 that expert umpires use systematic and refined perceptual-cognitive strategies, comprising a long final fixation (gaze anchor) on the stumps at ball-pad impact.

A gaze anchor (Vater et al. 2019) involves a fixation located in the centre of multiple critical cues in order to distribute attention to several sources of information using peripheral vision. Importantly, the actual fixation location may not contain any task-specific information that is being processed by the fovea, but is equidistant to the pertinent cues (Vansteenkiste et al. 2014). A long, stable fixation before a critical action, termed the quiet eye (QE) (Vickers, 1996), has been reported to be related to more accurate performance in a range of targeting and interceptive tasks (Vickers, 2016a). Effective quiet eye is typically predicated by an earlier fixation onset on a target (Causer et al. 2010), allowing for maximum information extraction of task-relevant information from the critical source. Further, due to the immense time constraints faced by umpires whilst each delivery is live (between the time the ball is released and when it strikes the batter's pad), it was suggested in Chapter 2 that there was only an allowance for umpires to allocate one fixation on an area of interest, as opposed to utilising strategies such as a visual pivot.

Researchers have shown reduced cognitive performance when switching between different task-sets, this phenomenon being termed the 'switch cost', which can lead to reduced overall performance and increased response time on the second task (Vandierendonck et al., 2010). Task sets can be considered distinct from one another should they possess task-specific processes such as perceptual encoding, memory retrieval, response selection or response execution (Schneider & Logan, 2007). A potential explanation for switch costs is related to impaired reorientation of visual attention (Longman et al., 2013; Longman et al. 2014), which occurs concurrently during task-set inhibition and/or task-set reconfiguration (Longman et al. 2016). Specifically, there is evidence that task-switching impairs spatial attentional re-allocation towards a secondary task (Longman et al., 2013; Longman et al. 2017; Longman et al., 2014). Longman et al. (2013) found when participants had to switch between a facial recognition task and letter recognition task, they were more likely to fixate on the irrelevant location. The term 'attentional inertia' was coined where the researchers suggested attentional parameters had not been fully reset towards the second task, resulting in an increased tendency to fixate on the previously relevant but now irrelevant task. In a follow-up study, Longman et al. (2014) provided further evidence of 'attentional inertia' during the task-switch as participants were more likely to fixate on the previously relevant task location as opposed to an irrelevant task that was not performed previously, suggesting attentional parameters were not fully reset as participants switched tasks. Longman et al. (2017) found that when the attentional switch between the first and second task was self-paced, there was no explicit bias in fixating on the previously relevant task, but the switch cost and attentional impairments remained. Taken together these data suggest that task-switching, regardless of preparatory periods, may modulate spatial attention allocation towards the second task.

To date, few researchers have examined whether calling the front foot no ball debilitates decision making in cricket umpires. One exception was Southgate et al. (2008), who had first class umpires view simulated LBW appeals and determine whether the ball pitched 'in-line' or 'outside the line' of the stumps. Prior to making the decision, they were required to either make a front foot no ball decision, a back foot no ball decision, or no additional decision. Results showed that when required to attend to either no ball task first, umpires were significantly less accurate at determining where the ball bounced in relation to the stumps. Such results are in line with switch-cost literature, as performance on the LBW task was significantly poorer when umpires switched from the no-ball task. However, there were no additional attention measures that would have permitted a more detailed understanding of how task switching influences umpire decision making.

The aim of the current study was to examine the effect of task-switching on gaze behaviour and decision-making accuracy in expert cricket umpires. A representative, sport-specific task was developed, which matched the processing demands and temporal constraints of cricket umpiring. In the task-switching condition, the umpires were required to make a front foot 'no ball' judgement, before adjudicating three LBW-related judgments; where the ball pitched, impacted the batter's pad, and would have hit/passed the wicket. In the control condition, the umpires only made the three LBW-related judgments. It was predicted that; 1) task-switching would debilitate umpire performance on the 'pitch' component of the LBW decision more than the pad and wicket decision of the task due to the timing and order of critical cue availability (Southgate et al. 2008); 2) a longer quiet eye (gaze anchor) on the stumps would lead to more accurate LBW judgements (Chapter 2); 3) the additional task-switching requirement of the prior 'no ball' judgment would lead to attention being allocated towards cues unrelated to the LBW decision making process more often than when umpires made exclusively LBW decisions with no preceding secondary task (Longman et al., 2017).

Methods

Participants

Participants were 15 expert umpires (M = 53 years, SD = 16) who had officiated in organised cricket at elite club level (n = 11) and national level (n = 4). The expert umpires had a mean of 11 years (SD = 7) of competitive umpiring experience and had accumulated a mean of 274 matches (SD = 156). Participants gave their informed consent prior to taking part in the study and the study was approved by the Research Ethics Committee of the lead institution.

Task & Apparatus

Gaze behaviours were recorded using the TobiiGlasses2 corneal reflection eye movement system (Tobii Technology AB; Danderyd, Sweden). The test film was recorded at the Marylebone Cricket Club Cricket Academy. Video footage from an umpire's perspective was recorded using a Canon VIXIA HFR706 camera (Tokyo, Japan). The camera was positioned in line with middle stump 1.00 m away from the non-strikers popping crease. A right-handed batter who competes in the Worcestershire Premier League faced a number of deliveries delivered by a BOLA Bowling Machine (Bola Manufacturing Ltd.; Bristol, UK), from over the wicket, at speeds between 65-80 mph. The batter was encouraged to play their 'natural game' whilst facing these deliveries. Deliveries that struck the batter's pad were termed 'appeals' and were reviewed via 'Hawk-Eye' (Basingstoke, UK), which reconstructed the ball flight characteristics should the obstruction not have occurred (Collins, 2010). Hawk-Eye technology utilises a theory of triangulation, which helps predict post ball-pad impact by measuring angles from the known points of the delivery's pre-impact flight (Duggal, 2014). In total, 16 appeals were used for the study, 12 appeals were deemed 'out' and four deemed 'not out' by Hawk-Eye. Based on the surface, 4 trials were deemed to have pitched on a 'good length' and 4 trials were deemed to have pitched on a 'full' length in each condition. Each task-switching trial was paired with a control trial which corresponded in the region the ball pitched, impacted the batter's pad and where it would have travelled post impact. As a result, in each condition hawk eye predicted 3 trials would have middle stump, 3 trials would have struck leg stump and 2 trials would have missed the stumps. Based on pilot testing, trials that were deemed too easy (85% and above in accuracy), were omitted from the final test film.

To examine the effect of task-switching, 8 of the trials required umpires make the front foot 'no ball' judgement prior to adjudicating the LBW appeal, whilst the remaining 8 trials exclusively involved adjudication of the LBW appeal. In the task-switching condition, umpires were required to direct their attention towards the popping crease (see Figure 3.1) where a cricket shoe was superimposed. If any part of the shoe appeared behind the popping crease the delivery was deemed legal. Based on research by Felton et al. (2019), the shoe appeared 100-125 ms prior to ball release from the bowling machine and remained grounded for a further 200 ms.

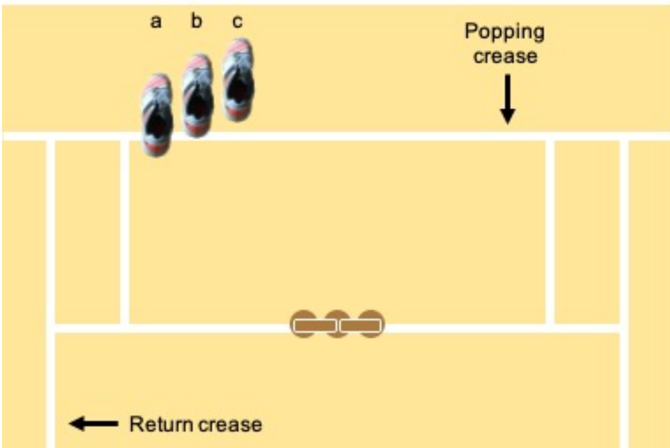

Figure 3.1: Examples of a front foot 'no ball': a) legal delivery; b) 'no ball'; and c) 'no ball'.

The footage was edited using Windows Movie Maker 2016 (Washington, USA). Each appeal formed one trial. For each trial the trial number, position of the delivery and condition (task-switching or control) were each shown for 3.0 seconds and were followed by a 3-second countdown. The video clip started 3.0 seconds before ball release, to represent the time for a bowler's run-up in a match scenario. The video clip continued for a further 3.0 seconds after ball-pad impact, and was followed by a black screen, which signalled the end of the trial. Task-switching trials and control trials were presented randomly.

Procedure

Participants were fitted with the TobiiGlasses2 (Tobii AB; Stockholm, Sweden) eye tracker and were calibrated using a one-point calibration card held by the researcher 1.00 m away. The test film was projected by an Epson EB-7000 projector (Suwa; Japan) onto a large Cinefold Projection Sheet (Draper Inc; Spiceland, IN; 2.74 m x 3.66 m). Participants stood 3.20 m away from this display to ensure it subtended a visual angle of 12.8 °, thereby replicating the height of the batter *in situ*. To cross-check calibration, participants viewed a still image of the pitch and were asked to direct their visual attention towards the stumps. This was repeated throughout the data collection period to ensure participant gaze remained calibrated with the eye trackers. The researchers provided the participants with an overview of the LBW rule as per Marylebone Cricket Club guidelines. To familiarise participants with the experiment protocol and response requirements, they observed two familiarisation trials, which showed LBW appeals similar to those in the test and an example of the front foot 'no ball' task. Participants verbally predicted the three components of LBW adjudication then viewed a handout that showed the Hawk-Eye ball flight path. This familiarised participants with the scale of the Hawk-Eye slides they would use to record judgments for each trial. Following this the testing period began. For the task-switching trials, participants were required to call any 'no ball' verbally, as they would in a game. After each trial participants positioned three balls (circles scaled to the Hawk-Eye image) on a computer image of the pitch. Specifically, the balls were positioned on Hawk-Eye slides corresponding to where they perceived the ball to have pitched, where it impacted the batter's front pad, and where it would have hit/passed the stumps had its flight not been obstructed (see Figure 3.2). Participants were asked to adjudicate the three variables in any order and in a time frame similar to how they would generally make decisions in a match. Once participants had made a judgement for one of the LBW variables, they could not alter this decision. This procedure was repeated for all 16 trials. The whole data collection process took approximately 35 minutes.

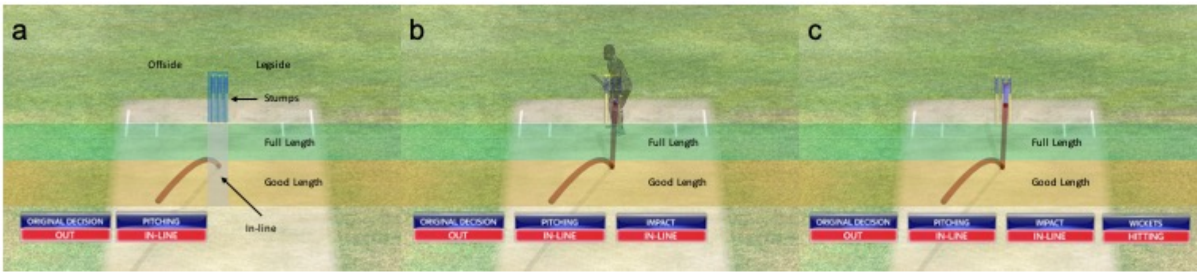

Figure 3.2: LBW decisions for: a) pitch; b) pad; and c) wickets. Panel 'a' includes eye movement areas of interest: stumps, full length and good length. Panel 'a' also includes labels for in-line, offside and legside.

Measures

Response accuracy was determined by *radial error* (cm), which was defined as the Euclidean distance of the participant's judgment of ball impact with the *pitch, pad,* and *stumps* compared to the Hawk-Eye data. This distance was scaled to quantify accuracy at a game scale (see Runswick et al. 2019). *Front foot 'no ball' accuracy* (%)

was defined as the percentage of correct responses. Fixations were defined as gaze being directed towards a location within 3 ° of the visual angle for a minimum of 100ms (Vickers et al 2019). *Number of fixations* were measured from the onset of the trial until the offset of the trial. *Average fixation duration* (ms) was calculated by dividing the total fixation duration by the number of fixations of each trial. *Final fixation duration* (ms) was the duration of the last fixation prior to ball-pad impact until conclusion of post-impact dwell time. Based on previous research (Causer et al. 2017), the *final fixation duration* was then split into two components: *pre-impact duration* and *post-impact dwell time* in order to identify changes in gaze strategy. *Pre-impact duration* (ms) was defined as the duration from the onset of the final fixation until ball-pad impact. *Post-impact dwell time* (ms) was defined as the fixation duration from ball-pad impact until offset of the fixation. *Final fixation location* (%) was defined as the percentage of trials participant's final fixation was located on a specific area. Four fixation locations were coded: *good length, full length, stumps, and other* (see Figure 3.2). The front pad of the batter occludes a large proportion of the stumps during a standard delivery. Therefore, when umpires directed their vision towards the batter's front pad, this was coded as '*stumps*' as the umpires typically maintained their gaze on the stumps after the batter had moved away, suggesting they were anchoring their gaze on the stumps as opposed to following the batter's pad.

Statistical Analysis

For each participant, in each condition, the three trials with the lowest overall radial error were classed as *successful*, whereas the three trials with the highest overall radial error were classed as *unsuccessful.* Radial error data were analysed by a 2 (Condition: task-switching, control) x 3 (Decision: pitch, pad, wickets) repeated measures analysis of variance (ANOVA). A paired *t*-test was conducted to examine differences in the percentage of correct 'no ball' decisions in *successful* and *unsuccessful* trials. Number of fixations, average fixation duration (ms), final fixation duration (ms), pre-impact duration (ms) and post-impact dwell time (ms) were analysed using separate 2 (Condition: task-switching, control) x 2 (Outcome: successful, unsuccessful) repeated measures ANOVAs. Final fixation location was analysed using a 2 (Condition: task-switching, control) x 2 (Outcome: successful, unsuccessful) x 4 (Location: good, full, stumps, other) repeated measures ANOVA. Effect sizes were calculated using eta squared (η^2) partial eta squared (ηp^2) and Cohen's *d* values, as appropriate. Greenhouse-Geisser epsilon was used to control for violations of sphericity and the alpha level for significance was set at .05 with Bonferroni adjustment to control for Type 1 errors. A priori power analysis using PANGEA (v0.2) (https://jakewestfall.shinyapps.io/pangea) for the 2 x 3 within-factors ANOVA with eight replicates per data point indicated that 15 participants was sufficient to detect a medium effect size (d = 0.5) interaction with a power of 0.85. Power of 0.80 was attainable for detection of medium-large effect sizes for the main effects of condition (d = 0.68) and decision (d = 0.66). For the 2 x 2 ANOVAs, 15 participants yielded power of 0.74 to detect a medium sized interaction (d = 0.5). For the paired t-test comparisons, G*Power (Faul et al. 2007) showed that 15 participants yielded power of 0.66 to detect a medium effect size (d = 0.5).

Results

Radial Error (cm)

Analysis of radial error data revealed a very large effect of decision, $F_{2, 28}$ = 16.55 p < .001, ηp^2 = .54, caused by significantly larger error on the judgments of wickets (M = 24.05 cm, SE = 1.71), compared to those for pitch (M = 13.75 cm, SE = 1.28) and pad (M = 16.19 cm, SE = 1.0) (both p < .01). Consistent with the experimental hypothesis, there was a significant interaction between condition and decision, $F_{2, 28}$ = 8.02 p = .002, ηp^2 = .36 (see Figure 3.3). This reflected that in judgements of pitch, as radial error was higher in the task-switching condition (M = 14.65 cm, SE = 1.08) compared to the control condition (M = 12.85 cm, SE = 1.56; d = .35). Conversely, radial error for pad judgements was significantly lower in the task-switching condition (M = 14.76 cm, SE = .84) than in the control condition (M = 17.61 cm, SE = 1.34; p = .05, d = .66). Judgments for wickets was not significantly different between the task-switching condition (M = 23.69 cm, SE = 1.34) and the control condition (M = 23.40 cm, SE = 2.16; p = .01, d = .04). The main effect of condition, $F_{1,14}$ = .66, p = .43, ηp^2 = .05, was small and statistically non-significant.

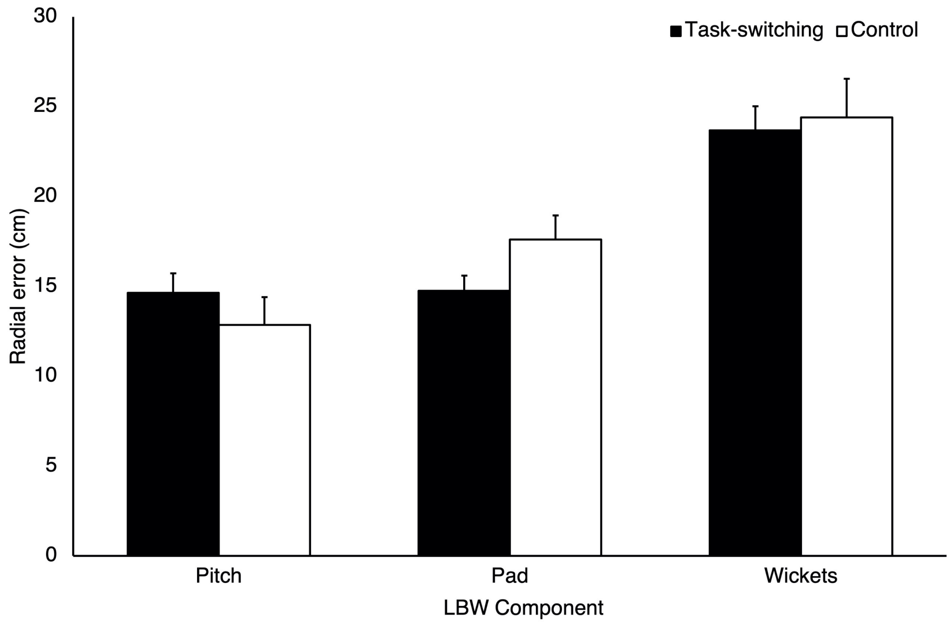

Figure 3.3: Radial error (cm; SE) for pitch, pad and wickets in the task-switching and control conditions.

Front foot 'no ball' accuracy (%)

There was no significant difference in the percentage of correct 'no ball' decisions in successful (M = 67.78 %, SE = 6.65) and unsuccessful trials (M = 66.67 %, SE = 5.27; *d* = .04) (t(14)= -.13, p = .90). This shows that higher performance on the 'no ball' judgment task did not affect combined accuracy across the three LBW judgments.

Number of Fixations

There was a very large effect of condition, $F_{1,14} = 41.60$, $p < .001$, $\eta p^2 = .75$, caused by umpires making more fixations in the task-switching condition (M = 7.05, SE = .41) than in the control condition (M = 4.76, SE = .33). The main effect of outcome, $F_{1,14} = .03$, $p = .87$, $\eta p^2 = .002$, and condition x outcome interaction, $F_{1,14} = .04$, $p = .84$, $\eta p^2 = .003$, were small and statistically non-significant.

Average fixation duration (ms)

There was a large effect of condition, $F_{1,14} = 13.11$, $p = .003$, $\eta p^2 = .48$. Average fixation duration in the task-switching condition was significantly shorter (M = 980.83 ms, SE = 66.68) than in the control condition (M = 1515.83 ms, SE = 139.34). The main effect of outcome, $F_{1,14} = .38$, $p = .55$, $\eta p^2 = .03$, and condition x outcome interaction, $F_{1,14} = .63$, $p = .44$, $\eta p^2 = .04$, were small and statistically non-significant.

Final fixation duration (ms)

There was a very large effect of condition, $F_{1,14} = 72.65$, $p < .001$, $\eta p^2 = .84$ (see Figure 3.4). Final fixation duration was shorter in the task-switching condition (M = 2197.11 ms, SE = 149.50) than in the control condition (M = 3344.89 ms, SE =

154.16). There was also a large effect for outcome, $F_{1,14} = 4.55$, $p = .05$, $\eta p^2 = .25$. Final fixation duration was longer in successful trials (M = 2942.45 ms, SE = 271.54) compared to unsuccessful trials (M = 2599.56 ms, SE = 130.57). The main effect condition x outcome interaction $F_{1,14} = .21$, $p = .65$, $\eta p^2 = .02$, was small and statistically non-significant.

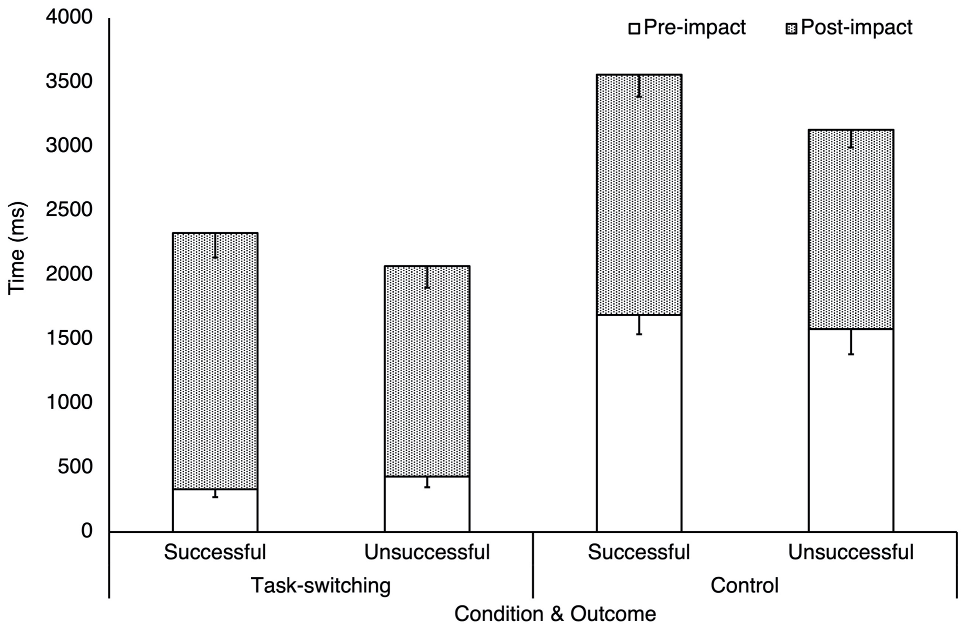

Figure 3.4. Final fixation duration (ms; SE), pre-impact duration (ms) and post-impact dwell time for successful and unsuccessful trials in the task-switching and control conditions.

Pre-impact duration (ms)

There was a very large effect of condition, $F_{1,14} = 186.21$, $p < .001$, $\eta p^2 = .93$ (see Figure 3.4). As expected, pre-impact duration was shorter in the task-switching condition (M = 381.56 ms, SE = 56.86) than in the control condition (M = 1633.78 ms, SE = 81.14). The main effect of outcome, $F_{1,14} = .01$, $p = .98$, $\eta p^2 < .01$, and the condition x outcome interaction, $F_{1,14} = .49$, $p = .50$, $\eta p^2 = .03$, were small and statistically non-significant.

Post-impact dwell time (ms)

There was a large effect of outcome, $F_{1,14} = 11.58$, $p = .004$, $\eta p^2 = .45$ (see Figure 3.4). Post-impact dwell time was significantly longer in the successful trials (M = 1932.00 ms, SE = 154.45) than in the unsuccessful trials (M = 1594.67 ms, SE = 129.11). The main effect of condition ($F_{1,14} = 1.31$, $p = .27$, $\eta p^2 = .09$) and the condition x outcome interaction ($F_{1,14} = .02$, $p = .89$, $\eta p^2 = .00$) were non-significant.

Final fixation location (%)

Analysis of umpires' final fixations revealed a strong interaction between outcome and location, $F_{3,42} = 5.80$, $p = .002$, $\eta p^2 = .29$ (see Figure 3.5). This reflected significantly more final fixations on the stumps in successful trials (M = 59 %, SE = 5), than in unsuccessful trials (M = 43 %, SE = 5) ($d = .61$). Conversely, significantly fewer final fixations were on other locations in successful trials (M = 8 %, SE = 3) than in unsuccessful trials (M = 18 %, SE = 4) ($d = .48$). There was a large effect of location, $F_{3,42} = 17.68$, $p < .001$, $\eta p^2 = .56$, caused by significantly more final fixations being located on the stumps (M = 51 %, SE = 5) compared to a full length (M = 20 %, SE = 2; $d = 1.93$), good length (M = 16 %, SE = 4; $d = 1.49$) and 'other' locations (M = 13 %, SE = 3; $d = 1.60$). There was also a strong interaction between condition and location, $F_{3,42} = 3.79$, $p = .02$, $\eta p^2 = .21$. This reflected significantly more final fixations on other locations in the task-switching condition (M = 22 %, SE = 6), than in the control condition (M = 3 %, SE = 2; $d = .98$). The condition x outcome x location interaction was non-significant, $F_{3,42} = 1.14$, $p = .34$, $\eta p^2 = .08$.

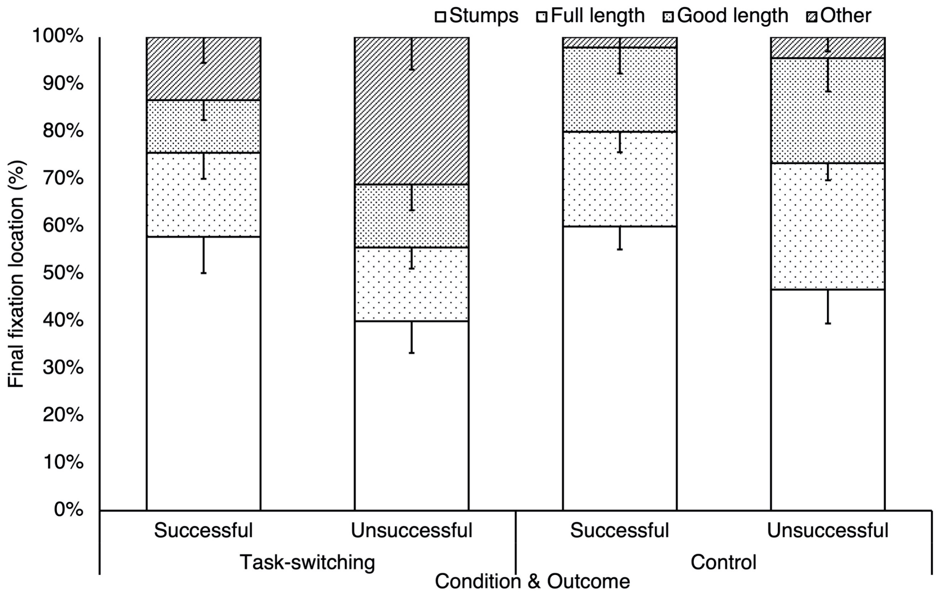

Figure 3.5. Final fixation location (%; SE) for successful and unsuccessful trials in the task-switching and control conditions for stumps, full length, good length and other locations.

Discussion

Across all LBW components combined, umpires maintained overall performance levels despite the addition of the secondary 'no ball' task-switching requirement. However, similarly to Southgate et al. (2008), task-switching led to reduced performance when determining the spatial position of where the ball bounced (pitched). This 'switch-cost' may have occurred due to a necessity to either reconfigure the cognitive system towards the new task or inhibit the activation of the previous task-set (Vandierendonck et al., 2010). Consequently, the poorer performance on determining the pitching location of the ball might have reflected these processes needing to occur between the completion of the 'no ball task' and the commencement of the 'LBW decision making task'. Whilst purely speculative, this unexpected finding might have emerged as a result of the optimal timing of a fixation being directed towards critical locations during ball-pad impact, whereby permitting increased attentional weighting to this task and not the preceding 'pitch' task. Task-switching also led to significantly more final fixations made on less-informative areas (other). When moving between fixation locations using saccades there is typically a spatial relocation error (Becker, 1972). Furthermore, researchers have consistently reported an undershoot of the target location by 5-10%, as well as the requirements of at least one 'catch-up' saccade to establish an accurate fixation on the intended target (Aitsebaomo & Bedell, 1992; Kowler & Blaser, 1995; Poletti et al. 2020). This inaccuracy can be explained by previous work reporting that task-switching results in spatial attentional re-allocation being directed towards cues unrelated to the secondary task when there is insufficient time to adjust attentional settings to completion (Longman et al., 2013, 2017; Longman et al., 2014). This may explain why more final fixations were made to less-relevant areas of the display when umpires made a saccade from the 'no ball' task to the main LBW judgments.

Despite task-switching appearing to modulate attentional allocation, across both conditions the umpires still utilised a gaze anchor on the stumps at the point of ball-pad impact; a technique associated with expert cricket umpires (Chapter 2). A gaze anchor is located in the centre of several critical cues (pitch, pad, stumps) in order to distribute attention to several cues using peripheral vision. This strategy enables multiple sources of information to be processed without the need for saccadic eye movements, therefore maximising the information that can be acquired (Vater et al., 2019). Final fixations were located on the stumps significantly more in successful trials compared to unsuccessful trials, providing some evidence that the gaze anchor on the stumps is the most effective strategy when required to consider the three components of the LBW decision. Like in Chapter 2, predicting the wickets component of the task resulted in less accuracy than the other two components. This was likely due to the nature of the wickets decision requiring a perceptual estimation based on aspects related to the delivery (Chalkley et al., 2013), whereas the other two components rely less on estimation, as spatial information related to the ball's impact points were fully visible during the appeal. Therefore, the final fixation on the stumps would have provided the umpires with more information to refine their estimation, on what appears to be the most difficult component of LBW decisions.

Whilst the location of the final fixation is important, the duration of it also critical to successful decision making. Whilst a longer QE duration led to more successful LBW decisions, a shorter QE duration in the task-switching condition did not impact overall LBW performance. This was due to the dwell component of the QE being significantly longer in accurate decisions. A longer dwell time or final fixation has long been associated with more successful performance, and was also reported in the current study (Wilson et al. 2016). In tasks with clear perception-action coupling the advantage is suggested to be with pre-programing of task-relevant information, such as distance, force and environmental factors (Wilson et al. 2015). However, in the current task, there is no clear action component, simply a perceptual judgment task. Therefore, the longer dwell period in the current study may have enabled more accurate processing of the ball flight characteristics as well as the prediction of the ball flight path after impact with the pad.

Due to the constraints during the task-switching condition, compared to the control condition, there were predictably more fixations of shorter duration and the pre-impact QE duration was significantly shorter. This observation is typically associated with a less efficient strategy in temporally constrained tasks (Mann et al., 2019), however, in the current task this was necessary to allow umpires to attend to both tasks. The timing of the 'no ball' decision enforced later onset of the final fixation associated with the LBW judgments, reflected in the shorter pre-impact duration in the task-switching condition (Figure 3.4). Earlier onset of final fixation has consistently been found to be a characteristic of more accurate performance in a range of targeting and interceptive tasks (for review see Vickers, 2016a). However, the onset of the final fixation has been often linked to benefits in pre-programming of movement parameters in a task that requires an action. Therefore, in the present task, which did not require any movement related behaviours, the dwell period held the salient role in information processing as the decision would have principally relied on the angle, deviation, and spatial position of the ball as it struck the batter's pad. This extended dwell period may have also enabled maintenance of top-down dorsal stream attentional control (Vickers et al. 2016b) so that all three LBW components were processed in the absence of attention being directed towards distractive stimuli. In addition to the applied implications, this finding extends theoretical understanding of the QE in that optimal onset and offset is likely task-specific and that a number of mechanisms related to attentional focus, pre-programming and inhibition (Gonzalez et al. 2017a) might all be involved during the fixation at different temporal moments. This perhaps points to a case for the development of an integrated model which incorporates multiple mechanisms that might interact with one another, and how each of them might possess a critical role in specific tasks.

Summary

Data from the current study show that prior attention to the bowler's foot to make a 'no ball' judgment did not impair overall LBW decision accuracy. However, it significantly affected the gaze strategy used by umpires and the radial error shown in the pitch judgment. Task-switching also led to shorter final fixation and pre-impact durations, both of which have been shown to lead to more successful performance.

However, irrespective of condition, umpires maintained a gaze anchor on the stumps in more successful trials. Despite attention being frequently directed to less relevant locations in the 'task-switching' condition, this gaze strategy ensured there were limited 'switch-costs' when performing the dual-task. Post-impact dwell duration was also longer in accurate decisions in both conditions, suggesting it plays an essential role in determining ball-flight characteristics related to velocity and angle of delivery, as well as spatial information about the batter and stumps. Taken together, these results partially support the ICC and their decision to remove the on field umpire's responsibility for calling front-foot no balls, and instead enabling the TV umpire to make these decisions (refer to Chapter 1). However, it is important to acknowledge that LBW decision making forms just one type of decision roles that an umpire is required to make. As such, further examination of how task-switching affects adjudication of catches and other types of decisions can help further establish whether calling of no-balls should be governed by on field or TV umpires. Nevertheless, the present study provides an indication that task-switching can affect decision making of LBWs, which have often been suggested to be amongst the most complex of tasks in sports officiating due to the umpires being required to extrapolate events that might have arisen, had other events not transpired (Craven, 1998).

Chapter 4:

The Effect of Quiet Eye Training on LBW Decision Making

Abstract

Within the perceptual-cognitive skill domain, 'Quiet Eye training' interventions have been developed and implemented in novice samples. Whilst these interventions have been extensively shown to improve performance in a variety of motor tasks, to date no studies have examined their effectiveness in a solely perceptual decision-making task. The aim of this study was to examine whether a Quiet Eye training intervention would improve leg before wicket (LBW) decision making accuracy in novice umpires. Participants (n = 72) were split into three groups: 1) Quiet Eye (QE) Training; 2) Technical Training (TT); and 3) Control. Participants performed 8 trials of a similar task to the experimental condition from Chapter 3, which formed a pre-test. Following this, the QE group viewed training videos providing instructions on expert umpire gaze behaviours whilst the TT group viewed videos including standardised umpire coaching instructions. The Control group did not receive any training. Participants then performed a further 8 trials of the LBW decision making task which formed the post-test. A one-week retention test was also completed. Findings showed that post-intervention, QE training improved decision-making accuracy in all three LBW components, whilst TT only improved accuracy in the 'wickets' component. However, in a one-week retention test, only the QE trained group maintained performance gains. The Control group did not change in decision accuracy across all three tests. These data have implications for the future training programmes of cricket umpiring, and would suggest perceptual-cognitive training interventions could be implemented alongside technical information to accelerate skill learning and ensure higher quality decision making.

In 1967, it was proposed by Paul Fitts and Michael Posner that there are three distinct stages of skill acquisition. The first stage, termed the *cognitive stage*, "…*involves encoding of the skill into a form sufficient to permit the learner to generate the desired behaviour to at least some crude approximation*" (Anderson, 1982). Here learners consciously rehearse the skill mentally and often follow explicit instructions step-by-step. Second, in the *associative stage* learners gain an increasing understanding of the task and are able to consciously identify and iron out errors in their execution (Anderson, 1982). Finally, the *autonomous stage* involves an indefinite improvement of the skill (Anderson, 1982), whilst also involving improved execution speed, accuracy and overall reduction of errors (Anson et al. 2005). Whilst it is widely accepted that mastery of any task requires thousands of hours of deliberate practice (Ericsson et al. 1993), attempts have been made to expedite this via various perceptual-cognitive interventions with the purpose of accelerating skill acquisition (Faubert & Sidebottom, 2012).

In Chapter 2 and Chapter 3, it was shown that an extended QE period on the stumps following ball-pad contact appeared to facilitate more accurate decision making in cricket umpires when making LBW decisions. With such results considered, the question arises; can the QE behaviours exhibited by the experts be practiced by novices to yield better performance and decision making (Farrow & Panchuk, 2016)? This is a question that has been presented since the initial studies examining perceptual-cognitive skill were published, and therefore 'Quiet eye' training interventions have been developed with the aim of enhancing skill acquisition of both novices and experts in a variety of tasks (Miles et al. 2015; Miles et al. 2017; Moore et al. 2012; Moore et al. 2013; Vine & Wilson, 2011; Vine et al. 2013; Vine et al. 2014).

Perhaps the study which provides the most insight regards the mechanistic benefits of QE training can be seen in Moore et al. (2012). In their study, novice participants performed 40 putts which formed baseline results, before they underwent QE or TT training depending on the group they were assigned to. In addition to absolute putting success and radial error measures, this study also assessed kinematic and physiological factors. Compared to baseline results, both groups significantly improved putting performance in the two retention tests on day five and day seven, highlighting the efficacy of both interventions. However, in the retention tests the QE group significantly outperformed the TT group both in the number of balls putted and by achieving lower radial error. Gaze behaviour analyses found that whilst both groups increased QE durations in the retention tests, the QE group increased theirs significantly longer than the TT group. The QE group also displayed more efficient putting kinematics in the retention test, by reducing lateral and vertical clubhead acceleration, which leads to better contact with the ball. Physiological changes were also apparent after the QE intervention, as participants showcased an early deceleration in heart rate prior to the putt, this being a characteristic of expert golfers. Further, at the point of striking the ball, the QE group recorded half of the electromyographic activity in the extensor carpi radialis of the left arm compared to the TT group in the retention test. Taken together, these findings highlight the effectiveness of QE interventions, as well as further mechanistic explanations as to why these interventions often display superior results to TT interventions.

However, to date there have been no studies which explore the efficacy of a QE intervention on a solely perceptual task which does not a possess a coupled motor action. Upon finding the reduced muscle activity which followed QE training, Moore et al. (2012) suggested that the intervention led to greater attentional resources being allocated towards the task. Further, it has been proposed an elongated QE leads to increased dorsal visual stream activity (Vickers, 2012; Vickers 2016a) and therefore it is possible that QE training interventions might prove to be of benefit to cricket umpiring. Therefore, the aim of this study was to examine whether QE training would enhance decision making in novice cricket umpires when making leg before wicket (LBW) decisions. As cricket umpiring does not involve an associated motor action in response to a stimulus, it is one of the few fast ball tasks that likely relies predominantly on optimal spatial attention allocation, a suggestion that is supported in Chapter 2 and 3.

It was hypothesised that:

1: Both QE and TT training would lead to an improvement in decision making performance across all Hawk-Eye components in the post-test (Vickers, 2017).

2: Only the QE group would maintain the beneficial effects in the retention test (Miles, 2017). 3: The control (CTRL) group would exhibit no changes across Hawk-Eye components in the pre-test, post-test and retention test.

Methods

Participants

The participants were 72 novice umpires (mean age = 20.44, SD = 3.21) who were randomly assigned into one of three groups. In total there were 21 participants assigned to a QE training group (mean age = 20.19, SD = 2.99), 27 participants assigned to a TT training group (mean age = 20.26, SD = 3.85) and 24 participants assigned to a control (CTRL) group (mean age = 20.67, SD = 2.58). Participants had no prior experience in cricket umpiring. Informed consent was provided prior to taking part in the study and the study was approved by the Research Ethics Committee of the lead institution.

Task & Apparatus

Visual Search Behaviours

Unlike in Chapter 2 and Chapter 3, visual search behaviours could not be collected due to the study being based online due to Covid-19 restrictions.

Test Films

LBW appeals for the test films were recorded at the Marylebone Cricket Club (MCC) Academy. Video footage from an umpire's perspective was recorded using a Canon VIXIA HFR706 camera (Tokyo, Japan). The camera was positioned in line with middle stump 1 metre away from the non-strikers popping crease. A right-handed batter from the MCC Academy faced a number of deliveries delivered by a BOLA Bowling Machine (Bola Manufacturing Ltd.; Bristol, UK) from both around and over the wicket at speeds between 65-80mph. In total, 8 unique appeals were used for the pre-test, post-test, and retention test. In each condition, there were 4 out decisions and 4 not-out decisions (two deliveries missing the wickets and two pitching outside leg-stump). Similarly to Chapter 3, in each phase 4 trials pitched on a 'good length' whereas the other 4 pitched on a 'full length'. Further, in each phase, 2 trials would have struck off stump, 2 trials would have struck middle stump and 2 trials would have struck leg stump. As with Chapter 3, each trial corresponded with another trial in the other two phases and were matched for both speed and the 'wickets' component of the LBW. Each test-film was edited in a similar manner to that seen in Chapter 3. Each trial commenced with a black screen with the trial number that was present for 3 seconds, before information was presented about the batter's batting orientation (right hand or left-hand batting grip) and the position of the delivery (over or around the wicket), which again lasted for 3 seconds. A 3 second countdown was followed by commencement of the trial. A 3 second lead in time was presented to the batter, before the ball was released from the machine. Following ball-pad impact, the participant was offered a further 3.0 seconds of visual information before a black screen signalled the end of the trial. The position of delivery for each trial was randomised to avoid any order effects.

Hawk-Eye

Hawk-Eye was used similarly to Chapter 2 and Chapter 3 to extrapolate where the ball pitched, impacted the pad and where it would have travelled post-impact.

Qualtrics

To distribute the test to as many participants as possible, the pre-test, acquisition phase, post-test and retention test were built into two separate surveys using Qualtrics (Qualtrics 2005, Utah, USA). Each trial was presented on a separate page of the survey.

Task

In the pre-test, post-test, and retention test, the following was presented; an embedded video of an LBW appeal, an image displaying three shoes, and an 'empty' Hawk-Eye diagram which was split into a grid of 35 x 43 squares (see Figure 4.1). The embedded video for each page was a different LBW appeal which participants were only able to watch once. The image of three shoes formed the 'no ball task' and depicted one image where the back of the shoe was completely in front of the crease, the next where the back of the shoe was located on the crease and the final image where the back of the shoe was located behind the crease. Participants had to click on the image of the shoe which they thought corresponded to where the front foot appeared in the video. On the Hawk-Eye grid, participants had to click exactly where they thought the ball bounced, where the ball struck the batter's pad and finally where the ball would have travelled had the obstruction with the pad not occurred. This provided the researchers with coordinates for the participant's recall and prediction of each LBW component. Upon completing this task, participants clicked 'arrow' at the bottom of the page to move onto the next trial.

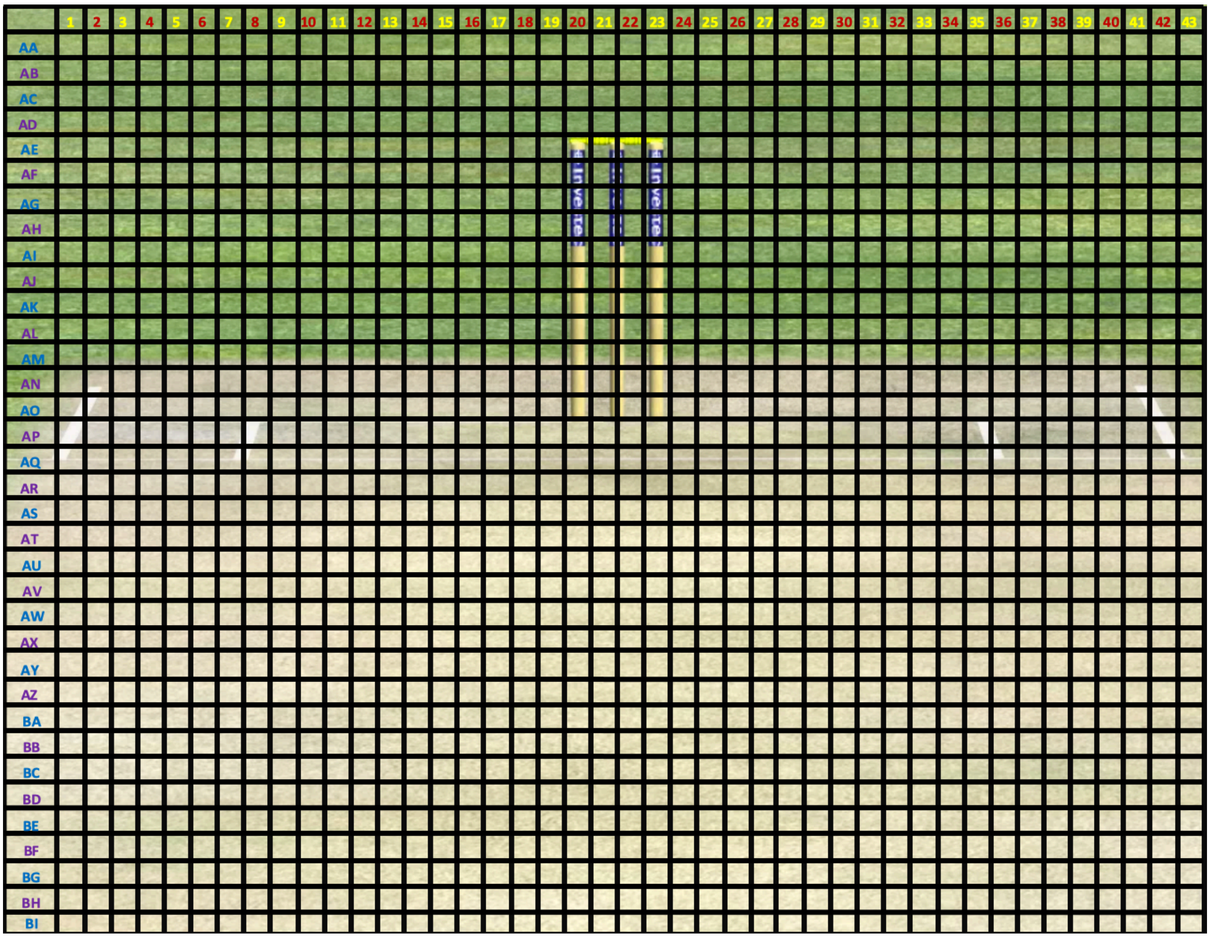

Figure 4.1: 'Empty' Hawk-Eye grid where participants clicked on to submit their 'pitch', 'pad' and 'wickets' decisions

Procedure

The testing period for this study was 7 days. On Day 1, participants were emailed a weblink which directed them to the correct test corresponding with the group they were assigned to. After reading the information sheet and providing informed consent they were shown an instruction sheet outlining the procedure. Importantly, participants were instructed that the ball could bounce anywhere on the pitch and that the ball might hit or miss the wickets, and that they could only view each trial once. Following this, a practice trial with the corresponding LBW data was presented so that participants could distinguish the scale between the simulated trials and the Hawk-Eye prediction. Once the instructions had been read, the pre-test began. After participants viewed an LBW appeal they were initially required to perform the 'no ball task' before they proceeded to provide LBW coordinates on the Hawk-Eye grid situated below the video. The pre-test comprised of 8 trials. The pre-test took approximately 15 minutes to complete.

Table 4.2: Step by step instructions for the QE and TT interventions

Quiet Eye Training Instructions	**Technical Training Instructions**
Fixate on the crease. The shoe will appear on the crease. Keeping your eyes still on the crease, determine whether ANY part of the shoe is BEHIND the line.	The shoe will appear on the crease. Determine whether ANY part of the shoe is BEHIND the line.
As soon as you have determined whether the shoe was behind the line, quickly transfer your gaze towards the stumps.	The ball will be released from the bowling machine after the shoe appears.
Keep a stable fixation on the stumps whilst the ball travels.	Take note of where the ball is travelling and where it might bounce

Continue to look at the stumps, even when the ball bounces. Determine where the ball pitches.	Determine whether the ball bounced to the left of the line of the stumps, in line with stumps or to the right of the line of the stumps. Consider imagining three lines on the pitch in front of the stumps to help you with this.
Maintain your gaze on the stumps even after the ball has impacted the pad. Determine where the ball hits the pad. Do not follow the ball post-impact.	It is a good idea to have doubts about any appeal that strikes the batter's pad ¾ of the way up. Determine the spatial positions of where the ball would have gone and how far it had to travel post pad-ball impact.
Continue to fixate on the stumps even if the batter moves, and do this till the end of the trial.	Always take into account how far the ball has to travel after striking the batter's pad as this will determine whether it will strike the stumps when it is travelling at an angle. Remember all of the components of the LBW when making your decision (where the ball bounced, where it impacted the batter, and where it would have travelled).

Upon completion of the pre-test, they next took part in the acquisition phase. The QE group and TT group viewed a 5-minute training video (Table 4.2), before viewing 16 LBW appeals so that they could practice what had been outlined in the video. The training videos followed Vickers et al. (2017) who similarly provided both QE and TT instruction via YouTube. The quantity of both instructional sets offered participants a similar amount of information to a number of studies (Moore et al. 2012; Moore et al. 2013; Vine et al. 2013) who used '6 training points'. This procedure was repeated a further two times, as they re-watched the training video before viewing a new set of LBW appeals. Like the other two groups, the CTRL group were required to watch the three videos of 16 LBW appeals, however they were not shown any training videos. The acquisition phase took approximately 30 minutes. A similar procedure to the pre-test was then followed in the post-test where participants made decisions on 8 new LBW appeals.

On day 7, all participants were sent a link which directed them to the retention test. Participants were reminded to utilise the information they had learnt in the acquisition phase on Day 1, before they performed 8 LBW decisions in a similar manner to the pre-test and post-test. Finally, participants were taken to a page thanking them and were debriefed.

Measures

Response accuracy was determined by *radial error* (cm), which was defined as the Euclidean distance of the participant's judgment of ball impact with the *pitch, pad, and stumps* prediction compared to the Hawk-Eye data. This distance was scaled to quantify accuracy at a game scale (see Runswick et al., 2019). The Rating Scale Mental Effort (RSME) was used to measure participant's subjective perception on their cognitive workload throughout each phase of the study.

Statistical analysis

Radial error data between the pre-test and post-test was analysed by a 3 (Group: QE, TT, CTRL) x 2 (Phase: Pre-Test, Post-Test) mixed-factor analysis of variance (ANOVA). Radial error data between the post-test and retention test was also analysed by a 3 (Group: QE, TT, CTRL) x 2 (Phase: Post-Test, Retention Test) mixed-factor analysis of variance (ANOVA). Radial error data between the pre-test and retention test was also later analysed by a 3 (Group: QE, TT, CTRL) x 2 (Phase: Pre-Test, Retention Test) mixed-factor analysis of variance (ANOVA). RSME data was analysed using a 3 (Group: QE, TT, CTRL) x 3 (Phase: Pre-Test, Post-Test, Retention-Test) mixed factor analysis of variance (ANOVA). Effect sizes were calculated using partial eta squared values ($\eta p2$). Greenhouse-Geisser epsilon was used to control for violations of sphericity and the alpha level for significance was set at .05 with Bonferroni adjustment to control for Type 1 errors.

Results

Radial error (cm)

Pre-Test to Post-Test

Pitch

There was a moderate between-subject main effect for pitch $F_{2,69} = 3.27$, $p = .04$, $\eta p^2 = .09$. Pitch radial error was significantly higher in the TT group (M = 21.95 cm, SE = 1.17) compared to the QE group (M = 17.85 cm, SE = 1.33) (p = .02) and CTRL group (18.50 cm, SE = 1.24) (p = .05). There was no significant difference in pitch radial error between the QE and CTRL group. There was also a moderate phase main effect $F_{1,69} = 6.54$, $p = .01$, $\eta p^2 = .09$. Pitch radial error was significantly lower in the post-test (M = 18.27 cm, SE = .84) compared to the pre-test (M = 20.59 cm, SE = .86) (p < .05). There was no significant group x phase interaction for pitch $F_{2,69} = 2.51$, $p = .09$, $\eta p^2 = .07$. However, pitch radial error for the QE group was significantly lower in the post-test (M = 15.41 cm, SE = 1.56) compared to the pre-test (M = 20.30 cm, SE = 1.59) (t (20) = 3.08, p < .01). There was no significant difference in pitch radial error in the TT group between the pre-test (M = 21.91 cm, SE = 1.40) and post-test (M = 21.99 cm, SE = 1.37) (t (26) = -.05, p = .96). Similarly, in the CTRL group there was also no significant pitch radial error difference in the pre-test (M = 19.57cm, SE = 1.48) and post-test (M = 17.43 cm, SE = 1.45) (t (23) = 1.46, p = .16).

Pad

The between-subject main effect for pad was non-significant $F_{2,69} = .11$, $p = .90$, $\eta p^2 = 003$. There was no significant difference in pad radial error between the QE group (M = 24.23 cm, SE = 1.61), TT group (24.74 cm, SE = 1.42) and CTRL group

(M = 25.26 cm, SE = 1.51) (p > .05). The phase main effect for pad was also non-significant $F_{1,69} = .09$, $p = .77$, $\eta p^2 = .001$. There was no significant difference in pad radial error in the pre-test (24.85 cm, SE = .93) and the post-test (M = 24.64 cm, SE = .96) (p > .05). There was a significant group x phase interaction for pad $F_{2,69} = 3.12$, $p = .05$, $\eta p^2 = .08$ (see Figure 4.3). The QE group had significantly lower pad radial error in the post-test (M = 22.83 cm, SE = 1.78) compared to the pre-test (M = 25.63 cm, SE = 1.71) (t (20) = 2.25, p = .04). In the TT group there was no significant difference in pad radial error in the pre-test (M = 24.26 cm, SE = 1.51) and the post-test (M = 25.22 cm, SE = 1.57) (t (26) = -.69, p = .50. In the CTRL group there was also no significant difference in pad radial error in the pre-test (M = 24.66 cm, SE = 1.60) and the post-test (M = 25.87 cm, SE = 1.66) (t (23) = -1.28, p = .21).

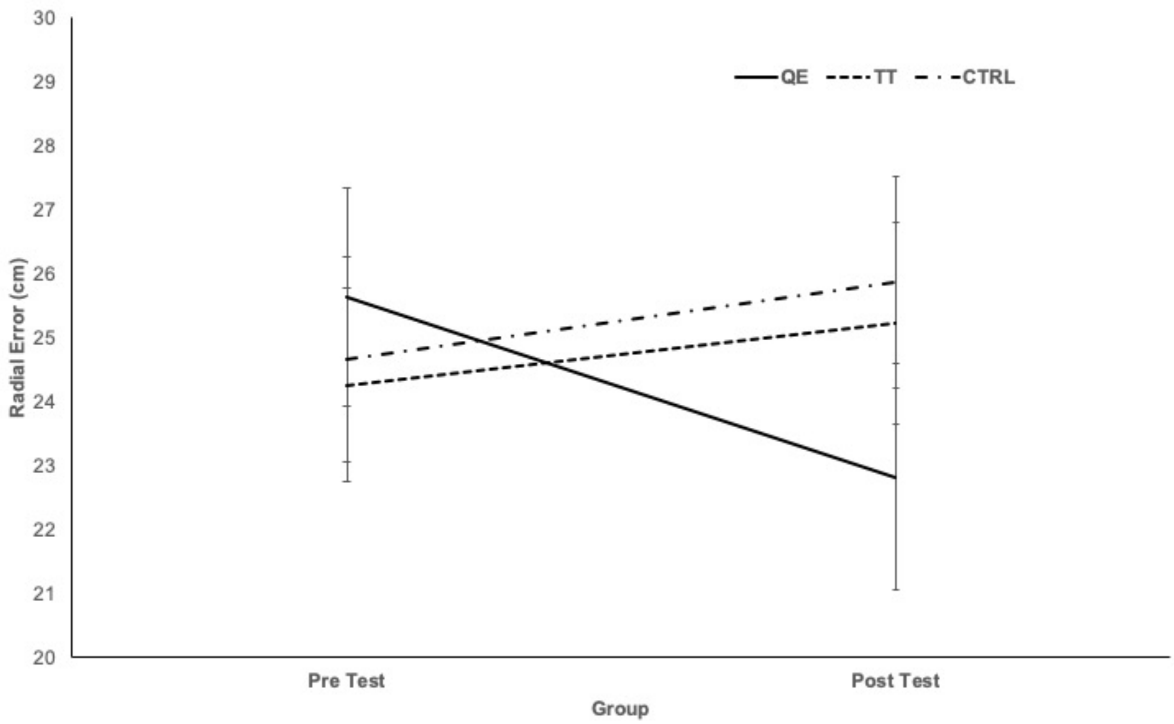

Figure 4.3: Radial error for pad in each group between the Pre-Test and Post-Test

Wickets

The between-subject main effect for wickets was moderate but statistically non-significant $F_{2,69} = 2.20$, $p = .12$, $\eta p^2 = .06$. There was no significant difference in wickets radial error between QE group (M = 27.26 cm, SE = 2.06), TT group (M = 26.57 cm, SE = 1.81) and the CTRL group (M = 31.77 cm, SE = 1.92) ($p > .05$). There was a large phase main effect for wickets $F_{1,69} = 19.50$, $p < .001$, $\eta p^2 = .22$. Radial error for wickets was significantly lower in the post-test (M = 26.78 cm, SE = 1.10) compared to the pre-test (M = 30.29 cm, SE = 1.26) ($p < .001$). There was also a moderate group x phase interaction for wickets $F_{2,69} = 5.18$, $p = .01$, $\eta p^2 = .13$ (see Figure 4.4). The QE group improved significantly from the pre-test (M = 30.09 cm, SE = 2.32) to the post-test (M = 24.42 cm, SE = 2.03) (t (20) = 3.89, p = 001). The TT group also significantly improved from the pre-test (M = 29.04 cm, SE = 2.05) to the post-test (M = 24.11 cm, SE = 1.79) (t (26) = 3.83, p = .001). However, the CTRL group did not show any differences between the pre-test (M = 31.73 cm, SE = 2.17) and the post-test (M = 31.82 cm, SE = 1.90) (t (23) = -.07, p = .95).

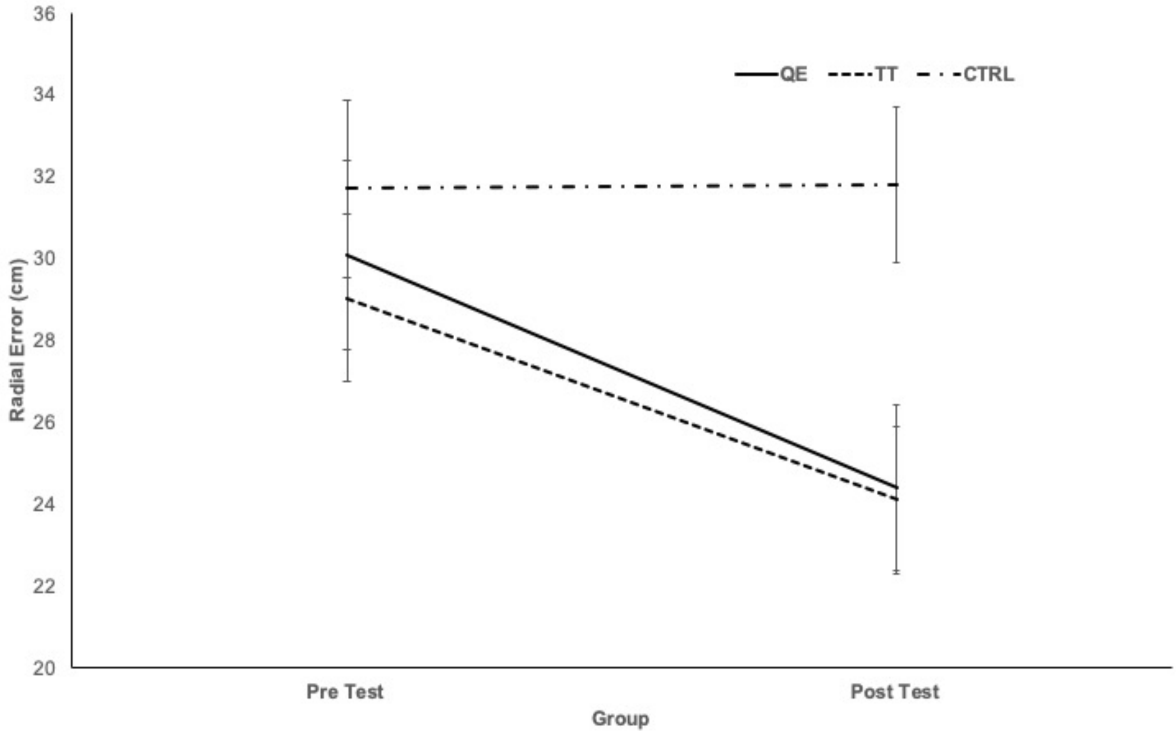

Figure 4.4: Radial error for wickets in each group between the Pre-Test and Post-Test

Post-test to retention

Pitch

The between-subject main effects for pitch were moderate but statistically non-significant $F_{2,41} = 2.45$, $p = .10$, $\eta p^2 = .11$. Pitch radial error was significantly higher in the TT group (M = 21.51 cm, SE = 1.66) compared to the QE group (M = 15.84 cm, SE = 1.96) (p < .05). Pitch radial error in the CTRL group (M = 18.84 cm, SE = 1.96) was not significantly different to the QE group or the TT group (p > .05). The phase main effects for pitch were small but statistically non-significant, $F_{1,41} = .44$, $p = .51$, $\eta p^2 = .01$. There was no significant difference in pitch radial error between the post-test (M = 18.39 cm, SE = 1.27) and the retention test (M = 19.08 cm, SE = 1.12) (p > .05). There was also no significant group x phase interaction $F_{2,41} = 1.76$, $p = .18$, $\eta p^2 = .08$.

Pad

The between-subject main effect for pad was small and statistically non-significant $F_{2,41} = 1.31$, $p = .28$, $\eta p^2 = .06$. There was no significant difference in pad radial error between the QE group (M = 22.52 cm, SE = 1.91), TT group (M = 26.00 cm, SE = 1.63) and CTRL group (M = 26.46 cm, SE = 1.91) (p > .05). There were no phase main effects for pad $F_{1,41} = .08$, $p = .77$, $\eta p^2 = .002$. Pad radial error was not significantly different across the post-test (M = 24.81 cm, SE = 1.10) and retention test (M = 25.17 cm, SE = 1.33) (p > .05). There was also no significant group x phase interaction for pad $F_{1,41} = 1.09$ $p = .34$, $\eta p^2 = .05$.

Wickets

The between-subject main effect for wickets was small and non-significant $F_{2,41} = 1.17$, $p = .32$, $\eta p^2 = .05$. There was no significant difference in wickets radial error between the QE group (M = 23.41 cm, SE = 2.45), TT group (M = 25.52 cm, SE = 2.08) and CTRL group (M = 28.68 cm, SE = 2.45) (p > .05). There were also no significant phase main effects for wickets $F_{1,41} = 1.64$, $p = .21$, $\eta p^2 = .04$. Wickets radial error was not significantly different across the post-test (M = 26.53 cm, SE = 1.46) and the retention test (M = 25.21 cm, SE = 1.43) (p > .05). However, there was a strong group x phase interaction for wickets $F_{1,41} = 3.44$, $p = .04$, $\eta p^2 = .14$ (see Figure 4.5).

In the post-test the QE group (M = 24.73 cm, SE = 2.65) and the TT Group (M = 24.39 cm, SE = 2.25) had significantly lower wickets radial error compared to the CTRL group (M = 30.48 cm, SE = 2.65). However, in the retention test, radial error was significantly lower in the QE group (M = 22.09 cm, SE = 2.60), compared to the TT Group (M = 26.66 cm, SE = 2.21) and the CTRL group (M = 26.87 cm, SE = 2.60) ($p < .05$).

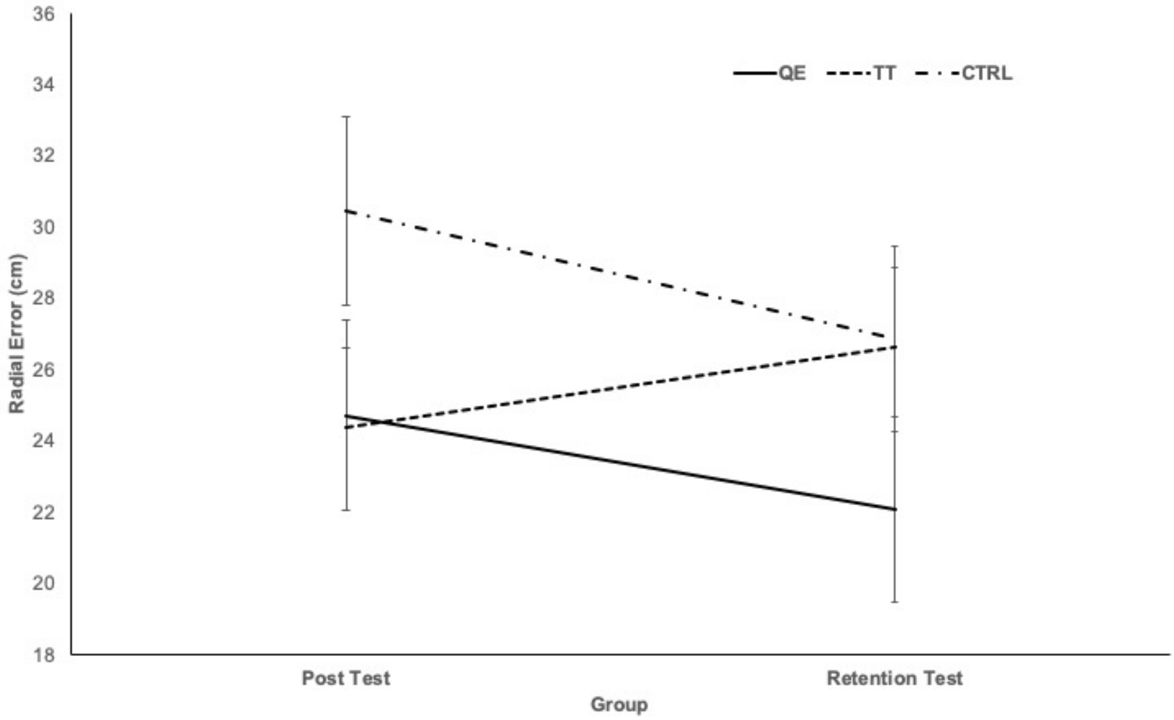

Figure 4.5: Radial error for wickets in each group between the Post-Test and Retention Test

Pre-test to retention

Pitch

The between-subject main effect for pitch was small and statistically non-significant, $F_{2,41} = 1.20$, $p = .31$, $\eta p^2 = .06$. There were also no main effects for phase, $F_{1,41} = .20$, $p = .66$, $\eta p^2 = .01$. The group x phase interaction for pitch was also small and statistically non-significant, $F_{2,41} = 2.09$, $p = .14$, $\eta p^2 = .09$.

Pad

The between-subject main effect for pad was small and statistically non-significant $F_{2,41} = .26$, $p = .78$, $\eta p^2 = .01$. There were no phase main effects for pad $F_{1,41} = .34$, $p = .56$, $\eta p^2 = .01$. However, there was a moderate group x phase interaction for pad, $F_{2,41} = 4.24$, $p = .02$, $\eta p^2 = .17$. This was reflected in the QE group having significantly lower pad radial error in the retention test (M = 21.20 cm, SE = 1.99) compared to the pre-test (M = 27.19 cm, SE = 2.17). Conversely, in the TT group there was no significant difference for pad radial error in the pre-test (M = 24.50 cm, SE = 1.84) and the retention-test (M = 21.02 cm, SE = 1.99). There was also no significant difference for the CTRL group between pad radial error in the pre-test (M = 24.96 cm, SE = 2.17) and the retention-test (M = 26.37 cm, SE = 1.99). The group x phase interaction was also small and statistically non-significant, $F_{2,41} = 2.09$, $p = .14$, $\eta p^2 = .09$.

Wickets

The between-subject main effect for wickets was small and statistically non-significant $F_{2,41} = .18$, $p = .84$, $\eta p^2 = .01$. However, there was a moderate phase main effect for wickets $F_{1,41} = 23.67$, $p < .001$, $\eta p^2 = .11$. This was reflected in radial error being significantly higher in the pre-test (M = 31.24 cm, SE = 1.69) compared to the retention test (M = 25.21 cm, SE = 1.43). The group x phase interaction for wickets was small and statistically non-significant, $F_{2,41} = 2.64$, $p = .08$, $\eta p^2 = .11$.

Discussion

There were no differences between the groups in pre-test radial error measures for pitch, pad and wickets, indicating all three groups started the study with a similar level of umpiring ability, and therefore any changes in radial error could to be attributed to the respective interventions. Only the QE group significantly reduced radial error for ‘pitch’ and ‘pad’ in the post-test compared to pre-test. For ‘wickets’, both the QE and TT group improved significantly in the post-test from pre-test, whilst no changes were seen in the CTRL group. In the one-week retention test, the QE group maintained the post-test improvements for the pitch, pad and wickets components. However, the post-test wickets performance improvements in TT group were lost in the retention test so that they were unable to significantly outperform the CTRL group on this component. The CTRL group again showcased no differences in radial error in all three components in the retention test compared to the pre-test and post-test.

In the post-test, the QE group were able to improve decision making accuracy in the pitch and pad components of the LBW decision, whereas the other two group’s radial error did not change from pre-test. This partially supported hypothesis 1, as whilst the QE group were able to significantly improve accuracy on these two components, it was also expected that the TT group would showcase similar improvements. However, in support of hypothesis 1, the QE and TT group improved their decision-making accuracy on ‘wickets’ in the post-test. It is possible that the TT group were unable to improve the other two Hawk-Eye components as they might have struggled to attend to all three tasks utilising the TT guidance which did not explicitly state they should anchor their gaze onto a single critical location. As a result, participants from this group might have been unable to transfer their attention towards three separate tasks and therefore only managed to improve their ‘wickets’ prediction.

Technical instruction 5 and 6 also provided explicit information on how to interpret the ball hitting the batter's pad in relation to the wickets task, whereas instruction on the other two Hawk-Eye components was less forthcoming. Conversely, the QE group improving accuracy on all three Hawk-Eye components might be explained by the intervention promoting the strategy of anchoring gaze onto the stumps.

The use of the gaze anchor (Vater et al. 2019) was proposed in Chapter 2 and Chapter 3 to permit expert umpires to process information related to all three LBW components concurrently, an idea similar to that offered by Schnyder et al. (2017). The performance improvements related to the intervention might be explained by theories relating to the two visual attention systems (Corbetta & Shulman, 2002; Milner & Goodale, 2008b). Similarly to Vickers (2017), the present study was unable to include the recording of eye movements to confirm the QE group anchored their gaze on the stumps and increased their QE duration, however a number of studies which utilised similar intervention protocols found they are effective at achieving this outcome. It has been suggested that a prolonged QE duration exerts a greater level of cognitive processing via the dorsal visual stream and therefore not only enhances attentional allocation towards task related cues, but also provides an individual with the ability to prevent distractive stimuli from being processed (Vickers, 2017). There is some evidence to support this idea, as studies have shown QE interventions prevent attention from being misallocated when participants are faced with pressurised situations (Moore et al. 2012; Moore et al. 2013; Vine & Wilson, 2011). For example, Miles et al. (2015) found that QE training led to children being better able to predict the location the ball would bounce off the wall, this being somewhat like the umpires being required to ascertain where the ball pitches and impacts the batter's pad. The idea that increased attention allocation towards task related cues via QE might contribute towards augmented cricket umpiring decisions is perhaps best outlined by Vickers (2012), who postulated that increased activation of the dorsal attentional stream via the QE might enable participants to sustain spatial focus of attention on a location in the external environment. Further, Moore et al. (2014) proposed that an extended QE might be the optimal gaze strategy for effectively storing critical locations in the visuo-spatial sketchpad of the working memory. As a result, it would leave participants better placed to process the three critical location points that are paramount in the decision making of cricket umpiring.

In support of hypothesis 2, the QE group were able to maintain performance gains seen in the post-test across all three Hawk-Eye components, suggesting that QE training can enhance the learning of LBW decision making. Also, in support of hypothesis 2, the gains made by the TT group on the wickets judgement immediately after the acquisition phase were lost one week later. Once again, the CTRL group experience no change from post-test to retention test accuracy in any of the Hawk-Eye components. Such results are somewhat replicated by Miles et al. (2017), who found in a catching task that whilst both QE and TT training improved catching performance of children in a one-week retention test, the QE group significantly outperformed the TT group after six weeks. Similarly, Moore et al. (2012) found a one-week after a QE intervention, novice golfers showcased a prolonged QE and lower radial error, compared to a TT. Taken together with the results from the present study, it is apparent that QE training expedites robust learning of both motor and perceptual tasks. Perceptual learning is defined as an improvement in the ability to respond the environment, and is explained through mechanisms such as optimization of attentional weighting (Jackson & Farrow, 2005). It is possible that enduring performance benefits related to QE training might be a result of the formation of implicit perceptual learning where the individual does not solely focus on the external target (Vine & Wilson, 2010). Causer et al. (2014a) suggested QE training facilitated performance of surgical knot tying in students due to it permitting a single relevant point of focus where movements and actions could be orientated around. Therefore, whilst not being explicitly instructed as to the successful technical related movement aspects of the surgery, it was suggested the prolonged QE duration enabled the students to learn the optimal method of organising their hands in a non-explicit manner. Although Fitts and Posner's model of skill acquisition relates to motor tasks like that of the surgeons in Causer et al. (2014a), with respect to umpiring, a prolonged fixation on the stumps might have provided the participants with a constant uninterrupted stream of information (Moore et al. 2014). This may have enabled implicit learning of information related to the ball, stumps, pitch and batter concurrently, and consequently helped participants overcome the cognitive stage of learning. Conversely, the TT group's instructions emulated the 'cognitive stage' where they were required to consciously consider the multiple permutations associated with each LBW component in a step-by-step manner (Anderson, 1982). Therefore, it might have required a longer intervention with further practice for the participants in this group to learn and automate the skill of making three decisions simultaneously. Further, the TT group might have relied on rule-based inferences which may have enhanced initial performance in the post-test, but with decay of procedural memory relating to the task, they may have been unable to maintain these improvements a week later. To some degree the QE training might therefore have led to processes that are somewhat similar to 'external focus of attention' theories, which report that providing learners with an external cue related to the outcome of the task prevents debilitative step-by-step consideration of task execution (Poolton & Zachry, 2007). When considering the means in which each intervention led to varying types of learning, it is entirely possible that the QE group received instructions that mirrored a 'guided discovery' approach. Specifically, the participants were directed towards a salient region on the display but were not provided instructions as to how to integrate the multiple cues to generate a decision. Conversely, the TT group were provided a greater number of rules related to the ball, batter and pitch, therefore this type of intervention being somewhat akin to an 'explicit instruction' approach (Jackson & Farrow, 2005). Vine et al. (2013) provide some evidence for the use of QE training to enable acquisition of implicit knowledge from a motor perspective, however one must be cautious of arising to concrete conclusions in the present study until additional measures are recorded. Whilst difficult to assess the degree of explicit and implicit learning of each group, perhaps future perceptual task-based QE studies might record participant task related confidence alongside each trial. Improved performance coupled with an absence of increased confidence might provide some insight as to whether QE training leads to the formation of implicit knowledge (Jackson & Farrow, 2005).

It is also somewhat difficult to make strong assertions as to the mechanisms underpinning the current data due to the lack of eye tracking available, due to testing restrictions. Whilst all studies examining the efficacy of QE interventions have led to an increase in QE duration, performance enhancement of cricket umpiring that was attributed to an increased final fixation duration on the stumps must be approached with hesitancy until further eye tracking measures can be put in place to validate this conclusion. Further, whilst several studies have included a one-week delayed retention test (Moore et al. 2012; Moore et al. 2013), the testing period was relatively short with respect to some other QE studies which have utilised an 8-week period (Miles et al. 2015; Miles et al. 2017) to test the efficacy of QE interventions.

Nevertheless the current study provides support that a QE intervention can significantly improve umpire decision making in novices across all three Hawk-Eye components, whilst a TT intervention seemingly exclusively enhances decision making accuracy on the wickets component. Further, after one-week, improved LBW decision accuracy effects persist with no apparent decline following QE training, whereas performance increments associated with TT instruction appear to decay within the same time window. Upon validation, it is recommended that a training programme could be used on a mass scale to accelerate the learning of novice umpires who have enrolled in the national umpire pathway. In turn this might ensure better decisions are made throughout a variety of cricket levels, especially in levels where ball tracking technology is unavailable to rectify incorrect decisions (Collins, 2010). This study also provides further evidence that the benefits of the QE might be related to attentional control mechanisms, and therefore should not be viewed solely as an optimal gaze strategy exclusive to activities that require sensorimotor pre-programming and online control of motor actions (Causer et al. 2017).

Chapter 5:

Epilogue

This Chapter will integrate all of the studies presented in this thesis with the aim of delineating the theoretical and applied implications related to the findings. Limitations of each study will also be discussed and potential avenues for future research will be considered.

5.1 Aims of the thesis

The general aim of this thesis was to utilise the expert performance approach proposed by Ericsson & Smith (1991) to provide an incisive understanding of how perceptual-cognitive skills contribute towards LBW decision making in cricket umpires. A plethora of research over the past two decades has established experts employ a range of refined perceptual-cognitive skills such as: greater effectiveness in moving eyes towards relevant areas of the environment to extract more informative information, the capacity to use cues from opponent kinematics to enable advanced anticipation of projectile flight, the facility to recognise patterns within team invasion sports and the capacity to use cognition to predict likely behaviours of an opponent in advance (Causer et al. 2012).

The first step in the expert performance approach prescribes researchers to 'capture superior performance'. In cricket, an abundance of research has shown expert batters have exclusively developed the ability to use perceptual-cognitive skills (Land & McLeod, 2000; Müller et al. 2006; Müller et al. 2009; Renshaw & Fairweather, 2000) to help them strike the ball, which can be delivered at a velocity that exceeds the reaction time of humans. Despite this, there is a scarcity of research examining the perceptual-cognitive skills employed by expert umpires when required to adjudicate LBW appeals. Umpires are faced with the same time constraints as the batters, and whilst it is accepted that compared to the batters, split second decision making is less decisive, the umpires must still process a vast amount of information that is visually available for little over 500-1000 ms (Southgate et al. 2008) with incorrect decisions influencing overall match outcomes and perhaps critically player's careers (Craven, 1998). Further, LBW decision making appears to be unique in that it requires the official to consider what events might have taken place had other events not occurred (Craven, 1998). The only preceding study that has examined whether expert umpires possess an advantage in LBW decision making was Chalkley et al. (2013). Whilst this study provided some evidence that umpires make better decisions than non-umpires, eye movement behaviours were not recorded, so conclusions with regards to the use of perceptual-cognitive skills were approached with hesitancy. Therefore, the aim of Chapter 2 was to build on Chalkley's initial study by examining whether umpires utilised specialised eye movement behaviours whilst making LBW decisions. Further adaptions were made to Chalkley's study to create a representative task that would provide a more acute understanding as to the differences between expert and novice umpires. Firstly Chapter 2 utilised Hawk-Eye technology to assess umpire decision making accuracy for all three components of the LBW as opposed to the temporal occlusion setup seen in Chalkley et al. (2013). Not only did this permit a batter to be struck on the pad, but it also allowed a full appeal to take place as opposed to occlusion of the display. This enabled the researchers to understand how decision-making accuracy would vary between the groups in a more ecologically reliable setting.

The second step of the expert performance approach, 'analysing expert performance' (Ericsson & Smith, 1991) helped formulate the aim of Chapter 3; does task-switching affect decision making accuracy in umpires. Within cognitive psychology laboratory tests, findings have constantly shown that switching between tasks causes a 'switch-cost' performance decline on the second task (Monsell, 2003).

One of the theories explaining the switch-cost suggests that during the period between the two tasks, there is often insufficient time for complete reconfiguration of attentional parameters towards the second task (Longman et al. 2013; Longman et al. 2014; Longman et al. 2017). This in turn reportedly leads to a less accurate saccadic refixation towards the second task. Despite this evidence, all studies that have explored the relationship between attention and the switch-cost have been laboratory-based and therefore such effects remain untested in more representative tasks. Chapter 3 aimed to understand whether the switch-cost occurs when cricket umpires shift attention from a front foot no ball task to the LBW task. Further, Chapter 3 aimed to examine whether eye movements would be directed to less informative areas on the during this task-switch in line with Longman et al. (2017).

Finally, the third stage of the expert performance approach, 'acquisition of expert performance and its mechanisms' (Ericsson & Smith, 1991), dictated the approach of Chapter 4; would LBW decision making accuracy be improved in novice umpires by training them expert eye movement behaviours identified in the earlier chapters. In Chapter 2 and 3, during the critical ball-pad impact, two separate groups of expert cricket umpires displayed a tendency to anchor their vision on the stumps at the strikers end of the pitch. Further a longer QE duration was seen as an effective strategy to increase decision making accuracy. These findings were used to design a QE intervention that was compared against a TT intervention derived from an official umpire's handbook, as well as a control group. A one-week retention test was also included to evaluate whether the intervention would render stable learning effects.

5.2 Summary of key findings

In Chapter 2, expert and novice umpires completed a simulated video-based LBW decision making task. To assess skill-based differences between the groups, participants were required to view 20 life sized LBW appeals and accurately determine where the ball pitched, where the ball struck the batter's pad, and where the ball would have ultimately travelled. These decisions were then compared against Hawk-Eye prediction data (Collins, 2010). Importantly this method provided a comprehensive understanding of whether skill-based differences existed, as opposed to studies that have relied on analysis of binary correct/incorrect decisions. Portable eye tracking glasses were also worn by participants with the intention of examining the eye strategies used by each group. Measures analysed included radial error and visual search behaviours. Visual search behaviours comprised of; the number of fixations, average fixation duration, final fixation duration and final fixation location.

Expert umpires displayed superior decision-making accuracy compared to novice umpires across all three Hawk-Eye components. This was in line with previous sports officiating research that outlines skilled officials typically make better decisions than less-skilled officials (Moore et al. 2019; Pizzera et al. 2018; Schnyder et al. 2017). Similarly to these studies, the expert umpires also appeared to also utilise a gaze anchor (Vater et al. 2019), where they directed their gaze towards the stumps more frequently than the pitch or other locations. It was suggested that this anchor was located on the stumps to enable processing of multiple information sources simultaneously via use of both foveal and peripheral vision. It was further proposed that this was a superior strategy to use of a visual pivot, which might have been less favourable due to information suppression that occurs as a result of saccades. Novices contrastingly directed their vision towards a 'good length' more often than the experts. It was suggested that they might have allocated attention towards a good length to extract information related to the pitch component of the task, this being the first task where visual information is presented.

Although expert umpires made more accurate decisions and used similar gaze strategies to that of other sporting officials, contrary to previous research (Mann et al. 2011; Vickers et al. 2015; Williams et al. 2002) the expert umpires utilised a significantly shorter QE duration compared to the novices. These findings occurred perhaps as a result of the experts being better able to generate more accurate decisions faster than novices and therefore better able to disregard incorrect alternative options (Raab & Laborde, 2011). Further, novices might have required more deliberate and hypothetical consideration of the potential options for each LBW component and consequently took longer to process the information from the environment. Despite this, a longer final fixation duration in both groups led to more successful binary decisions being made. This finding was in line with multiple studies that have found that performance accuracy is mediated by a prolonged final fixation in both expert and novice performers respectively (Causer et al. 2012). It was argued that a prolonged fixation might have increased top-down controlled task orientated attention and therefore prevented distractions to debilitate task overall decisions (Moore et al. 2014). Alternative explanations such a pre-programming and online control of movements (Causer et al. 2017) were ruled out due to the task not requiring a motor response coupled to the perception. The number of fixations were not significantly different between the two groups or in correct and incorrect decisions.

Chapter 3 was designed to provide further insight into the underlying mechanisms related to expert cricket umpiring (Ericsson & Smith, 1991). Specifically, to better understand the real-world demands of umpiring, this chapter examined whether umpire's decision making would be affected by the requirement to task-switch between calling the front foot no ball and adjudicating an LBW appeal. A sample consisting of 15 expert umpires made decisions on 16 simulated LBW appeals.

Two conditions were developed to examine the switch cost; a control condition (replication of the procedure as that seen in Chapter 2) and a task-switching condition where umpires determined the spatial positioning of an induced shoe on the crease before making the three decisions on the LBW appeal. The task-switch condition allowed the researchers to examine whether calling the front foot no ball would reduce accuracy on determining where the ball pitched like that in Southgate et al. (2008). This study furthered Southgate's findings by also examining whether this task-switch would affect decision making accuracy of the other two LBW components. Like Chapter 2, eye trackers were again worn this time to examine whether attention would be affected by task-switching (Longman et al. 2014). Measures remained the same as Chapter 2, however the final fixation duration was broken down into 'pre-impact duration' which represented the duration the final fixation was held prior to ball-pad impact, and the 'dwell period' which reflected the duration the final fixation was held post ball-pad impact.

Results showed that when calling the front foot no ball, umpires were significantly less accurate when determining where the ball pitched. This finding supported Southgate et al. (2008) who made a similar observation. It was suggested that as determining the pitching location was the first decision required following the task-switch, this would have been disrupted most by task-set reconfiguration/inhibition processes. Unexpectedly, umpires were significantly more accurate when determining the 'pad' component in the task-switching condition. This finding perhaps emanated from the optimal timing of fixation relocation being directed towards areas of interest related to the LBW appeal from the crease. With regards to the fixation relocation, like Chapter 2, the umpires anchored their final fixation on the stumps significantly more than all other locations across both conditions. This finding provided further support for the utility of a gaze anchor in this task (Vater et al. 2019). Despite this finding, when required to task-switch the umpires directed their final fixation more towards 'other' irrelevant locations compared to the control condition. This finding was in line with literature which has shown that upon task-switching, attentional settings also require reconfiguration and therefore a switch between two tasks can lead to an inaccurate fixation on the second task (Longman et al., 2013; Longman et al., 2014; Longman et al. 2017). Results from this chapter also supported Chapter 2 data in that a longer final fixation duration irrespective of condition led to more successful LBW decisions. Upon further examination into the onset and offset of this QE period, it was found that despite having a shorter 'pre-impact' final fixation duration during the task-switching condition, decision making accuracy was unaffected. This came as little surprise, as most literature surrounding the benefits of an early onset of QE emphasise its role in pre-programming and online control of a movement (Causer et al. 2017) and was therefore less relevant to umpiring. Instead, it was found that the 'dwell' period of the QE was the principal predictor for in umpiring success. It was suggested that this dwell period might have contributed to more accurate processing of ball flight properties such as angle, deviation and spatial positioning as it struck the batter's pad. Like in Chapter 2, the number of fixations on each trial did not appear to be a precursor to decision making accuracy on this task.

The final experimental chapter of this thesis, Chapter 4, examined whether the eye movement behaviours that expert umpires displayed in Chapter 2 and Chapter 3 could be trained in novice umpires to generate better decision-making in an online intervention. A cohort of 72 novice umpires were split into three groups: QE training group, TT group, and CTRL group. Unlike Chapter 2 and Chapter 3, due to government COIVD-19 regulations during the months that data was collected, eye movement data was not recorded. Participants performed the same task as the task-switching condition from Chapter 3. Upon making 8 initial decisions that formed the pre-test, participants underwent a 30-minute intervention that differed based on which group they were assigned to. Following training they immediately performed a post-test and one-week retention test. The post-test and one-week retention tests were similar to the pre-test but with previously unseen trials. The measures recorded were radial error for each LBW component across the phases.

In the post-test, only the QE group improved performance on the pitch and pad components of the LBW rule compared to pre-test results. However, both the QE and TT groups improved on the wickets component between these two phases. This finding arose, as it was proposed that the TT intervention primarily provided instruction on how to perform the wickets aspect of the decision, and provided little to no guidance on how to make accurate decisions on the other two components. By contrast, the QE group improving accuracy of all three tasks furthered the idea that a prolonged final fixation helps maintain top-down goal orientated attention during umpiring (Corbetta & Shulman, 2002). This may have not only enhanced spatial focus on the critical points of information, but in turn might have prevented distracting stimuli from being processed (Vickers, 2017). Further, the intervention might have enhanced storing of visual information related to the three critical location points of the ball's location in the visuo-spatial sketchpad (Moore et al. 2014). It was also found in the one-week retention test, the QE group maintained performance levels from the post-test, whereas the TT group's wickets accuracy declined. It was argued that similarly to tasks with a motor component QE training might have promoted a form of implicit learning where they were able to identify multiple critical cues such as ball flight properties, batter position and the stumps and how these factors would interact with each other. Conversely, the TT intervention offered step-by-step explicit information related to LBW appeals and therefore might have required further training to fully automate the skill of processing numerous information points simultaneously.

This summary of findings has highlighted the principal findings made in Chapters 2, 3 and 4. The following sections will consider the theoretical and applied implications of the thesis.

5.3 Theoretical Implications

This thesis examined and extended the literature of a variety of theoretical concepts related to perceptual-cognitive skill, task-switching and QE training. These theoretical implications will be discussed below.

Perceptual-Cognitive Expertise/Gaze Strategies

This paragraph will discuss the implications related to the final fixation location seen in Chapters 2 and 3, whilst theoretical implications surrounding the QE will explored in depth in a later paragraph.

As is the case with the majority of research examining expertise, Chapter 2 demonstrated that expert umpires possess a distinct advantage over novice umpires in determining the location of all three components of an LBW appeal. However, this was one of the first studies within sports officiating to utilise an objective performance measure in the form of Hawk-Eye, unlike those which have adopted subjective measures (Pizzera et al. 2018; Spitz et al. 2016). A plethora of studies indicate that superior performance seen in experts are often be underpinned by the use of specialised visual strategies where they direct their vision to more salient cues in the environment at the critical times (Mann et al. 2011). Of late, researchers have taken further interest in examining the strategies engaged by expert officials who adjudicate elite sport. In addition to specialised perceptual-cognitive skills, it has become apparent that like elite athletes, the expert officials hold a decision-making performance advantage over lesser skilled counterparts. The stable gaze strategies that have been displayed in these expert performers have been termed the *gaze anchor*, *foveal spot* and *visual pivot* (Vater et al. 2019). It has been recognized in this thesis that the gaze anchor is the preferred strategy used by most expert officials that have been examined (Moore et al. 2019; Schnyder et al. 2017), suggesting peripheral vision plays a primary role in decision making. Chapter 2 and Chapter 3 furthered the case for the gaze anchor as two separate groups of cricket umpires had a propensity to fixate on the stumps as opposed to areas such as the pitch or the ball. This finding further supports the idea that when determining the spatial location and timing of a projectile in relation to other stationary and dynamic objects/people, this gaze strategy is perhaps optimal. For example, elite and trainee rugby referees officiating on scrums fixated more on central regions, perhaps to attend to the ball and front rows who might cause infractions such as collapsing, standing up and wheeling (Moore et al. 2019). Similarly in football, assistant referees fixated on an imaginary offside line between the passer and the striker (Schnyder et al. 2017). It was put forward by the authors of this study anchoring the gaze on this region at the decisive moment of the pass would enable a better understanding of the attacker's position relative to the second last defender and the ball. Whilst cricket umpiring and these two tasks are distinct, they share similar properties that might be explain why the gaze anchor is an optimal gaze strategy in various sports officials. All three task require simultaneous processing of multiple information sources from the display which must be considered in relation to each other. Therefore, the stumps, offside line and central pack region might all provide a central cue which the officials can allocate a stable gaze towards. Peripheral vision might then be used to attend to all dynamic information sources such as the cricket ball, attacker/passer and the back-row forwards in relation to the central anchor point. This gaze strategy might be of less importance when the official must consider information that need not be placed in relation to other objects in the display. This type of task might instead benefit from strategies such as the foveal spot or visual pivot which would promote higher acuity and depth processing of a single information source.

Quiet Eye and Quiet Eye Training

Whilst the location of fixation appeared to be of importance, each experimental chapter in this thesis furthered the idea that long stable QE is also of benefit for tasks that do not require a motor response. Chapter 2 established that a longer QE duration during the critical point of ball-pad led to more successful decisions in both expert and umpire's alike. This extended the current knowledge as it was the first study to identify that QE might be a predictor of performance in perceptual-tasks in addition to the more widely covered motor tasks. However, the principal explanation for the benefits of the QE are pre-programming and online control of movement parameters, and therefore the mechanisms as to how it promoted more accurate LBW decision making remained somewhat unclear. It was suggested that the prolonged final fixation rendered an increase in processing via the dorsal visual stream (Vickers, 2017), this being the attentional network that has been attributed to successful object location identification (Zachariou et al. 2014). Chapter 3 explored how the onset and offset of the QE would affect decision making success. With the no-ball task being introduced into this chapter, it was inevitable that the pre-impact duration of the QE would be significantly reduced. However, this had no effect on decision making success. Instead, it was shown that performance success was in fact predicted by a longer dwell period of the QE. This finding suggested that not only might the QE be generally of benefit to performers from a variety of disciplines, the importance of its onset and offset is likely determined by the specific properties of the task. The final theoretical implication surrounding the QE in this thesis came in Chapter 4, where the effectiveness of an online QE intervention was tested. Findings from this study supported previous literature which has found that QE training expedites better task performance in novices in a similar manner to TT (Moore et al. 2012). As previously mentioned, this finding further supported the idea mentioned in (Moore et al. 2012; Moore et al. 2013; Vine et al. 2011) that an extended QE increases top-down goal orientated processing. Also, in line with Moore et al. (2012), the QE intervention led to novices retaining performance increments unlike those who underwent TT further supporting the idea that QE training results in the formation of implicit knowledge that might be more robust to effects of decay (Vine & Wilson, 2010). This was also the first study, to the author's knowledge, that highlighted the efficacy of an online QE training programme. This provides researchers with a novel method of testing the effectiveness of programmes in tasks which do not require a motor component, with online studies being beneficial in that they might enable larger sample sizes to collect data from. Further, for studies that aim to examine a motor related task, the training intervention can be disseminated to participants online as opposed to being delivered in-situ, with this method perhaps enabling more efficient data collection where on-site visits are only required when collecting data.

Task-Switching

In Chapter 3, a number of findings provide theoretical implications related to task-switching literature of cognitive psychology. Literature surrounding the topic has consistently showcased that when a rapid switch is made from one task to another, performance measures on the second task are usually lower than if the task were performed in isolation (Monsell, 2003). This performance decline has been coupled with a clear effect on attentional allocation when initially performing the second task (Longman et al. 2017). However, the majority of studies to date which have tested task-switching have employed the 'task-switching paradigm' which is primarily a laboratory-based design. As such, to the researcher's knowledge there are no studies that have examined the switch-cost and its attentional impacts in a representative task. This can perhaps be attributed to the fact that in most instances, when task-switching between real world tasks, individuals can afford a higher response time and higher error rate on the second task. Further, few day-to-day activities require an immediate task-switch to the extent that the switch-cost will be noticeable. However, cricket umpiring offered a chance to examine task-switching in an applied setting outside of traditional methods. With umpires requiring to assess the bowler's spatial positioning in relation to the crease before performing a multitude of tasks related to the delivery, this task offered an opportunity to examine whether the task-switching theory translates to an applied setting. In corroboration of the predictions of the switch-cost, Chapter 3 found that the umpires performed worse when determining where the ball 'pitched' upon task switching compared to when making LBW decisions exclusively. This difference was attributed to the switch-cost, as the pitch aspect of the LBW is the first component that required consideration following adjudication of the front foot no ball. This study was perhaps the first to extend the task-switching literature by showcasing potential switch-costs in an applied setting. Chapter 3 also found that upon task-switching the umpires were more likely to allocate their attention to 'other locations'. This data furthered the idea that the task-switch affects attentional allocation (Longman et al. 2017) and that this theory must be considered alongside the more cited explanations of the switch-cost. This theoretical implication as well as the ones previously mentioned provide a number of applied implications that will be considered in the following section.

5.4 Applied Implications

Chapter 2

Chapter 2 was the first study to date that established a simulated LBW task could be developed to differentiate decision making skill between groups of umpires. An adaption of this task might therefore be considered as a tool to ascertain the more competent umpires from lesser ones for future appointments. Specifically, this might enable cricket boards around the world to establish which umpires are able to better cope with the demands of the LBW appeal better than others. Further, in the professional game umpires would be able to distinguish any existing weaknesses they possess in each LBW component or when adjudicating specific types of deliveries.

Within the amateur game in the UK, some leagues exist where expert umpires are not appointed to fixtures and consequently club members or players are required to umpire a set number of overs. A similar task to this could be disseminated to cricket clubs to enable identification of which players are be better suited to umpiring matches. This chapter also established that a prolonged QE duration was beneficial for both expert and novice umpires alike. Whilst the applied implications of QE training will be explained later on, across the country, amateur club players can be instructed to maintain a prolonged fixation on the stumps during LBW appeals should they be required to officiate on their matches. This might ensure better decisions are made in competitions which do not offer the technology for on field players to review the umpire's LBW decisions.

Chapter 3

The initial rationale behind this chapter arose when in 2020 the ICC announced for the first time in Test cricket, as a trial the front foot no ball would be called by the third umpire. This trial period was implemented to ascertain the benefits of umpires exclusively adjudicating on 'play situations'. Data gathered in Chapter 3 supports this decision, as task-switching from the front foot no ball task to the LBW task appeared to debilitate decision making accuracy on the pitch component of the decision. For some deliveries, it is of major importance as to where the ball pitches in relation to the stumps. More specifically any appeal that pitches outside the leg stump should always be determined 'not out' and therefore it is of the highest importance that umpires accurately make this decision. This also supported the applied implications of Chapter 2 which highlighted the potential benefits of allocating gaze towards the stumps are the point of ball-pad impact. Further, a prolonged QE duration was associated with more accurate decisions in both conditions examined within the chapter. As technologies to adjudicate 'no balls' are not readily available to most leagues in cricket, this result further emphasises the necessity for those adjudicating cricket matches to utilise the abovementioned gaze behaviours to prevent the switch-cost effect as much as possible.

Chapter 4

Chapter 4 demonstrates that QE training might provide another method of improving umpire decision making in addition to the existing training courses. A plethora of studies have established their effectiveness, and this chapter found that the benefits of such training are also applicable to novice cricket umpires. Various cricket boards across the world offer novice umpires training in the form of incremental development phases, and therefore a similar intervention to that of Chapter 4 could be delivered at an early stage to expedite immediate improvements. This course could also be disseminated via an online platform similarly to Chapter 4 to ensure a wider reach to all those enrolled on the courses. Such interventions might also be developed and delivered to players by cricket clubs so that they are fully trained for instances where they are required to officiate. This intervention should not be implemented as an alternative to current training programmes as it is of extreme importance that new umpires become familiar with the numerous technicalities associated with umpiring. From an experiential account, an online approach provided several challenges that should be addressed if such a design is implemented when following the expert performance approach (Ericsson & Smith, 1991). Perhaps the first consideration that future researchers must make is identifying a platform that offers methods of collecting data that is sensitive as the first step of Ericsson & Smith's framework prescribes. The next challenge was to ensure participants were aware of the demands of the task with the researcher's being unable to provide 1 on 1 guidance prior to initiation of the data collection. Whilst this might not pose an issue to studies utilising self-report methodologies, the complex nature of this design, which involved the execution of 4 decisions, increased the researcher's consideration of how the instructions would be interpreted by participants. Therefore, to assess the clarity of the instructions, pilot testing was conducted on a number of students similar in their cricket experience and age to that of the sample examined. The instructions were also presented prior to the pre-test and importantly in the one-week retention test so that any effects could be attributed to the intervention as opposed to individual differences in declarative and procedural memory functions between the participants and groups.

5.5 Limitations and Future Research

As is the case with research, limitations of the methodology existed in this thesis which help provide questions for future research. Each chapter possessed general and specific limitations which will be discussed

General Limitations

In Chapter 2 and Chapter 3, most of the expert umpires examined, officiated in elite club cricket, the highest form of amateur cricket. Whilst many of these umpires had officiated in hundreds of matches including first class and international players, they were unpaid and therefore deemed non-professionals. Within professional cricket in England, each year the England Cricket Board (ECB) recruits a number of umpires onto the ‘First Class Umpires List’ and another set of umpires onto the ‘Reserve First Class Umpires List’. Whilst it remains to be seen whether these umpires retain a performance advantage over the those tested within the thesis, in theory due to being termed a ‘professional’ they would be assigned to a group termed ‘elite’. Further, a selection of umpires considered to be the best from each first-class list globally are appointed onto the International Cricket Council Elite Panel. As such, future research must examine these two groups in a similar manner to Chapter 2 and Chapter 3 to establish; whether they also use a gaze anchor, whether they also exhibit similar behaviours when task-switching and ultimately whether their decision-making skills exceed those of the present sample similarly to Spitz et al. (2016) and Hancock and Ste-Marie (2013), or if performance accuracy in LBW decision making plateaus at the sub-elite level.

Another limitation of each chapter was that deliveries utilised in this study were released at speeds ranging between 65-80mph. Whilst each trial in the thesis did vary in release point, angle of trajectory and swing, professional cricket can at times involve bowlers delivering the ball at a velocity of over 95mph. On top of this, professional spin bowlers are capable of implementing revolutions on the ball so that it considerably deviates from a typical post bounce trajectory. As such, future research should examine how these two contextual variables influence umpire decision making and whether the strategies presented in this thesis can counter these extra demands. Another future research direction would be to further examine peripheral vision processing. Expert umpires in Chapter 2 and Chapter 3 appeared to use a gaze anchor to process various information cues, however it remains to be seen whether they possess an advantage for processing this information over lesser skilled counterparts. Some evidence examining experienced and inexperienced motorcar drivers (Crundall et al. 1999) suggests that deliberate practice might lead to an advantage in processing cues located away from the fovea via an expanded FFoV. Such an advantage might render umpires the ability to utilise a gaze anchor whereby they can process information related to where the ball pitches and strikes the batter’s pad without requiring additional fixations which might be suboptimal due to the unique time constraints posed in cricket. Similar methodologies to that of Crundall et al. (1999) with a umpiring task might be implemented to examine whether this is a phenomenon that applies to cricket umpires and other expert performers. It was also suggested throughout each experimental chapter that a prolonged QE might have enabled the prevention of distractive stimuli being processed, however further measures can be put in place to test this hypothesis. This might be achieved when it is possible to record eye tracking, by adding a transfer condition where participants are placed under stressful situations in Chapter 4 to enable understanding of whether the QE prevents the predictions of ACT in which fixations distributed more frequently across the display for shorter durations (Moore et al. 2012). Finally, to further validate the findings from each chapter, an in-situ design might be of benefit. However, before such a study design is implemented, some of the issues related to practicality must be addressed. Perhaps the greatest challenge would be that each participant must view the same amount of deliveries that possess the same contextual factors (where it pitches, angle of deviation, where it would have travelled etc.) which would be difficult to control for due to atmospheric conditions holding a principal role in this. Despite being less practical than the methodologies used in this thesis, a design such as this would potentially further emphasise the findings made in this thesis and might also provide an indication of whether decision making accuracy varies throughout different time periods of matches. Each chapter within this thesis also held their own distinct limitations and areas for future research which will be considered below.

Chapter 2

Whilst the aims of Chapter 2 were to provide descriptive findings related to expert-novice decision making accuracy and eye movements, and to provide predictive validity of the task, some limitations were apparent. Firstly, unlike Chapter 3, the no-ball task was not included in this chapter. Whilst Chapter 3 confirmed expert umpires still opted for a gaze anchor when required to perform the no-ball task, it is possible that by including it within Chapter 2, the poorer performance seen in novice umpires might have been further exacerbated. Future research might also seek to examine umpire thought processes during decision making via qualitative methods to examine whether the expert performance advantage was a result of distinct contemplation of the appeal. This would be straightforward to implement unlike other more dynamic sports, as umpires remain largely stationary throughout the task. It has been reported that elite athletes possess superior working memory processing abilities (Vaughan & Laborde, 2021). As cricket umpiring is a task that likely requires use of the visuospatial and central executive functions, inspection of whether expert-novice differences are predicted by working memory processes might be of some use. Should general working memory advantages not exist, domain-specific LT-WM advantages (Ericsson & Kintsch, 1995) can also be examined between groups. Examination of both of these cognitive functions could be of high importance for both umpire training and selection purposes. Further breakdown decision making with respect to delivery type might also be of use, and whether increased deviation of the pitch via swing and spin might lead to a greater understanding of where the expertise advantage lies within the LBW appeal.

Chapter 3

The aim of Chapter 3 was to examine if task-switching affected LBW decision making of expert umpires. Whilst including the front foot no ball task somewhat alleviated a limitation of Chapter 2, this chapter only included expert and not novice umpires. Limitations also surrounded the induced shoe that aimed to represent the no-ball task. Firstly, the shoe was clearly visible on all task-switch trials from the instance it appeared. However, from an umpire's perspective the bowler's body positioning sometimes obstructs clear view of where they ground their shoe (Figure 5.1) for a period before they release the ball. As a result, umpires are sometimes required to wait until the follow through before adjudicating the legality of the delivery. This would lead to reduced time to transfer attention towards the stumps from the crease.

Figure 5.1: An initial obstruction of a view of the bowler’s landing point

Another limitation that was mentioned as applicable to all three chapters was that the speed of delivery did not vary substantially throughout chapters in this thesis. This might have been a more considerable limitation in Chapter 3 compared to the other experimental chapters. Research has shown the severity of the switch cost increases in direct relation to the time between the completion of the first task and commencement of the second task being shortened (Arrington & Logan, 2004). This time period, termed the response stimulus interval (RSI), would have been vastly reduced if the chapter included bowlers that exceeded 90mph. Future research should therefore address this by manipulation of delivery speeds and investigate whether the switch-cost related performance decline is further exacerbated in relation to delivery speeds increasing. Finally, within Chapter 2, trials were controlled to only include deliveries that were released from right arm over the wicket. With accuracy of the 'pitch' component decreasing whilst task-switching, there should be investigation of whether the same effect occurs in 'right arm around the wicket' appeals. Unlike 'over the wicket trials' the pitch component on these trials hold importance as one of the principal considerations is whether the ball pitches outside the line of the leg stump. Future research might also consider whether task-switching affects other important umpiring decisions such as caught behind appeals, which likely require processing an alchemy of visual and auditory information. Any attentional misallocation therefore might negatively affect these decisions in addition to the pitch component of the LBW.

Chapter 4

Due to the government regulations, the researchers were unable to physically collect data from participants. As such several limitations existed with Chapter 4. However before considering these limitations, it would be appropriate to broadly outline the intended design of Chapter 4 before COVID-19 restrictions came into effect. Having identified an expert prototype in Chapter 2 and Chapter 3, the next step was to collect eye movement data from the novices whilst they made the LBW decisions in the pre-test. Results in this phase would have dictated which group they would be allocated into. The next stage of the intervention would have involved presenting the expert prototype alongside the novice's own gaze behaviour so that a comparison could be made between their respective QE characteristics. Participants would have then performed training blocks, but unlike Chapter 4, eye movement data would have been recorded again so that the researchers could trace learning of the expert prototype. An ideal QE training study would have also included an anxiety based transfer test following the retention-test like in Moore et al. (2012) and Moore et al. (2013). This would have permitted the researchers to understand whether anxiety affects attention in line with attentional control theory (ACT) to the extent that LBW decision making accuracy is disrupted and whether QE training protects umpires from this.

to measure whether participants would continue maintain a gaze anchor on the stumps or their attention would be misallocated as per ACT. Depending on participant drop-outs, a 6-week retention period like that seen in Miles et al. (2015). Whilst the online methodology offered similar results to that expected from typical QE studies, limitations existed that prevented definite conclusions from being made. Perhaps the most obvious limitation related to this and other online methodologies, was that data was collected online without presence of the researchers. Whilst this was the only option at the time of collection and did provide the benefit of being able to disseminate the study to a large sample, the researchers were to some degree unable to control certain factors that would often be controlled in a typical experimental setting. First, with respects to the pre-test, post-test and one-week retention test, the researchers were unable to determine whether participants engaged in each trial. Should future perceptual-cognitive training studies require distribution via an online platform, perhaps following the training phase, the participants could be tested on the relevant information from the intervention via a questionnaire. The other limitation related to the online nature of the task was that eye tracking data was not collected. As a consequence, performance increments seen in the QE group could only be circumspectly explained by the intervention.

In addition to the issues surrounding COVID-19 regulations, some limitations existed related to the protocol of the study which could be addressed in future research. Like previous research, this Chapter included a one-week retention test (Vine & Wilson, 2010; Vine & Wilson, 2011; Vine et al. 2013). However recently, studies such as Miles et al. (2017) have collected data after one and six weeks respectively. This six-week delayed retention further permitted the authors of this study to establish whether their training intervention led to an enduring change in visual attention processes and overall performance. Future studies around QE training in umpiring and indeed other domains should follow Miles et al. (2017) as a template to gain further understanding of skill learning. The chapter also did not combine TT and QE interventions to understand whether such a combination further expedites learning in the task. Finally, QE training studies might also prove to be useful in expert cricket umpires, however this hypothesis requires testing. Should this type of training render improved decision making capabilities in this group, then governing bodies can use regular training and testing similarly to 'Professional Game Match Officials Limited' to ensure high standards are maintained at both professional and development pathway levels.

5.6 Concluding Remarks

To summarise, this thesis utilised the expert-performance approach to provide the first extensive investigation of the use of perceptual-cognitive skills in cricket umpiring. Research has consistently established that perceptual-cognitive skills can predict performance in elite and amateur sport (Causer et al. 2012). Some isolated studies have highlighted perceptual-cognitive skills perform a role in mediating decision making in sporting officials (Pizzera et al. 2018; Schnyder et al. 2017; Spitz et al. 2016), however this area has received little attention in comparison to the research surrounding athletes. The current thesis aimed to examine various processes related to expert cricket umpires and whether these processes could be embedded in novices to expedite learning. Literature surrounding sports officiating was extended as two groups of expert umpires from separate leagues in different regions of the United Kingdom utilised similar gaze behaviours suggesting this is a skill developed through extensive deliberate practice. Literature surrounding the QE was also extended as this thesis established that a prolonged final fixation can enhance the performance of tasks that do not necessitate a movement response. This result was consistently reported throughout the thesis suggesting an attentional component of the QE exists in addition to the often-reported pre-programming (Causer et al. 2017) and inhibition explanations (Klostermann et al. 2014). Importantly, the benefits of the QE extended into the final experimental chapter which demonstrated that this perceptual-cognitive skill could be taught to novice umpires for the advancement of their LBW decision making accuracy. Overall this thesis provides theoretical implications that can help navigate perceptual-cognitive skill research in a new direction that involves examination of perceptual attributes more closely, whilst applied implications can be readily implemented across the cricket pyramid to improve the standard of LBW decision making.

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Appendix

Appendix 1

Table 7.1: Gaze strategies used by elite sport officials and athletes

Reference & Sport	Participants	Materials	Task/Procedure	IVs	DVs	Key Results	Gaze strategy
Spitz, J., Put, K., Wagemans, J., Williams, A.M., Helsen, W.F. (2016). Visual search behaviors of association football referees during assessment of foul play situations. Cognitive Research: Principles and Impliactions, 1, 1-11. Football Refereeing	20 elite refs from the Belgian first and second division 19 sub-elite refs from lower levels and no professional experience	Tobii T120 Eye Tracking 17-inch monitor	Filled questionnaire out for experience Viewed videos from a first-person perspective of fouls 10 open play fouls and 10 corner situations Referees had to make one of four technical decisions Also had to make a disciplinary decision	Expertise	Visual search behaviour Search rate Fixation location at the point of the foul Decision making accuracy Type of decision error	Referees spent significantly more time fixating on contact zones In open play, elite referees fixated significantly more on the attackers contact zones than the sub-elite referees Elite refs were better at determining corner fouls, but no difference in open play fouls between the groups In corners, both groups spent more time looking at contact zones Elite referees made significantly better decisions in the corner fouls situation	Foveal Spot
Moore, L.J., Harris, D.J., Sharpe, B.T., Vine, S.J.,	9 elite rugby referees	SensoMotoric Instruments (SMI)	Rugby union refereeing	Expertise	Decision making accuracy	Elite and trainee refs made significantly more accurate decisions than the player group	Gaze Anchor

Wilson, M.R. (2019). Perceptual-cognitive expertise when refereeing the scrum in rugby union. Journal of Sports Sciences, 37(15), 1778-1786. Rugby Union Refereeing	9 trainee rugby referees 9 non-rugby referees (players)	Eye Trackers 83-inch LCD Projector	Viewed 10 scrum videos Had to make one of four decisions Participants stood 2.50 m from the screen, with a 45° visual angle After each video clip, the screen went black for 10 s while participants verbalised their decision.		Search Rate Fixation Location %	All 3 groups spent more time looking at central pack locations compared to outer and non-pack locations at the critical moment Elite and trainee groups fixated on central pack locations more compared to the player group at the critical moment Player groups fixated more on outer pack and non-pack location at the critical moment compared to elite and trainee groups	
Pizzera, A., Möller, C., & Plessner, H. (2018). Gaze Behavior of Gymnastics Judges: Where Do Experienced Judges and Gymnasts Look While Judging? Research Quarterly for Exercise and	35 women's gymnastic judges 15 deemed high level judges HLJ with Level A-C license 20 deemed low level judges LLJ	Tobii TX300 and 46-inch LED display (1,920 pixels × 1,080 pixels)	Had to judge 21 handspring forward with a half turn on/half turn off the vault 7 different gymnasts performing 3 handsprings 3 familiarisation trials Trials were played randomly	Judging expertise Motor experience	Judging Performance Visual Search Fixation Locations Fixation Duration Expertise	HLJ made significantly more accurate judgements than LLJ HLJ had more fixations on the gymnast during the whole skill and landing phase HLJ looked significantly more on the head and arms of the gymnast (perhaps arms being the important location for	Gaze Anchor

Sport, 89(1), 112-119. Gymnastics Judging	with Level D license					this skill) compared to LLJ	
Schnyder, U., Koedijker, J.M., Kredel, R., & Hossner, E. (2017). Gaze behaviour in offside decision-making in football. German Journal of Exercise and Sport Research, 47, 103-109. Assistant Football Referees	3 experts from the highest Swiss league, and also international level 3 near-experts from the Swiss second and third leagues	EyeSeeCam eye trackers	ARs adjudicated the offside appeals from in-situ simulations from 3 attackers, 3 defenders and a goalkeeper who had practiced 9 attack scenarios which were performed 9 times each, leading to 36 in-situ offside verdicts Performed in a stadium for ecological validity	Expertise	Decision Response Accuracy Fixation location at the point of pass Final fixation duration Final fixation onset Final fixation offset Total Number of fixations Number of fixations before the final pass	Decision accuracy 85.9% judgements were correct in both groups combined Experts made significantly more correct decisions than near experts (91.4% vs 79.8%) Both groups fixated significantly more on the offside line (63.4% for experts, 64.3% for near experts) compared to the defenders, attackers, passer and ball ARs more likely to make a correct decision when looking at the offside line compared to “other than offside line” locations (attacker, defender, passer and ball all grouped together)	Gaze Anchor

						No differences in number of fixations Total final fixation duration and final fixation offset at the point of pass, might have been significantly higher in correct decisions compared to incorrect decisions with a larger sample size (269ms difference), perhaps suggesting higher QE periods lead to better offside decision making	
Hausegger, T., Vater, C., & Hossner, E. (2019). Peripheral Vision in Martial Arts Experts: The Cost-Dependent Anchoring of Gaze. Journal of Sport and Exercise Psychology, 41(3), 137-145 2 forms of Martial Arts	10 international Qwan Ki Do (QKD) experts (fist and foot strikes) 10 international Korean Tae Kwon Do (TKD) experts (foot strikes)	EyeSeeCam (ESC) eye tracker Three	Attacks included both fist and foot strikes Random attack sequences initiated by the attacker viewing a chart behind the participant Participant had to either defend or retreat from attacks	Type of martial arts	Gaze anchor height Percentage of location viewing time Number of saccades	QKD athletes anchored their gaze higher than the TKD athletes in the start phase and during the first attack QKD looked more at the opponent's head than TKD athletes TKD athletes looked more at the upper torso QKD looked more at the head in the start phase, and more at the upper and lower torso and hips in the 3 attack phases	Gaze Anchor

						TKD athletes looked more at the head in the start phase, and more at the lower torso in the 3 attacking phase	
Piras, A., Pierantozzi. E., & Squatrito, S. (2014). Visual Search Strategy in Judo Fighters During the Execution of the First Grip. International Journal of Sports Science and Coaching, 9(1), 185-197 Judo	9 expert judo fighters with 16 years average national level 11 non expert university students with 14 hours judo experience	EyeLink II eye tracking system	Participants had to attack and defend: lapel attack, sleeve attack, lapel defence, sleeve defence	Experti se	Search rate Fixation transitions Percentage fixation location	Search Rate Greater number of fixations for sleeve attack compared to sleeve defence Experts had fewer fixations of longer durations No number of fixation differences Fixation Transitions Novices made a greater number of transitions from: lapel to lapel, lapel to sleeve, sleeve to lapel Experts made a greater number of transitions from: lapel to lapel and face to face suggesting more use of peripheral vision Experts looked at the lapel and face significantly more than	Gaze anchor

						other areas like the jacket skirt, sleeve, hands and 'other' locations Novices looked at the sleeve area more than the expert's group	
Ripoll, H., Kerlirzin, Y., Stein, J., Reine, B. (1995). Analysis of information processing, decision making, and visual strategies in complex problem-solving sport situations. Human Movement Science, 14, 325-349 French Boxing	6 expert national team boxers 6 intermediat es at first class level 6 novices with one year of non-competitio n experience	SONY VPH 600 QJ/Q/M trichrome overhead projector onto a 200 x 170 cm screen Video-oculograph ic system (Nat Eye Mark Recorder V)	Experiment 1 Simple situations, where participants only had to respond to attacks OR openings in each trial Complex situations where participants had to respond to both attacks AND openings in each trial Experiment 2 Same as the complex experiment 1 in the complex situations, but involved eye tracking	Experti se Task comple xity	Experiment 1 Reaction to attacks Reaction to openings Decision making accuracy Experiment 2 Number of fixations Fixation location % Sum of fixation durations per location Mean duration of fixations per location	Experiment 1 No difference in how many correct responses for simple situations, in both attack or opening conditions In complex situations, experts made significantly more correct decisions in response to being attacked than intermediate and novice boxers No difference between groups in response accuracy to openings Experiment 2 Experts made two and three times fewer fixations than intermediates and novices	Visual Pivot

					Visual search	Experts mainly looked at the opponents head, whilst intermediates were more spread out across the head, upper torso and arms/fists Novices looked more at the opponents arms/fists Experts mean fixation on the head was much much longer than other regions Novice mean fixation was longer on the arm/fists than the head and trunk Intermediates also had longer mean fixations on the head, but they were more spread out across the 3 locations, and the difference wasn't as great as the experts Experts had an organised visual search around the head, where they could use covert attention to saccade to	

						areas of interest before returning back to the head	
Milazzo, N., Farrow, D., Ruffault., & Fournier, J.F. (2016). Do karate fighters use situational probability information to improve decision-making performance during on-mat tasks? Journal of Sports Sciences, 34(16), 1547-1556. Karate fighters	14 elite international karate fighters 14 novice karate fighters with 1 year recreational experience (no competitive experience)	SMI, Eye Tracking Glasses 2.0	Participants had to make decisions reacting to being attacked by an opponent Required to touch opponent without being hit	Expertise	Decision making response time Decision accuracy (judged by international karate coaches) Mean fixation duration Mean number of fixations Mean number of fixation locations Location percentage (17 different locations) Verbal reports relating to the Recognition-	Decision response time Experts made significantly faster decisions than novices Expert fighters were significantly faster at decision making after 6 of the 10 attacks had taken place Decision time negatively related to fixation duration, knowledge Experts were significantly more accurate in decision making than novices Decision accuracy was negatively related to the mean number of visual fixations, and the mean number of fixation locations Experts had less fixations of longer durations compared to novices	Visual Pivot

						Experts fixated on less locations compared to novices Mean fixation duration was positively correlated to knowledge Number of fixations, and number of fixation locations were negatively related to knowledge Experts looked significantly more at the head and torso of the opponent Novices looked significantly more at the pelvis and front hand of the opponent	
Ryu, D., Abernethy, B., Mann, D.L., Poolton, J.M., & Gorman, A.D. (2013). The role of central and peripheral vision in expert decision making. Perception, 42, 591-607. Basketballers	11 skilled basketballers from the top tier of their national league 11 less skilled recreational basketballers	Eyelink II eye tracking system Videos shown on eyelink II monitor (338 × 270 mm)	Participants sat 2ft from the eye tracker monitor 20 practice trials Participants had to decide whether the player in possession should pass to a teammate or drive to the basket at the point of occlusion 3 conditions were	Expertise Type of visual information	Response accuracy Search Rate Number of fixations on each area of interest Fixation location %	Response Accuracy Skilled players more accurate across all 3 conditions Skilled players performed above chance level in all 3 conditions, whereas less skilled players performed above chance levels only in the full vision condition Response time was faster in skilled players	Visual Pivot

			Full image control- all visual information was shown Moving window condition- only foveal information was shown, and peripheral vision was occluded Moving mas condition- foveal vision was occluded, and participants could only see peripheral information		Fixation transitions (from the ball carrier, to another location and back to the ball carrier) Saccadic Amplitude Frequency of saccadic amplitudes	than less skilled across all 3 conditions Search Rate No main effect for search rate Both groups had more fixations on the ball carrier and the defender marking him Skilled participants had the same number of fixations on the ball carrier in all 3 conditions, even when foveal information on him was occluded Less skilled participants made less fixations on the ball carrier, when foveal information was occluded Fixation Location Skilled players looked at the ball carrier more when peripheral vision was occluded Less skilled players looked at the ball carrier less in both occlusion conditions Fixation transitions	

						Skilled players made the same number of transitions in all 3 conditions from the ball carrier, to other locations and back to the ball carrier, suggesting use of a visual pivot Less skilled players made less transitions when peripheral vision was occluded, but not in the other 2 occlusion conditions Frequency of saccadic amplitudes In the foveal information occlusion condition there was an increase in the frequency of small saccades, and a decrease in the frequency of large saccades compared to the full vision condition In the peripheral information occlusion condition there was a decrease in small saccades and increase in large saccades	

						compared to the full vision condition	
Takeuchi, T., Inomata, K. (2009) Visual Search Strategies and Decision Making in Baseball Batting. Perceptual and Motor Skills, 108, 971-980. Baseball batters	7 expert university baseball players 7 randomly selected non-experts with no baseball experience	Eye Mark Recorder Model EMR-8	Pitcher threw 10 deliveries to the batter as they stood behind a protective net	Expertise	Mean fixation duration on the pitcher's motion Mean number of fixations Mean number of areas fixated on Fixation location percentage (head/face, shoulder, chest/trunk, lower body, pitching arm, release point) Decision making accuracy Timing of decision via button push	Mean number of areas fixated on In the initial and middle phase there were no differences in the number of areas fixated on as both groups fixated more on the proximal part of the pitcher's body (head, chest and trunk) In the final phase, experts fixated on the pitching arm and release point significantly more than the non-experts, as they shifted their observation point from the head, chest and trunk of the pitcher, to the pitching arm and point of release The non-expert group fixated their eyes on the pitcher's face and head in the final phase Decision making accuracy Experts were significantly more accurate	Visual Pivot in preparation Foveal Spot at the point of ball release

Kato, T., Fukuda, T., (2002). Visual search strategies of baseball batters: Eye movements during the preparatory phase of batting. Perceptual and Motor Skills, 94, 380-386. Baseball batters	9 experts of university level 9 novice university students with no experience	Freeview eye trackers 21 inch CRT monitor	Stood 1 metre away from the screen Viewed 10 types of pitches thrown by a pitcher on a regulation baseball pitcher's mound instructed to view the videotape carefully as if batting	Experti se	Distribution of fixations Fixation locations in different temporal phases	Distribution of Fixations Most of the expert's fixations were located on the pitcher's upper body Most of the novice's fixations were located on the pitcher's upper body Novices distribution of fixations were wider than that of the experts Experts organised their vision around the pitcher's shoulder-trunk region Novices fixation points were scattered all over, from top to bottom Fixation locations in different temporal phases In phase 1 and 2 of the pitcher's action, experts fixated significantly more on the pitcher's shoulder and trunk region than novices	Visual Pivot in preparati on Gaze Anchor at the point of ball release

						In phase 3 experts fixated on the expected pitching arm before positioning was actually completed meaning they accurately estimated the movement of the arm In phase 4, which was the release point of the ball experts fixated on the pitcher's elbow whereas novices fixated on the shoulder-trunk region	

Appendix 2

Table 7.2: Quiet Eye Training Studies

Reference	Participants and Procedure	DVs	Key Results
Adophe, R.M., Vickers J.N., & Laplante, G. (1997). The Effects of Training Visual Attention on Gaze Behaviour and Accuracy: A Pilot Study. *International Journal of Sports Vision*, 4(1), 28-33. Volleyball	3 expert volleyball players and 6 near-expert volleyball players put into just a QE group 6-week testing period Pre-test, acquisition, retention	QE Duration Gaze Behaviours Performance Ball Flight Information Step and Pass Behaviours	Participants improved tracking onset, QE duration and offset Participants showed improvement in accuracy over 3 seasons of international competition
Harle, S.K., Vickers, J.N. (2001). Training Quiet Eye Improves Accuracy in the Basketball Free Throw. The Sport Psychologist, 15, 289-305. Basketball Free Throws	3 teams of basketball players, Team A placed into QE group and Team B and Team C in control group 1. Pre-test 2. Season 1 3. Retention Test 4. Season 2	Season 1: Free Throws Made QE Duration QE Location Relative Shot Duration Season 2: League Free Throws Made between all three teams	Team A improved free throw performance significantly in the Retention-test compared to the pre-test Team A significantly improved free throw performance from season 1 to season 2. Team A had a significantly higher free throw performance in season 2 compared to Team B and Team C Team A had significantly longer QE in the retention-test compared to the pre-test Team A changed the timing of their shot in the retention-test, allocating 5% more time to the prep-down phase
Causer, J., Holmes, P.S., & Williams, A.M. (2011). Quiet Eye Training in a Visuomotor Control Task. *Medicine and*	20 international level skeet shooters split into QE and Control Group 8 week testing period	QE Duration Eye Movement Behaviours	QE group significantly improved their QE durations in the retention test compared to the pre-test QE group significantly improved their shooting accuracy in the retention test compared to the pre-test

Science in Sports and Exercise, 43(6), 1042-1049. Skeet Shooting	1. Pre-test 2. Training phase 3. Retention test of 30 trials Scores from three competitions before and after the training intervention of 125 shots	Shooting Accuracy Gun Barrell Kinematics	No differences in QE duration or shooting accuracy in the control group in the pre-test and retention test QE group showed more efficient gun movement in the retention test compared to the pre-test unlike the control group Improvements in the QE group were transferred to the competition domain
Causer, J., Vickers, J.N., Snelgrove, R., Arsenault, G., & Harvey, A. (2014a). Performing under pressure: Quiet eye training improves surgical knot-tying performance. *Surgery, 156*(5), 1089-1096. Knot tying surgery	20 first year surgery students split into QE or TT groups 1. Pre-test 2. Training phase 3. Simple knot, low anxiety condition 4. Complex knot, low anxiety condition 5. Simple knot, high anxiety condition 6. Complex knot, high anxiety condition	Knot Tying Performance QE Duration Number of Fixations Total Movement Time	All participants improved knot tying performance in the low anxiety conditions compared to the pre-test QE group maintained performance under high anxiety, whilst the TT group's knot tying performance decreased nearer pre-test test levels in these conditions QE group had significantly longer QE durations and fewer fixations than the TT group
Causer, J., Harvey, A., Snelgrove, R., Arsenault, G., & Vickers, J.N. (2014b). Quiet eye training improves surgical knot tying more than traditional technical training: A randomized controlled study. *The American Journal of Surgery, 208*, 171-177. Knot tying surgery	20 first year surgery students split into QE or TT groups 1. Pre-test 2. Training phase 3. Retention test 4. Transfer test	Knot tying performance Percentage QE duration Number of fixations Total movement time Total movement phase time	Both groups improved knot tying performance from the pre-test to the retention and transfer tests QE group performed significantly better than the TT group in the retention and transfer tests QE group had significantly longer QE duration, fewer fixations and fixated more precisely on each placement position than the TT group in the retention and transfer tests Longer QE durations associated with better performance
Vine, S.J., Moore, L.J., & Wilson, M.R. (2011). Quiet eye training facilitates competitive putting	22 elite male golfers split into QE and Control group	Competitive Performance before and after training phase	QE group putted more balls in the retention test than the Control group but this was not significant QE group had lower performance error than the Control group

performance in elite golfers. *Frontiers in Pscyhology, 2*(8). Golf Putting	1. Recorded 10 competitive rounds prior to experimental session 2. Pre-test 3. Training phase 4. Another 10 competitive rounds within 3 months after the training session 5. Retention test 6. Anxiety transfer test	Experimental Performance Outcome (Balls Putted) Experimental Performance Error (Distance ball finished away from the hole) QE Duration State Anxiety	QE group had significantly higher QE duration in the retention test, whilst the Control group had no difference in QE duration between the pre-test and retention test Both groups had a significant reduction of QE duration in the transfer test QE group had a significantly longer QE duration in the transfer test compared to the Control group QE group had significantly better experimental performance outcome and experimental performance error in the transfer condition, compared to the Control group QE group made significantly less putts per round in competition after training, whilst the Control group showed no differences
Wood, G., Wilson, M.R. (2011). Quiet-eye training for soccer penalty kicks. *Cognitive Processing, 12*, 257-266. Soccer Penalties	20 university level soccer players split into QE and Placebo groups 7 week testing period 1. Pre-test 2. Training phase 3. Retention test 4. Anxiety transfer test	Shooting accuracy QE Duration Success Rate Cognitive State Anxiety	After 3 weeks of training both group group improved their horizontal penalty placement QE group had less penalties saved during the training period than the Placebo group No difference in penalty success in retention test between groups QE group had increased fixation durations on the ball prior to initiating the kicking action QE group displayed more distal final aiming fixations which were 3x as long as the Placebo Group QE group maintained a more distal aiming fixation in the transfer test whereas the Placebo group showed an impaired centralized gaze

			No difference in performance between groups in the transfer test (only 1 shot may have contributed to this) QE Group improved in the retention test and maintained this improvement in the transfer test
Wood, G., & Wilson, M.R. (2012). Quiet-eye training, perceived control and performing under pressure. *Psychology of Sport and Exercise*, 13, 721-728. Soccer Penalties	20 university level soccer players split into QE and Practice groups 7 week testing period 1. Pre-test 2. Training phase 3. Retention test 4. Anxiety transfer test	Penalty shooting performance QE Duration Cognitive & Somatic Anxiety Control Beliefs	QE group adopted more distal aiming fixations with longer durations in the retention and transfer test QE group was significantly more accurate in penalty shooting in the retention and transfer test compared to the Practice group Both groups felt increased competence after training
Vine, S.J., & Wilson, M.R. (2010). Quiet Eye Training: Effects on Learning and Performance Under Pressure. *Journal of Applied Sport Psychology*, *22*, 361-376. Golf Putting	14 male undergraduate students split into QE and TT groups 8 day testing period 1. Pre test 2. Training phase 3. Retention test 4. Anxiety transfer test	Performance score (archery style target) QE Duration State Anxiety Movement durations	All groups significantly improved from the pre-test to retention test QE group had significantly longer QE durations in retention and transfer tests compared to TT group QE period of TT group also significantly increased in retention test QE group maintained performance in transfer test whilst TT group significantly declined in performance QE group had longer preparation and backswing durations than the TT group Both groups QE duration significantly reduced in the transfer condition, but the QE group's QE duration was 2.8s and the TT group's QE duration was 894ms suggesting QE group still was at the optimal level

Vine S.J., & Wilson, M.R. (2011). The influence of quiet eye training and pressure on attention and visuo-motor control. *Acta Psychologica*, *136*, 340-346. Basketball Free Throws	20 male undergraduate students split into QE and TT groups 8 day testing period 1. Pre test 2. Training phase 3. Retention test 4. Anxiety transfer test	Free throw performance QE Duration State Anxiety	Both groups significantly improved performance from pre-test to retention tests QE group maintained long QE duration in transfer test and therefore maintained performance from retention test TT group performed significantly worse in transfer test and had a significant reduction in QE
Vine, S.J., Moore, L.J., Cooke, A., Ring, C., & Wilson, M.R. (2013). Quiet eye training: A means to implicit motor learning. *International Journal of Sport Psychology, 44*(4), 367-386. Golf putting	45 undergraduate students split into QE, Analogy and Explicit Learning (TT) groups 7 day testing period 1. Pre-test 2. Training phase 3. Retention test 4. Anxiety transfer test	Radial Error QE Duration Cognitive Anxiety Conscious Processing	QE group significantly outperformed both other groups in the retention test QE and Analogy groups performed significantly better in the transfer test than the Explicit Learning group QE group had significantly higher QE period in retention and transfer test compared to the other two groups Analogy and Explicit Learning groups increased their QE duration between pre-test and retention test
Moore, L.J., Vine, S.J., Cooke, A., Ring, C., & Wilson, M.R. (2012). Quiet eye training expedites motor learning and aids performance under heightened anxiety: The roles of response programming and external attention. *Psychophysiology, 49*, 1005-1015. Golf Putting	40 undergraduate students split into QE and TT groups 7 day testing period 1. Pre-test 2. Training phase 3. Retention test 4. Anxiety transfer test	Radial Error QE Duration Cognitive Anxiety Putting Kinematics Muscle Activity	Both groups significantly improved from pre-test to retention test QE group putted significantly more balls than TT group in the retention test and had significantly lower radial error Both groups QE was longer in the retention test compared to pre-test although the QE group's QE duration was significantly longer than the TT group in the retention test QE group maintained both QE duration and performance in transfer test TT group had significantly lower QE duration in transfer test and performed significantly worse in this condition

Moore, L.J., Vine, S.J., Freeman, P., & Wilson, M.R. (2013). Quiet eye training promotes challenge appraisals and aids performance under elevated anxiety. *International Journal of Sport and Exercise Psychology, 11*(2), 169-183. Golf Putting	30 undergraduate students split into QE and TT groups 7 day testing period 1. Pre-test 2. Training phase 3. Retention test 4. Anxiety transfer test	Radial Error QE Duration Cognitive Anxiety Cognitive Appraisal	Both groups QE was longer in the retention test compared to pre-test QE group had significantly higher QE duration and lower radial error than TT group in retention test QE group had significantly higher QE duration and lower radial error than TT group in transfer test QE group reported greater perceived coping resources in the transfer test compared to the TT group
Moore, L.J., Vine, S.J., Smith, A.N., Smith, S.J., & Wilson, M.R. (2014). Quiet Eye Training Improves Small Arms Maritime Marksmanship. *Military Psychology, 26*(5-6), 355-365. Marksman Shooting	20 participants split into QE and TT groups One day testing period over 2 sessions 1. Pre-test 2. Training Phase 3. Retention test	Initial Shot Radial Error Average Radial Error QE Duration Gaze Locking	QE groups was significantly more accurate for both initial shot and average shot radial error in the retention test than the TT group QE group increased their QE duration and had greater target locking in the retention test, whilst the TT group showed no changes in visual search behaviour
Miles, A.L., Vine, S.J., Wood, G., Vickers, J.N., & Wilson, M.R. (2014). Quiet eye training improves throw and catch performance in children. *Psychology of Sport and Exercise, 15*, 511-515. Children throwing a tennis ball against the wall and catching it	38 children (mean age 10.32 years) split into QE and TT groups 1. Pre-test 2. Training phase 3. Retention test	Catching performance % QE Duration Ball Flight Time Periods	QE group improved at catching the ball significantly more than the TT group QE group significantly increased QE durations when fixating on the target on the wall and tracking the ball after the training phase TT group had no increases in QE duration Both groups had significantly better ball flight characteristics in the retention-test in the retention-test suggesting QE training

			enhanced focus and anticipation as opposed to just biomechanical advantages
Miles, C.A.L., Wood, G., Vine, S.J., Vickers, J.N., & Wilson, M.R. (2015). Quiet eye training facilitates visuomotor coordination in children with developmental coordination disorder. *Research in Developmental Disabilities, 40*, 31-41. Children with developmental coordination disorder throwing a tennis ball against the wall and catching it	30 children with developmental coordination disorder (mean age 9.07 years) split into QE and TT groups 8 week testing period 1. Pre-test 2. Training phase 3. Retention test of 10 trials	Catching Performance % QE Duration during pre-throw and pre-catch General Gaze Behaviours Elbow angle during catch attempts	QE group increased QE significantly during pre-throw and pre-catch of the ball, and retained this improvement after 6 weeks Both groups significantly improved catching performance from pre-test to the first retention test QE group significantly improved catching technique compared to the TT group
Miles, C.A.L., Wood, G., Vine, S.J., Vickers, J.N., & Wilson, M.R. (2017). Quiet eye training aids the long-term learning of throwing and catching in children: Preliminary evidence for a predictive control strategy. *European Journal of Sport Science, 17*(1), 100-108. Children throwing a tennis ball against the wall and catching it	35 children split into QE and TT groups 8 week testing period 1. Pre-test 2. Training phase 3. Retention test	Catching performance % QE Duration pre-throw on the wall and pre-catch on the ball Ball Flight Time Periods	QE group performed significantly better after training in both retention phases QE group significantly outperformed TT group in delayed retention test, suggesting QE training is useful with long term motor learning QE group significantly increased their QE duration from the pre-test to the retention tests whereas the TT group did not Increased QE duration on the wall predicted catching performance as opposed to QE on tracking the ball
Vickers, J.N., Vandervies, B., Kohut, C., & Ryley, B. (2017). Quiet eye training improves accuracy in basketball field	213 university students split into QE and TT groups Also split into novice and intermediate groups	Field shooting accuracy %	In the pre to post-test, the novice QE participants improved significantly more in throws than the novice TT participants, although the novice TT participants also improved

goal shooting. *Progress in Brain Research, 234*, 1-12. Basketball Throws (no eye tracking)	One day testing period 1. Pre-Test 2. Training phase 3. Anxiety transfer test		In the pre to post-test, the intermediate QE and TT participants maintained but did not improve performance From post to transfer-test, all groups deteriorated but the intermediate QE group maintained a relatively high accuracy level compared to the other groups

Appendix 3 - Published papers

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Howzat! Expert umpires use a gaze anchor to overcome the processing demands of leg before wicket decisions

Pravinath Ramachandran, Matt Watts, Robin C. Jackson, Spencer J. Hayes & Joe Causer

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Howzat! Expert umpires use a gaze anchor to overcome the processing demands of leg before wicket decisions

Pravinath Ramachandran[a], Matt Watts[b], Robin C. Jackson[c], Spencer J. Hayes[d] and Joe Causer[a]

[a]Research Institute of Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, UK; [b]School of Life Sciences, Coventry University, Coventry, UK; [c]School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, UK; [d]Department of Psychology and Human Development, UCL Institute of Education, University College of London, London, UK

ABSTRACT

Cricket umpires are required to make high-pressure, match-changing decisions based on multiple complex information sources under severe temporal constraints. The aim of this study was to examine the decision-making and perceptual-cognitive differences between expert and novice cricket umpires when judging leg before wicket (LBW) decisions. Twelve expert umpires and 19 novice umpires were fitted with an eye-tracker before viewing video-based LBW appeals. Dependent variables were radial error (cm), number of fixations, average fixation duration (ms), final fixation duration (ms), and final fixation location (%). Expert umpires were significantly more accurate at adjudicating on all aspects of the LBW law, compared to the novice umpires ($p < .05$). The expert umpires' final fixation prior to ball-pad contact was directed significantly more towards the *stumps* ($p < .05$), whereas the novice umpires directed their final fixation significantly more towards a *good length* ($p < .05$). These data suggest that expert umpires utilize specialized perceptual-cognitive skills, consisting of a *gaze anchor* on the stumps in order to overcome the processing demands of the task. These data have implications for the training of current and aspiring umpires in order to enhance the accuracy of LBW decision-making across all levels of the cricketing pyramid.

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Perceptual-cognitive skill; expertise; gaze behaviours; decision making; gaze anchor

Cricket umpires make decisions regarding batter dismissals that consequently determine match outcomes (Sacheti et al., 2015). Of the modes of dismissals within cricket (see Marylebone Cricket Club, 2017), none has led to as much controversy and dispute as the leg before wicket (LBW) (Chedzoy, 1997; Sacheti et al., 2015; Southgate et al., 2008). LBW appeals occur when the ball strikes the batter on any part of their body (usually leg pads) apart from the bat and hands (Craven, 1998). For a bowler to dismiss a batter via LBW, the umpire must consider whether the delivery met a number of specific criteria (Crowe & Middeldorp, 1996). For every delivery, the umpire must initially determine whether the bowler's front foot grounds behind a line termed the crease (Adie et al., 2020).[1] Subsequently, the umpire must consider where the ball bounced (pitched), where the ball impacted the batter in relation to the stumps, and the more challenging judgement of whether the ball would have continued on its flight path to hit the stumps had the obstruction with the batter not occurred (Southgate et al., 2008). Therefore, the LBW rule appears to be one of the few regulations in sport where an official must determine what might have happened (would the ball have hit the stumps?) if other events did not occur (ball flight path being obstructed by the leg), which contributes to the dispute amongst players, media and followers of cricket (Crowe & Middeldorp, 1996). A number of contextual factors further add to the difficulty of the umpire's LBW verdict, such as the batter's stance (Southgate et al., 2008), dynamics of the delivery (spin and swing) and the ball's surface degradation (Chalkley et al., 2013). In spite of these challenges, it has been shown that professional umpires are highly accurate at making LBW decisions. Adie et al. (2020) examined 5578 decisions made in elite level cricket in Australia between 2009–2016 and found that umpires were correct 98.08% of the time. Further, when they broke down the match format, 96.20% of "out" decisions were correct in first-class cricket, 96.29% in One Day cricket and 86.15% in T20 cricket.

In 2008, the International Cricket Council (ICC) introduced the Decision Review System (DRS) into international cricket. This permits the captains of either team to refer a limited number of decisions made by the on-field umpires to the third umpire who is able to utilize an array of replays and technologies to assess the accuracy of the original decision (Borooah, 2013). Utilizing statistics from the DRS in international test cricket (July 2008 to March 2017) ESPN Cricinfo estimated that 74% of the reviews involved LBW appeals, with the overturn rate being at 22% (Davis, 2017, June, p. 1). Whilst initially this proportion seems high, it must be stressed that these officials are often placed under severe constraints when making these decisions (Chalkley et al., 2013; Southgate et al., 2008). More specifically, in certain scenarios, umpires must process information related to the ball's (7.29 cm) flight that can travel at velocities up to 95 mph over 20 m. These constraints offer umpires approximately 543 ms to process the

CONTACT Joe Causer j.causer@ljmu.ac.uk Research Institute of Sport and Exercise Sciences, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, UK

[1]Since 2020 this task was no longer performed by international umpires after a number of controversial events, and therefore this decision is made by the third umpire with use of TV replays.

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multitude of visual and auditory information required to make a single decision (Southgate et al., 2008). To help combat these processing demands, it has been suggested that umpires utilize specific perceptual-cognitive behaviours that contribute to the increased likelihood of correct decisions (Southgate et al., 2008).

Cricket batters face similar temporal constraints, and researchers have highlighted differing gaze behaviours to attempt to overcome these demands (Croft et al., 2010; Land & McLeod, 2000; Mann et al., 2013). Upon ball release from the bowler, expert batters generally make an anticipatory saccade to its pitching point (Croft et al., 2010). However, following the ball pitching, two distinct strategies were identified. Land and McLeod (2000) reported that batters made a saccade towards the ball about 200 ms after its bounce before attempting to pursuit track the remainder of its flight, whereas batters from Mann et al. (2013) made a saccade towards the bat at the point it contacted the ball. The variability in ball tracking techniques utilized within cricket batting was highlighted by Croft et al. (2010), who reported that whilst individual batters displayed a consistent gaze strategy, these strategies varied greatly between participants with a mixture of saccades and pursuit tracking being used at different time points before and after the ball bounced.

When tracking a projectile, such as a cricket ball, it has been suggested that use of a series of fixations or saccades limits the amount of information that can be efficiently processed (Ludwig, 2011). Therefore, in these scenarios, a single stable fixation can enable more accurate performance (Wilson et al., 2015). In a recent review, Vater et al. (2020) identified 3 unique stable gaze strategies utilized by athletes that have similar characteristics but have a functional difference: 1) foveal spot; 2) gaze anchor; and 3) visual pivot. First, the *"foveal spot"*, is a strategy that involves an individual processing information with their visual attention directed towards a central cue with the aim of accurate information processing via the fovea (Vaeyens et al., 2007). Second, the *"gaze anchor"* is a location in the centre of several critical cues in order to distribute attention to several cues using peripheral vision. Importantly, the actual fixation location may not contain any task-specific information that is being process by the fovea, but is equidistant to the pertinent cues (Vansteenkiste et al., 2014). Third, the *"visual pivot"* acts as a centre point for a series of fixations to important locations to minimize the retinal distance between critical cues. Similar to the gaze anchor, it is possible that there is no task-specific information located at the visual pivot, but it is the most efficient central position for subsequent visual scanning (Ryu et al., 2013). Given the spatial-temporal constraints that cricket umpires are under, making numerous judgements and predictions in less than 550 ms (Southgate et al., 2008), a stable fixation, such as a gaze anchor, may be the most efficient and effective strategy to process the relevant information.

Therefore, the aim of the current study was to establish whether skill-based differences exist between expert and novice cricket umpires when making judgements that are crucial for LBW decisions. Furthermore, this study aimed to elucidate whether expert umpires possess specialized visual strategies that enhance LBW decision-making. It was predicted that: 1) expert umpires will outperform novice umpires on adjudicating of all three components of LBW appeals; 2) expert umpires will utilize a specialized visual strategy consisting of fewer fixations of longer durations to more informative locations (Williams, 2009); and, p. 3) expert umpires' final fixation before the ball strikes the batter's pad will be a *gaze anchor* between a *good length* and the middle of the stumps.

Method

Participants

Participants were 12 expert umpires (M = 58 years of age, SD = 10) and 19 novice umpires (M = 42 years of age, SD = 7). The expert umpires had officiated in organized cricket at elite club (n = 9), minor counties (n = 2) and first-class cricket (n = 1). The expert umpires had a mean of 11 years (SD = 5) umpiring experience, accumulated over a mean of 100 matches (SD = 12). Additionally, the expert umpires had accumulated a mean of 279 (SD = 390) matches of playing experience in competitive club cricket. The novice participants had not umpired in any form of organized cricket. Participants gave their informed consent prior to taking part in the study and the study was approved by the Research Ethics Committee of the lead institution.

Task & Apparatus

Visual search behaviours were recorded using the TobiiGlasses2 corneal reflection eye movement system (Tobii Technology AB; Danderyd, Sweden). The test film was recorded at the Marylebone Cricket Club Cricket Academy. Video footage from an umpire's perspective was recorded using a Canon VIXIA HFR706 camera (Tokyo, Japan). The camera was positioned in line with middle stump 1.00 m away from the non-strikers popping crease. A right-handed batter who competes in the Worcestershire Premier League faced a number of deliveries delivered by a BOLA Bowling Machine (Bola Manufacturing Ltd.; Bristol, UK), from both around and over the wicket, at speeds between 65–80 mph. The batter was encouraged to play their "natural game" whilst facing these deliveries. Deliveries that struck the batter's pad were termed "appeals" and were reviewed via "Hawk Eye" (Basingstoke, UK), which reconstructed the ball flight characteristics should the obstruction not have occurred (Collins, 2010). Hawk Eye technology utilizes a theory of triangulation, which helps predict post ball-pad impact by measuring angles from the known points of the delivery's pre-impact flight (Duggal, 2014). In total, 20 appeals were used for the study with 11 being delivered from around the wicket, and 9 being delivered from over the wicket. A total of 16 appeals were deemed "out" and 4 deemed "not out" by Hawk Eye. Based on pilot testing, trials that were deemed too easy (85% and above in accuracy) were omitted from the final test film.

The footage was edited using Windows Movie Maker 2016 (Washington, USA). Each appeal formed one trial. For each trial, the trial number and position of the delivery (over or around the wicket) were each shown for 3.0 s and were followed by a 3.0s countdown. The video clip started 3.0 seconds before ball release, to represent the time for a bowler's run-up in a match scenario. The video clip continued for a further 3.0 s after ball-pad impact and was followed by a black screen, which signalled the end of the trial. The position of delivery for each trial was randomized to avoid any order effects. Additionally, five *catch trials* were randomly included in the test film, in which the batter successfully hit the ball so that participants were not always presented successive LBW appeals, and thus increased task realism.

Procedure

Participants were fitted with the TobiiGlasses2 eye tracker and were calibrated using a one-point calibration card held by the researcher 1.00 m away. The test film was projected by an Epson EB-7000 projector (Suwa; Japan) onto a large Cinefold Projection Sheet (Draper Inc; Spiceland, IN; 2.74 m × 3.66 m). Participants stood 3.20 m away from this display to ensure it subtended a visual angle of 12.8°, thereby replicating the height of the batter *in situ*. To cross-check calibration, participants viewed a still image of the pitch and were asked to direct their visual attention towards the stumps.

Initially, the researchers provided the participants with an overview of the LBW rule as per Marylebone Cricket Club guidelines, using standardized diagrams and text. To familiarize participants with the experiment protocol and response requirements, participants observed two familiarization trials, which showed LBW appeals similar to those in the test. Participants verbally predicted the three components of the LBW adjudication and then were given a handout that showed the Hawk Eye ball flight path. This familiarized participants with the scale of the Hawk Eye slides they would be adjudicating on for each trial. Following this, the testing period began. During the testing period, the participant viewed each trial and was then asked on a computer to position 3 balls (circles scaled to the Hawk Eye image) on a pitch image, once the display had gone black. Specifically, the balls were positioned on Hawk Eye slides corresponding to where they perceived the ball to: have pitched; impacted the batter's front pad; and where it would have hit/passed the stumps had its flight not been obstructed (refer Figure 1). Participants were asked to adjudicate the three variables in any order they saw fit and in a time frame similar to how they would generally make decisions in a match. Once participants had made a judgement for one of the LBW variables, they could not alter this decision. This procedure was repeated for all 20 trials. The whole collection process took approximately 40 minutes.

Measures

Response accuracy was determined by *radial error* (cm), which was defined as the Euclidean distance of the participant's judgement of ball impact with the *pitch, pad*, and *stumps* compared to the Hawk Eye data. This distance was scaled to quantify accuracy at a game scale (see Runswick et al., 2019). *Number of fixations* were measured from the onset of the trial until the offset of the trial. *Average fixation duration* (ms) was calculated by dividing the total fixation duration by the number of fixations of each trial. *Final fixation duration (ms)* was the duration of the last fixation prior to ball-pad impact until offset of the fixation or end of the trial. *Final fixation location* (%) was defined as the percentage of trials participant's final fixation was located on a specific area. Five fixation locations were coded: *good length, full length, short length, stumps, other location* (see Figure 2). The front pad of the batter occludes a large proportion of the stumps during a standard delivery. Therefore, when umpires directed their vision towards the batter's front pad, this was coded as "*stumps*" as the umpires typically maintained their gaze on the stumps after the batter had moved away, suggesting they were anchoring their gaze on the stumps as opposed to following the batter's pad.

Statistical analysis

Radial error data were analysed by a 2 (Expertise: expert, novice) x 3 (Decision: pitch, pad, stumps) mixed-factor analysis of variance (ANOVA). Number of fixations, average fixation duration (ms) and final fixation duration (ms) were analysed using separate 2 (Expertise: expert, novice) x 2 (Outcome: correct, incorrect) mixed-factor ANOVAs. Final fixation location was analysed using a 2 (Expertise: expert, novice) x 2 (Outcome: correct, incorrect) x 5 (Location: good, full, short, stumps, other) mixed-factor ANOVA. Effect sizes were calculated using partial eta squared values (ηp^2).

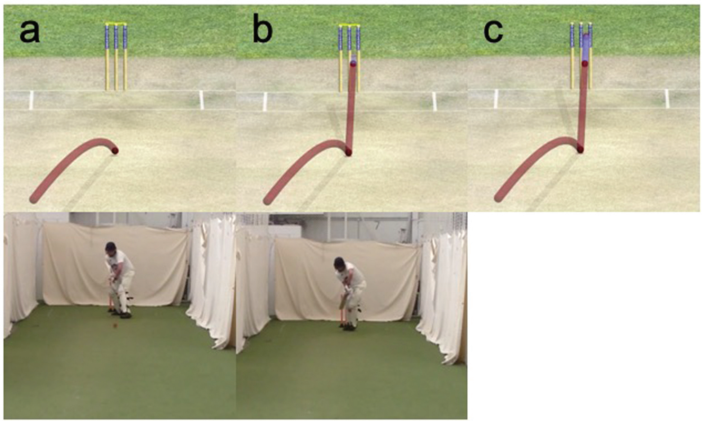

Figure 1. Frames from test film with associated Hawk Eye footage for: a) pitch, b) pad, and c) stumps.

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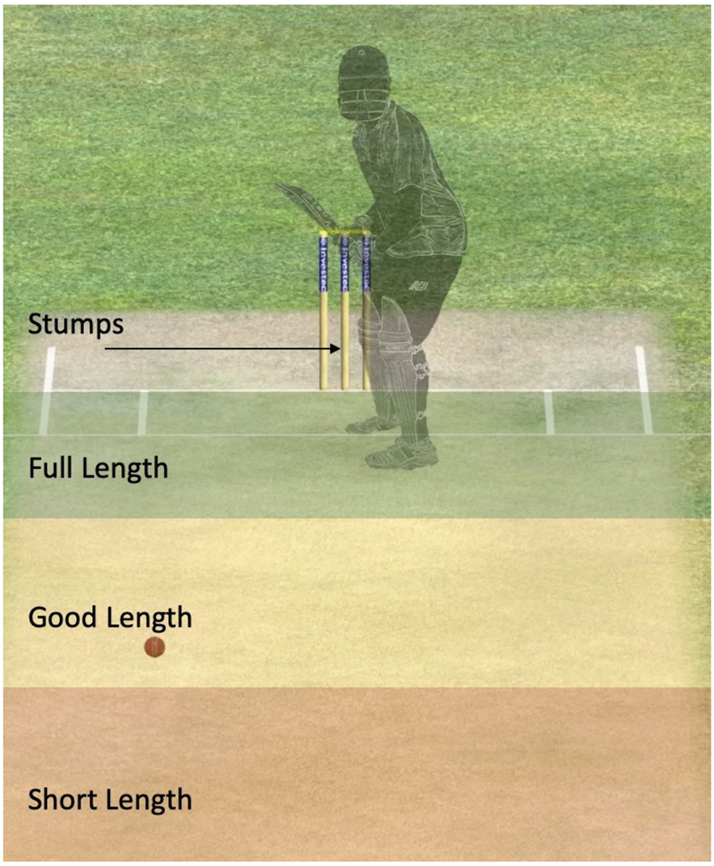

Figure 2. Final fixation locations: *good length, full length, short length, stumps.*

Greenhouse-Geisser epsilon was used to control for violations of sphericity and the alpha level for significance was set at .05 with Bonferroni adjustment to control for Type 1 errors. A priori power analysis using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) for a 3 × 2 within-between ANOVA indicated a total sample size of 28 was needed to detect a medium effect (f = 0.25) for the within-participant and interaction effects. The pool of expert umpire participants was limited so it is important to note that statistical power for tests of between-participant effects was only sufficient to detect larger effects (f > 0.42).

Results

Radial error (cm)

There was a large main effect of expertise, $F_{1,29} = 8.88$, $p = .01$, $\eta p^2 = .23$ (see Figure 3). Novice umpires had significantly higher error (*M* = 25.87 cm, *SE* = 1.31) than the expert umpires (*M* = 19.61 cm, *SE* = 1.64). The novice group were less accurate at determining the ball's impact with the *pitch* (*M* = 24.60 cm, *SE* = 2.29), *pad* (*M* = 22.65 cm, *SE* = 1.83) and *stumps* (*M* = 30.35 cm, *SE* = 2.02), compared to the expert group (pitch: *M* = 20.57 cm, *SE* = 2.88; p < .05; pad: *M* = 16.15 cm, *SE* = 2.30; *p* < .05; stumps: *M* = 22.11 cm, *SE* = 2.55; p < .05). There was also a large main effect of Decision, $F_{2,58} = 4.80$, $p = .01$, $\eta p^2 = .14$. Radial error was significantly higher for *stumps* (*M* = 26.23 cm, *SE* = 1.63) compared to *pad* (*M* = 19.40 cm, *SE* = 1.47; *p* < .05). There was no significant Group x Decision interaction $F_{2,58} = .46$, $p = .63$, $\eta p^2 = .02$.

Number of fixations

The main effects of expertise, $F_{1,27} = 1.536$, $p = .23$, $\eta p^2 = .05$, and outcome, $F_{1,27} = 2.183$, $p = .15$, $\eta p^2 = .08$, were small to moderate hence were statistically non-significant. This reflected a similar number of fixations for correct trials (*M* = 4.4, *SE* = .32) and incorrect trials (*M* = 4.7, *SE* = .33); and between expert (*M* = 5.0, *SE* = .47) and novice umpires (*M* = 4.2, *SE* = .39). The

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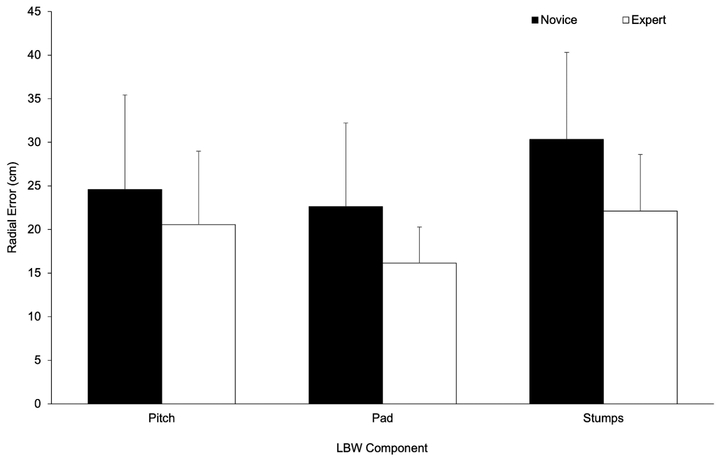

Figure 3. Radial error (cm) for expert and novice umpires, for *pitch, impact* and *stumps*.

Expertise x Outcome interaction was non-significant, $F_{1,27}$ = 1.082, p = .31, ηp^2 = .04.

Average fixation duration (ms)

There was a large effect of expertise, $F_{1,27}$ = 5.347, p = .03, ηp^2 = .17. The average fixation duration for novice umpires (M = 1520.42 ms, SE = 152.31) was significantly longer than for expert umpires (M = 972.91 ms, SE = 181.29). The main effect of outcome was small and non-significant, $F_{1,27}$ = 1.318, p = .26, ηp^2 = .05, which reflected the similar average fixation duration for correct (M = 1361.06 ms, SE = 143.85) and incorrect (M = 1226.67 ms, SE = 125.22) trials. The Expertise x Outcome interaction was non-significant, $F_{1,27}$ = .389, p = .54, ηp^2 = .01.

Final fixation duration (ms)

There was a large effect of expertise, $F_{1,27}$ = 7.787, p = .01, ηp^2 = .22. The final fixation duration was significantly longer in the novice group (M= 2906.14 ms, SE = 235.27) than the expert group (M = 1885.56 ms, SE = 280.02). There was also a moderate to large main effect of outcome, $F_{1,27}$ = 5.500, p = .03, ηp^2 = .17. Final fixation duration was significantly longer for correct (M = 2612.58 ms, SD = 1083.65) compared to incorrect trials (M = 2355.08 ms, SD = 1173.60). The Expertise x Outcome interaction was non-significant, $F_{1,27}$ = 1.743, p = .20, ηp^2 = .06.

Final fixation locations (%)

There was a very large main effect of location, $F_{2.04,\ 53.09}$ = 17.80, p < .001, ηp^2 = .41. (see Figure 4). A higher percentage of final fixations were directed towards the *stumps* (M = 41.95%, SE = 4.97) than towards a *good length* (M = 21.51%, SE = 4.01), a *full length* (M = 27.47%, SE = 3.14) (p < .05), a *short length* (M = 2.54%, SE = 1.09) and *other locations* (M = 7.68%, SE = 2.14) (all p < .01). A significantly higher percentage of fixations were directed towards a *good length* and a *full length* than towards a *short length* and *other locations* (all p < .01). There was also a large interactive effect between expertise and location, $F_{2.04,\ 53.09}$ = 7.04, p < .001, ηp^2 = .21. This reflected that the percentage of final fixations directed towards a *good length* was higher in the novice group (M = 35.85%, SE = 5.02) than the expert group (M = 7.17%, SE = 6.24; p < .05), whereas the percentage of final fixations directed towards the *stumps* was lower in the novice group (M = 28.89%, SE = 6.24; p < .05) than in the expert group (M = 55.51%, SE = 7.75). All other main effects and interactions were non-significant (all p > .05).

Discussion

In line with hypothesis 1, expert umpires were much more accurate on all aspects of the decision-making task, compared to the novice group. Experts demonstrated lower radial error when judging the location of the ball's pitch and impact with the batter's pad, and when predicting the location the ball would have passed the wickets had it not been obstructed. As well as providing predictive validity for the task, these data demonstrate that umpires possess domain-specific expertise in this complex decision-making task. These data corroborate previous literature that has shown that expert sports officials are able to make more accurate decisions, by developing refined perceptual-cognitive strategies through deliberate practice activities, specifically competitive match exposure (MacMahon et al., 2007). As performers become more expert they have been shown to use working memory more efficiently (Ericsson, 2008). In the current task, determination of *pitch* and *pad* primarily required the umpires to accurately track and recall the ball's spatial location, which might rely on the use of working memory (Furley & Wood, 2016). Researchers have proposed that when performing the task in which they are expert, performers are capable of

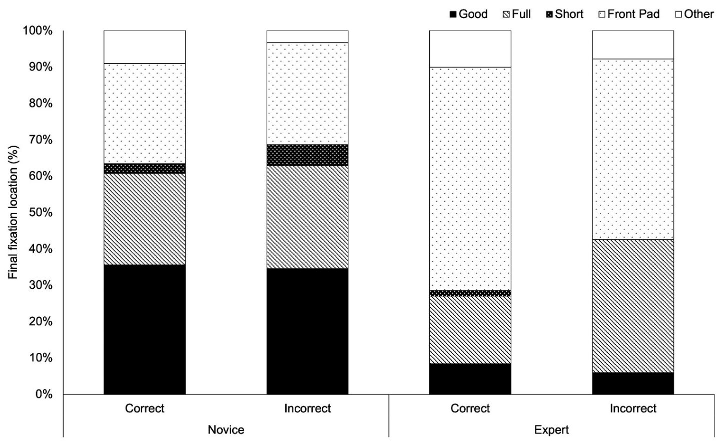

Figure 4. Final fixation locations (%) for experts and novices on correct and incorrect trials for *good, full length, short length, stumps* and *other* locations.

circumventing the limits of working memory by directly accessing domain-specific information from long-term memory through retrieval cues in short-term working memory (Ericsson & Kintsch, 1995). This may explain the more accurate decisions of the experts in the *pitch* and *pad* judgements. Such an explanation would be in line with the assumption that whilst elite officials do not have a greater working memory capacity for general tasks, they acquire strategies that enable a more efficient use of working memory in domain-specific activities (Spitz et al., 2016).

Despite their differences, both groups were less accurate when predicting *stumps* compared to *pad*. This can be explained by the fact that judging ball flight path after ball-pad contact requires a perceptual judgement based on a variety of factors such as batter stance (Southgate et al., 2008), dynamics of the delivery (spin and swing) and the ball's surface degradation (Chalkley et al., 2013). Conversely, when judging ball-pad impact, all visual information was present so the umpire did not need to consider these contextual factors.

As well as accuracy differences, previous studies of expertise in sport have consistently reported differences in the number of fixations and average fixation duration between skill levels in a variety of task (Mann et al., 2007). It is generally accepted that in a temporally constrained decision-making task, such as the current study, a more efficient strategy consists of fewer fixations of longer duration (Mann et al., 2019). This is predominantly to reduce suppression of information during saccadic eye movements in order to maximize the information that can be gathered (Ludwig, 2011). However, we found no significant difference in the number of fixations between the groups. Furthermore, the average fixation duration for the novice group was significantly *longer* than that of the expert umpires, although this was not associated with more accurate decision-making.

The finding that final fixation duration was significantly longer for the novices compared to the experts conflicts with hypothesis 2. Previous studies (Raab & Laborde, 2011) have shown that experts are better able to generate the first and best option, produce fewer overall options and are quicker to generate the first option than near-experts and novices, therefore requiring a shorter final fixation. Conversely, the novices require a much longer final fixation in order to extract the information needed to make a judgement as they have less refined perceptual-cognitive strategies (Mann et al., 2019). This is supported by reports that experts favour intuitive decision-making, compared to novices, who tend to be more deliberative (Raab & Laborde, 2011). Novices have been shown to generate more options (Raab & Laborde, 2011) and take longer to generate an initial response (Raab & Johnson, 2007). Conversely, experts have been shown to generate fewer options and pick the first option more often (Raab & Laborde, 2011), a strategy that has been shown to result in better and more consistent decisions (Johnson & Raab, 2003). This take-the-first heuristic allows the experts to make quick decisions under limitations of time, processing resources, or information. Whilst these decisions are usually accurate, they can sometimes be affected by biases (Raab & Johnson, 2007). Whilst cricket umpiring generally allows some time for deliberation, it could be argued that the speed at which critical visual information becomes available dictates that intuitive decision-making plays a key role.

In hypothesis 3, it was predicted that expert umpires would use a perceptual-cognitive strategy that consisted of a final fixation point (gaze anchor) on a location central to the critical information sites. In support of this, the more accurate decisions made by the expert group across all of the conditions could be explained by their allocation of attention to the *stumps* significantly more than their novice counterparts, who tended to allocate their final fixation towards a *good length* on the pitch. Such differences also corroborate previous research within fast-ball sports (Broadbent et al., 2015), which have shown specialized perceptual-cognitive skills utilized by expert performers enhance their ability to locate and identify salient cues, which ultimately aid decision-making success. A *gaze anchor* is located in the centre of several critical cues (pitch, pad, stumps) in order to distribute attention to several cues using peripheral vision. Use of the gaze anchor has been seen to enhance decision-making of football officials in expert and near-expert assistant football referees, who anchored their gaze on the offside line as opposed directing foveal vision on either the passer, the ball or the attacker (Schnyder et al., 2017). Notably, the actual fixation location (stumps) from the present study may not contain any task-specific information that is being processed by the fovea, but is equidistant to the pertinent cues (Vansteenkiste et al., 2014). Therefore, by anchoring their gaze towards the stumps, the expert umpires are capable of utilizing their peripheral vision to ascertain the position the ball pitched as well as the initial angle of delivery using the relative motion around the central point. Consequently, information processing via foveal vision directed towards the stumps might have enhanced their ability to perceive the height and line of impact with the pad and thus provided them with an increased accuracy when judging the trajectory of the ball towards the stumps.

Conversely, the novice umpires might not have utilized both foveal and peripheral vision to make the judgements and might have fixated on a good length due to *pitch* being the first consideration needed when applying the LBW law. Subsequently, due to the demands of processing multiple trajectories and impact points, working memory capacity of the novices may have been overwhelmed, leading to less accurate decisions on the later variables. The *information reduction hypothesis* (Haider & Frensch, 1999) postulates that when individuals practice a task, they selectively allocate attentional processes towards task-relevant information at the expense of task-redundant information which limits the load on working memory processes, and as a consequence enhances performance. In the current study, the expert's anchoring their vision on the *stumps* may have permitted them to selectively process critical information related to *pad* and stumps and thus reduce task-redundant processing. Consequently, load on the working memory will have been reduced and recall of all three components of the LBW law may have been enhanced.

Summary

Taken together, these data show that expert umpires have developed a systematic perceptual-cognitive strategy, comprising a gaze anchor, that enables them to overcome the processing demands and maximize accuracy in a complex decision-making task. These data provide an important first step towards the design of training interventions to help less-skilled umpires develop a more refined and systematic visual strategy to enhance decision-making. However, further research is required to determine the processing demands in umpires during a delivery, which includes other elements, such as the front-foot no-ball call, and other external factors influencing attentional control. For example, the use of a real-life bowler, and the front-foot no-ball decision, would increase the representativeness of both the batter's biomechanics (Pinder et al., 2009) and the overall match demands of an umpire, which may alter the umpires' visual strategy. It is possible that the limited time between the front-foot grounding and the ball-pad impact might impair the use of the gaze anchor and require umpires to implement an alternative gaze strategy. Understanding the development of these domain-specific perceptual-cognitive skills and the effect of other attentional and contextual factors will be critical in designing any future training interventions.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Pravinath Ramachandran http://orcid.org/0000-0003-2502-3105
Matt Watts http://orcid.org/0000-0002-5814-8556
Robin C. Jackson http://orcid.org/0000-0001-7983-3870
Spencer J. Hayes http://orcid.org/0000-0002-8976-9232
Joe Causer http://orcid.org/0000-0002-8939-8769

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