VISION AND EXPERTISE FOR INTERCEPTIVE ACTIONS IN SPORT

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‘When I ask myself, “Who are the happiest people on the planet?” my answer is, “Those who can’t wait to wake up in the morning to get back to what they were doing the day before.”’

James Cronin
ABSTRACT

Exquisite visually-guided movements underpin expertise in fast interceptive sports. The assumption that skilled performance relies on superior visual skills has been challenged by studies of sporting expertise which typically advocate vision to be a poor predictor of sporting success. This discordance is addressed in this thesis by examining whether visual degradation (in the form of blur) affects the performance of an interceptive action where successful execution demands precise spatial and temporal visual-motor control.

The vision of skilled cricket batters was blurred using contact lenses (four increasing levels: plano, +1.00, +2.00, +3.00) in each of two experimental phases. In the first phase batters faced a bowling-machine and in-situ bowlers to examine the effect of blur on bat-ball interception. The highest level of blur (+3.00) was required to produce a significant decrease in batting performance when facing the bowling-machine at medium-paced ball-velocities (105-115 kph). A similar effect of blur was found when facing in-situ bowlers of comparable ball-velocity, however performance was found to be affected by a lower level of blur (+2.00) for faster-paced ball-velocities (120-130 kph). The +1.00 blur was concluded even at this higher ball-velocity to have no measurable effect on interceptive performance in a natural setting.

The second phase sought to investigate the effect of blur on anticipation: a perceptual skill established to be an important component of expertise in many interceptive sports. It was established, using temporal occlusion of a bowling sequence, that optimal anticipation required an opportunity for bat-ball interception (facilitating close coupling between perception and action). Coupled anticipation demonstrated velocity-dependent resilience to blur; +3.00 and +2.00 were required for respective decreases in the anticipation of action-sequences for medium- and fast-paced ball-velocities. Remarkably, results suggest that blur
may enhance uncoupled (verbal) anticipation according to the movement velocity of the bowler.

Experimental results led to the conclusion that clear vision is not necessarily required for optimal interceptive performance, even when the demanding spatio-temporal task simulates the conditions experienced at the highest levels of competition. Results are interpreted based on the predictions of the dual-pathway theory of vision, including differences in the underlying visual information processed via these pathways.
ACKNOWLEDGEMENTS

So I have learned that there is a good reason this research is unique. It has been a most challenging and at times confronting adventure, but ultimately one which has been most beneficial and rewarding. Of course it would have been impossible to perform this work without the invaluable help and support of many friends and colleagues.

To kick things off I would like to thank my dynamic duo of supervisors, Professor Bruce Abernethy and Dr Damian Farrow. Things could barely have worked out better – Bruce has provided important structure and academic integrity, whilst Damo has sourced the incredible resources to help ‘make it happen’ and guide me along the way. Firstly to Bruce - whose papers I loved reading as an undergrad - it has been an absolute privilege to learn from the best in the business. The advice that Bruce has given has been impeccable; providing me with complete academic freedom and support whilst also guiding me into a niche area which takes advantage of my unique academic background. Damian has made me feel at home at the AIS and provided me with amazing opportunities that would not have been previously conceivable. It has been an exciting journey being on the cutting edge of a new discipline applied in a high-performance setting. It is surprising that I ever saw Damo considering our different time-scales – my emails sent just before going to bed would occasionally coincide with his replies sent just as he was waking up. It has been a great experience to work with a creative thinker not afraid to innovate and have a crack – whilst also sharing a beer or red when the opportunity (relatively regularly) presented itself.

The work presented in this thesis was produced first as an academic staff member of the UNSW School of Optometry and Vision Science (SOVS), second as a beneficiary of the SOVS Postgraduate Scholarship, and finally as a Skill Acquisition Specialist at the Australian Institute of Sport. Thanks must go to each of these organisations for their patience and support of my studies. Research performed in Chapters 3 & 5 was funded by a Cricket Australia Sport Science
Sport Medicine Research Grant, whilst the work in Chapter 4 was supported by AIS Discretionary Research Funding. Particular thanks to Marc Portus (CA) for his facilitation of funding and resources. Contact lenses used in Chapters 3 & 5 were kindly supplied by Johnson & Johnson Vision Care. I have been extremely fortunate to have travelled widely as a result of the work presented in this thesis; this includes trips to Barbados, South Africa, Portugal, USA, Canada, Bangladesh, France, New Zealand, and Hong Kong. My sincere thanks to those who helped to send me on all of these wonderful learning adventures: UNSW School of Optometry and Vision Science, the Australian Institute of Sport, the UNSW Graduate Research School PRSS Scheme, Department of Optometry and Vision Science – University of Auckland, and Cricket Australia.

This thesis has been a tale of two cities, with people located in each who have provided fantastic support. Firstly in Sydney, I’d particularly like to thank Professor Fiona Stapleton who arranged for the efficient and timely provision of supervisory and scholarship support. I’d like to thank my Friday afternoon HOSAC drinking buddies Stephen Dain (he who brought me into this whole academic caper) and Kay Dulhunty (she who has since helped keep me sane) – I always loved the red wine and snacks to finish off the week, though you guys probably shouldn’t have driven home. Thanks to Barbara Junghans for nurturing my teaching along the way – sorry I haven’t returned to fulfil your retirement plans (though I really know you are happy about it – the same can’t be said for Ron!). And to my wise old mate Paul Gifford, thanks for the sound advice, the lounge to sleep on, and the many Coopers Pale at the Rege. Thanks also to my students with whom I kicked this project off: Nathan Ho, Neilsen De Souza, Damien Watson, and Scott Taylor.

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I guess a PhD is the product of a life-time of learning, and I have been truly blessed to have two parents who have supported every single step I have taken. I look back now and realise that it must have been quite tough to see your son firstly drop out of a perfectly good medical degree, and then secondly to drop out of a perfectly good optometric profession – just to go back to uni and study sports science! Not once did either Mum or Dad question me, rather they supported every move I made – it is a measure of the quality of people they are.
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Finally, one week after finishing the first draft of this thesis, I lost one of my best mates. He was my drinking buddy, my travelling companion, my fellow sports watcher (and Parra fan), and my (equal) biggest supporter. The bottle of red following graduation will be the loneliest of my life. I miss you Dad.
This thesis is produced as a direct result of the opportunities provided to me by my parents.
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PUBLICATIONS AND PRESENTATIONS

Sections of this thesis have been published (or submitted for publication) and/or presented at relevant scientific, optometric, or coaching conferences.

PUBLICATIONS

Chapter 2


Chapter 3


Chapter 4


Chapter 5

Appendix A


Appendix B


**REFEREED ABSTRACTS**


**SPORTS COACHING PROFESSIONAL PUBLICATIONS**

KEYNOTE SCIENTIFIC CONFERENCE PRESENTATIONS


SCIENTIFIC CONFERENCE PRESENTATIONS


the Australian Association for Exercise and Sport Science (AAESS). From research to practices, Sydney, Australia.


INVITED PROFESSIONAL CONFERENCE PRESENTATIONS – OPTOMETRY


INVITED SPORTS COACHING EDUCATION PRESENTATIONS


Mann, D. L. (2008). Hitting what you can’t see (or at least is damn tough to see!). Australian Institute of Sport SmartTalk, Canberra, Australia.


CHAPTER 1

VISION AND PERCEPTION FOR INTERCEPTIVE ACTIONS IN SPORT

‘For an idea that does not first seem insane, there is no hope.’

Albert Einstein
Interceptive actions are an essential part of everyday life, with exquisite interactions between perception and action supporting adaptation and survival in an ever-changing environment. From the day of birth humans learn to acquire and adapt the skills necessary to perform these actions, rapidly embedding them within daily routines. An interceptive action involves an actor perceiving relative motion with, and formulating a response to, a targeted object (Davids, Savelsbergh, Bennett, & Van der Kamp, 2002). These actions are demonstrated in daily activities such as sitting on a chair, typing on a keyboard, or sipping wine from a glass. The successful execution of these motor actions requires the actor to be in the right place at the right time, exerting an appropriate amount of force (Keil & Bennett, 2002). For many of these activities, the demands on the visual-motor system are relatively easy to surmount (e.g., shaking hands or kicking a stationary soccer ball), whilst for other tasks such as landing a fighter-aircraft, the surgical removal of a brain-tumour, or returning a 200 kph tennis serve, the task demands can appear, at times, insurmountable.

Complex time-stressed interceptive actions performed in the sporting environment can represent some of the most spatially and temporally complex activities achievable by humans, necessitating exceptionally precise visual-motor control for their successful completion. Accordingly, these tasks are regularly used as a vehicle to better understand the complimentary roles of perception and action in goal-directed behaviour. Skilled golfers learn to regularly hit a ball in excess of 200 m, allowing for course obstacles and wind whilst imparting appropriate amounts of spin to land the ball within close proximity of the intended target. Likewise archers will allow for environmental conditions to shoot an arrow over 70 m yet regularly hit a target 40 cm in diameter. In these closed activities, the object to be acted upon is typically stationary, but most importantly the skill takes place in a stable and predictable environment, resulting in a skill which is self-paced. In contrast, open skills will

---

1 Three activities well practiced in the preparation of this thesis.
typically impose more excessive spatial and temporal demands on the performer in order to adapt to a constantly changing environment; usually requiring the performer to act upon a moving target at a specific (externally-paced) point in time. In an open striking task, an actor must manipulate an implement to intercept a target which is in motion - an action common in sports such as tennis, baseball, hockey, squash, cricket, and badminton. In a sport like table tennis, the demands are extraordinary – in swinging a bat to hit the approaching ball (which is 40 mm in diameter), skilled players are reliably able to time their moment of contact with precision less than 6.5 ms (Bootsma & van Wieringen, 1990). It is remarkable that the visual-motor system is capable of such feats, and evidence over the last 20 years has helped to provide a theoretical foundation for understanding how these tasks are achieved.

This introductory chapter seeks - in four parts - to outline the literature addressing the role vision plays when performing interceptive tasks in sport. The first part (Section 1.1) provides a brief understanding of the neurological basis for online interceptive movements, in particular focusing on the role of visual information. The second part (Section 1.2) provides a more extensive review of the literature examining visual information underpinning the execution of goal-directed interceptive actions. The third part (Section 1.3) addresses the role of the eyes and measures of primary visual function for the performance of interceptive tasks in sport. This section particularly seeks to evaluate the evidence for and against visual attributes acting as a limitation to sporting performance. The fourth and final part (Section 1.4) draws this information together to develop a clear rationale, and plan, for the experimental series reported in this thesis.

1.1 THE NEUROLOGICAL BASIS OF INTERCEPTIVE ACTIONS

The visual system is understood to have first evolved to facilitate the visual control of goal-directed movements, rather than for the provision of a perceptual interpretation of the surrounding environment (Goodale & Westwood, 2004). Vision as we “know” it - as a
phenomenological experience of the world around us - is a relatively recent development in the evolutionary process. The dual-pathway theory of vision (Goodale & Milner, 1992; Goodale, Milner, Jakobson, & Carey, 1991; Milner & Goodale, 1995) has been an important conceptual advance in seeking to understand the cortical origins of online movements. Within this framework, visual information is processed according to its intended function along two parallel but interacting pathways. These functionally- and neurally-distinct systems process information with some degree of independence: the ventral pathway providing a conscious visual percept of the organism’s surrounding environment, and the dorsal pathway providing the visual control of online actions.

The dorsal ‘vision-for-action’ system is understood to be the older of the two systems, having developed to produce visually-guided goal-directed movements. It generally functions sub-consciously and acts directly on visual information using an egocentric frame of reference (Milner & Goodale, 1995). The notion of sub-conscious vision is one which may not be easily conceptualised. It can be better understood using a consideration of light-sensitive insects such as the water beetle larva (Schöne, 1962), which developed early in the evolutionary chain. Light-detection for this particular water-living insect is recognised to have a singular role – to guide movement in the direction of light – an important function in order to reach oxygen at the water surface. Larvae when placed in an aquarium illuminated from below will swim towards the light at the bottom of the aquarium - resulting in suffocation. It is conceivable that conscious perception is not required for such a task; the movement system can act directly and sub-consciously using a sensor capable of detecting light. Just as human baroreceptors do not rely on conscious awareness for the regulation of blood-pressure, the water beetle larva provides an account of vision being able to sub-consciously direct a goal-directed action.

The relatively more recent evolution of a ventral ‘vision-for-perception’ pathway has produced a percept of conscious vision, enabling intentional cognitive operations to be
performed based on a visual representation of the world. From a Darwinian perspective this advance has lead to distinct advantages in adaptive behaviour, enhancing both procreation and survival (Goodale & Westwood, 2004). In contrast to the dorsal system, the ventral visual pathway functions in an allocentric manner, with object-centred information used to recognise and identify items of interest. Accordingly the ventral system is memory-based, with tight links to stored representations of objects and events to correctly identify items of interest (Brown, Halpert, & Goodale, 2005).

Neuroimaging studies have identified the separate cortical regions associated with processing for each of the two visual systems (Culham et al., 2003), though their complete separation may be an over-simplification. The dorsal system is located in the posterior parietal brain region, whereas the ventral processing occurs in the infero-temporal cortex. The two pathways retain important interactions; for example the dorsal system is capable of controlling the grasp of an object, but not of processing its semantic meaning. When grasping tools such as a hammer or screwdriver, interference to semantic processing has been shown to have no effect on the ability to grasp the implement, but does interfere with the ability to correctly grasp the tool by its handle (Creem & Proffitt, 2001). The dorsal stream was interpreted to be responsible for the action produced in the accurate grasp of the tool, with the ventral stream required to provide meaning to that object and ensure that the grasping action was performed at the correct location (the handle). It is clear that interactions occur between the two pathways, yet the current understanding of how this cooperation takes place is limited, particularly considering the incongruence in the speed of processing between the two systems; in general dorsal processing is comparatively expeditious when compared to the somewhat slower ventral system processing (Goodale & Milner, 1992).

The distinction between the two visual systems based on functionality has been highlighted elegantly, though at times controversially, by the use of visual-illusions (see Goodale, Gonzalez, & Króliczak, 2008 for a review). An illusion occurs as the result of an
incorrect perceptual interpretation of a visual stimulus, and therefore the dorsal pathway is proposed to be resistant to illusions as it acts directly rather than via perceptual processing. Aglioti, DeSouza, and Goodale (1995) demonstrated that a perceptual interpretation - but not a grasping motion – was deceived by an illusion where a target disc with larger circles around its circumference appeared smaller than an equally-sized disk with smaller circles around the circumference. The insensitivity of a motor response to a visual illusion is consistent with the dual-pathway model of vision, with the dorsal pathway acting directly on egocentrically-based information.

It is important to establish that not all visually-guided movements are controlled by the dorsal pathway; given appropriate conditions the ventral system can dominate movement control. Online movements requiring real-time interactions between perception and action appear to be dorsally dominated, however the imposition of a time delay prior to movement will engage the ventral system for action control (Goodale, Westwood, & Milner, 2004). Furthermore, movement execution concurrent with verbalisation appears to encourage engagement of the ventral system in the control of goal-directed actions (Rossetti, 1998).

Anatomical and physiological evidence suggests that each of the visual streams do not receive comparable sources of information from the primary visual cortex (Milner & Goodale, 1995). The ventral pathway is understood to produce the very clear and colourful phenomenological representation of the world that most people regard as ‘vision’ (Goodale & Milner, 1992; Milner & Goodale, 1995). In contrast, visual information to the more primitive dorsal system is blurred and insensitive to colour, though it does retain enhanced perception of contrast and movement – each important sources of information when taking into consideration the functional demands of the pathway. A histological examination of the neural pathways emanating from the retinae provides a useful explanation for the existence of these visual differences, and for what the functional implications may be. Two primary parallel pathways emerge from the retina, each producing disparate signals specific to the retinal
ganglion cells from which they are sourced (Hubel & Wiesel, 1962; Livingstone & Hubel, 1988). The so-called parvocellular (parvo) and magnocellular (magno) pathways project from the retina to six functionally and anatomically separate layers in the lateral geniculate nucleus (a neural processing centre located in the thalamus); furthermore this segregation remains as the axons project onwards to the primary visual cortex (V1; see Figure 1.1). The visual information conducted by the parvo and magno divisions differ on four primary attributes: acuity, contrast sensitivity, colour, and processing-speed (Livingstone & Hubel, 1988). The parvocellular system is characterised by high spatial resolution (acuity) and colour-sensitivity; but it is slow to be processed, and has low sensitivity to contrast. Conversely, the magnocellular system has low spatial resolution (acuity) and is insensitive to colour, but it is processed quickly, and is very sensitive to contrast. This segregation of information into parvo- and magnocellular streams was initially thought to be further retained beyond V1, characterising exclusive input to the ventral and dorsal projection streams (Livingstone & Hubel, 1988). This was soon found not to be the case (Merigan & Maunsell, 1993; Schiller & Logothetis, 1990) - whilst the parvo system projects almost exclusively to the ventral stream, the magno system projects to both the ventral and dorsal extrastriate areas (Milner & Goodale, 1995; Van Essen & DeYoe, 1995). As a result, the ventral stream is sourced from both the parvo- and magnocellular streams, though the relatively greater parvocellular input places greater reliance on information rich in spatial frequency and colour. In contrast, the dorsal visual stream is sourced almost exclusively from the magnocellular pathway, resulting in relatively fast processing of high-contrast, but colour insensitive and blurred visual information. Subsequent examinations have further differentiated the two pathways based on peripheral vision; the dorsal system evenly represented across the visual field, unlike the ventral system which has a strong bias towards central vision (Brown et al., 2005; Colby, Gattass, Olson, & Gross, 1988).
Differentiation of the two visual streams based on primary visual attributes such as acuity and contrast sensitivity may have a sound theoretical basis, yet to date there is limited evidence to demonstrate that this discrepancy translates to functional differences. Brown, Halpert & Goodale (2005) illustrated that when using peripheral vision, task-performance is more variable for a perceptual task than for an action-based task. This finding was interpreted to reflect the relatively poorer peripheral information fed to the ventral stream, with the dorsal stream relatively more sensitive to peripheral visual information. Norman (2002) presented further support when he proposed that the difference in sensitivity to fine acuity across the two streams would result in visual blur adversely affecting the ventral but not the dorsal system. He used this reasoning to interpret previous studies which found that blur decreased shape but not size constancy (shape constancy relies on central vision whilst size constancy relies on peripheral vision; Leibowitz, Wilcox, & Post, 1978), and that blur decreased road-sign recognition but not safe driving through a slalom course (Higgins, Wood, & Tait, 1998). In each case, Norman (2002) proposed that the tasks adversely affected were ventrally-based, but those impervious to blur were dorsal in nature. The difference in sensitivity to fine
acuity between the two streams does suggest that the dorsal system may be more resistant to blur. It may be a fault in logic to assert however, as Norman (2002) appears to have done, that blur will cause an immediate decrease in the performance of a ventrally-based task. From a philosophical perspective, if for example a person with blurred vision was able to recognise an object as being an elephant, this is not proof of the recognition task being dorsally-based; rather it is a reflection of blur not being a limiting factor in the ventral recognition of the elephant. It is apparent, though, that there is a difference in sensitivity to blur across the two streams; the ventral system is likely to be more susceptible to blur-induced decreases in performance. The interaction of blur with the functioning of the two pathways is an interesting issue which will be revisited later in this chapter.

It is apparent that separate visual pathways have evolved to support action-production and visual-perception. Anatomical evidence (and limited experimental substantiation) suggests that the two visual pathways rely on different visual input, which may as a result lead to functional differences. Having reviewed the neural processing of visual information for perception and action, it is now important to turn to a consideration of the informational sources which underpin interception.

### 1.2 INFORMATION SOURCES UNDERPINNING INTERCEPTIVE ACTIONS

This section addresses the sources of visual information which are relied upon to produce skilled interception in sports involving a striking task. For a considerable selection of these tasks, the receiver attempts to intercept an object either hit (e.g., tennis, volleyball) or projected (e.g., baseball, cricket) by an opposing player. The wide variety of different interceptive actions may rely on very specific control processes according to a range of task constraints including target size, velocity, and task goal (Tresilian, 2005). For this reason it is important to specify the task to be examined from the outset: this thesis will focus on a hitting task, more specifically that of cricket batting. In the sport of cricket, a player (the batter), must
hit a ball bowled toward them by an opposing player 17-18 m away (the **bowler**); at the elite level this can require the interception of balls travelling in excess of 150 kph (40 m/s), resulting in ball-flight durations as low as 450 ms. In cricket, bat-ball interception typically occurs **after** the ball has bounced on the ground (**pitch**), with no restriction in the direction that the batter can hit the ball. The ball can deviate laterally in the air (**swing**), and furthermore, variations in the condition of the pitch (including hardness and surface irregularities) can alter the vertical and lateral trajectory of the ball post ball-bounce. As a result, successful interception requires the batter to overcome extraordinary spatial and temporal demands; for a bat roughly 10 cm wide to hit a ball 7.2 cm in diameter, at the highest levels of competition temporal precision in the order of 2-3 ms may be required (McLeod & Jenkins, 1991; Regan, 1997). These excessive demands provide situations where the visual-motor system is operating near its limit; few sporting tasks - if any - necessitate a greater degree of temporal accuracy (McLeod & Jenkins, 1991).

There are two major sources of visual information available to inform the requirements for successful interception. The first and most obvious involves information pertaining to ball-flight which includes object velocity, trajectory, and spin; collectively specifying the time and location that the object will arrive. The second source of visual information is the advance, pre ball-flight information evident from the kinematic patterns of the opposition player’s movements. Expert sportspeople are better able to anticipate ball-flight characteristics based on this advance information (Abernethy & Russell, 1987a; Jones & Miles, 1978), using it to facilitate more effective interceptive movements (Renshaw & Davids, 2004; Shim, Carlton, Chow, & Chae, 2005).
1.2.1 Ball-flight information

1.2.1.1 Early theories of visual-motor control

Traditional examinations of visual-motor control have been dominated by the role of cognitive knowledge structures, an approach heavily influenced by theories of information processing prominent in cognitive psychology throughout the latter half of the 20th century. This approach is based on the Cartesian notion of the mind controlling the body: visual information must be processed to have meaning, with the output used to generate an appropriate action response (Descartes, cited in Haldane & Ross, 1978). In studies of sporting movements, this constructivist approach has justified the examination of perception independent of action (Williams, Davids, & Williams, 1999).

The separation of action from perception led to the belief that the performer’s role in interception was to select an appropriate response from a repertoire of pre-programmed actions (Schmidt, 1975; Tyldesley & Whiting, 1975). Poulton (1957) argued that two predictions are necessary for successful interception. The first requires a forecast of the exact time and place that the object will arrive; for skilled players this requires an internal algorithm to compute this outcome based on perceived distance and velocity (which Poulton named perceptual anticipation). The second prediction necessitates a calculation of the exact moment that an appropriate movement response must be initiated (termed receptor anticipation). From this perspective the performer, through extensive practice of a movement, learns how long it takes to execute a response; according to the anticipated time of arrival their simple role is to decide when the response must be initiated. On this basis the operational timing hypothesis (Tyldesley & Whiting, 1975) was developed, describing the skilled performer’s a priori knowledge of the time taken to execute a chosen movement, hence reducing their role to one requiring a calculation of the point in time when movement initiation is required. Skilled performers in fast striking sports are known to be characterised
by responses with highly consistent movement times. This has been demonstrated in sports such as table tennis (Bootsma & van Wieringen, 1990; Tyldesley & Whiting, 1975), field hockey (Franks, Weicker, & Robertson, 1985), and cricket (Elliott, Baker, & Foster, 1993; Stretch, Buys, DuToit, & Viljoen, 1998; Stuelcken, 2002); indeed this consistently in movement patterns has characterised expert from novice performers (Bootsma, Den Brinker, & Whiting, 1986; Weissensteiner, 2008). This consistency in the time of execution has been interpreted as evidence for the existence of a motor program (Keele, 1968; Lashley, 1917), where the overall movement follows a pre-organised sequence of neuromuscular signals. From this perspective the performer learns the amount of time required to execute each of the responses across their repertoire of motor programmes. In doing so, the expert performer is able to isolate the exact moment in time, prior to the point of object arrival, that a response must be initiated to ensure appropriate interception. Schmidt (1975), in the development of schema theory, further conceptualised a generalised motor program where the memory structure for movement could be scaled according to the time taken to execute the movement (by altering a rate parameter), and scaled according to the amplitude of the movement (by altering a force parameter). These theories of visual-motor control describe an important role for vision in the initiation of a movement, but attribute minimal need for vision once the movement has begun, as actions of short durations were not thought to be altered. In this sense the discrete movements were often treated as being open-loop, rationalising that after movement initiation there is not enough time for vision to alter movement execution.

1.2.1.2 Perception-action coupling for visual-motor control

More recent studies of visual-motor control describe vision as having a critical role throughout the course of movement execution, with interceptive responses dependent on a cyclical relationship between perception and action. Gibson (1979) proposed that perception and action interact in a complex manner and that if vision is to be understood experimentally,
then this essential reciprocity of perception and action must be reflected in experimental paradigms examining goal-directed movements. In this sense Gibson considered studies separating the sensory and motor components of movement to be a misrepresentation of reality. From this perspective, rather than embracing the idea of a motor program, the theory is based on the premise that visual information is used to guide and modify actions throughout their execution. This is in contrast to vision simply being used in a discrete fashion to determine when a motor program of known duration must be initiated. Lee et al. (1983) presented one of the first studies to support this interaction between perception and action, showing that visual information was used to not only initiate, but also to guide a movement as it naturally unfolds. Participants in the study by Lee et al. were required to jump to hit a falling ball; results demonstrated that rather than the participants being shown to follow a pre-programmed jump, online alterations were made to the knee and elbow angles according to the time to contact with the ball (though for alternate interpretations, see Tresilian, 1993; Wann, 1996). The duration of this action was roughly 700 ms, with visual information used to regulate movement up until 55-130 ms prior to ball contact (the so-called visual-motor delay). Bootsma and van Wieringen (1990) supported this finding using a more temporally demanding task - the table tennis forehand drive - a movement typically performed in less than 200 ms. When comparing a series of forehand drives, greater temporal accuracy was revealed at the moment of bat-ball contact than at the moment of movement initiation. Later movement initiation times were found to be correlated with faster movement acceleration. Bootsma and van Wieringen (1990) proposed that this compensatory variability of movement was an online adaptation to critical visual ball-flight information, and they put this forward as evidence against the use of motor programs for movement control. Furthermore, two of the five skilled participants in their study demonstrated evidence for within-trial movement adaptations which occurred after movement initiation, exhibiting a visual-motor delay of 105-122 ms.
Subsequent work has further developed the understanding of interceptive motor control based on the use of critical perceptual information to produce online action modifications (e.g., Bardy & Laurent, 1998; Burgess-Limerick, Abernethy, & Neal, 1991; Lee, Young, & Rewt, 1992). In a more recent study, Sevrez et al. (2009) examined the movement behaviours of gymnasts performing backward circles on a high bar under different loading conditions. Irrespective of the magnitude (2 or 4 kg) or location (shoulders, waist, or ankles) of load added to the body, gymnasts were able to manipulate their swing duration and centre of mass to successfully complete the backwards circle. Rather than following a predetermined action plan (Schmidt, 1975; Tyldesley & Whiting, 1975), gymnasts adapt to the loadings bycoupling their movements (by manipulation of their centre of mass) according to a first-order temporal relation (time to vertical position). In this particular task, proprioceptive and vestibular information appear to be more important than visual input for successful motor control.

Evidence for the online modification of interceptive movements has generated support for a prospective (rather than predictive) mode of control; actions are produced according to perceptual variables which guide the action, rather than the performer being required to predict environmental outcomes such as the place or time of contact (Montagne, 2005). This theory is based on direct perception (Gibson, 1979), where environmental information sources directly specify actions rather than requiring computations to predict spatio-temporal properties. In such a theory, vision clearly has a critical role to play, with task-specific factors such as the relative rate of change of visual angle (tau; Lee, 1976) and the maintenance of a constant bearing angle with a target (Chardenon, Montagne, Laurent, & Bootsma, 2004) used to underpin effective perception-action coupling.

It is evident that skilled visual-motor control is highly task-specific, and as a result it is worth at this point again turning to an account of the task of interest throughout this thesis, that of cricket batting.
1.2.1.2.1 Critical ball-flight information.

Open interceptive responses are required of the cricket batter as he/she selects their response from a wide repertoire of shots, aiming to hit the ball in any chosen direction with a specific amount of force. The skilled batter will attempt to hit the ball away from eleven fielders to score as many runs as possible before the ball is returned to the wicket. Considerable precision is required of the interceptive response; a ball which is missed and hits the stumps being protected by the batter, or a ball hit in the air and caught by a fielder will each cause the batter to be dismissed and no longer eligible to bat. As the batter usually hits the ball after it has bounced on the (at times uneven) ground, a skilled batter may attempt to hit the ball either as soon as possible after it bounces, or alternately may wait as long as possible after ball-bounce before playing their shot (Müller & Abernethy, 2006b).

Glencross & Cibich (1977) performed an early chronometric analysis of cricket batting which assumed that movement time for the complete batting movement was fixed, and that no temporal overlap was possible between decision processes and motor execution. It was concluded that the temporal constraints for batting were such that when allowing for the visual-motor delay, a response against a fast bowler must be decided on prior to ball-release (see Howarth, Walsh, Abernethy, & Snyder, 1984 for a similar example in squash). This pre-release decision on the initiation of movement suggested that if the overall movement was not alterable during its execution then vision of ball-flight information would not be required for successful bat-ball interception. More recent experimental evidence in cricket batting suggests otherwise, with the in-situ occlusion of ball-flight information resulting in marked decreases in interceptive performance (e.g., Müller & Abernethy, 2006a; Müller et al., 2009). In other words, successful interception in cricket batting requires ball-flight information to regulate the execution of the interceptive movements.

Rather than the overall batting action being considered as one complete movement, the action sequence generated by a skilled batter has been described as taking place in two
separate phases (Abernethy, 1984): (i) a gross (predominantly lower body) positional movement, and (ii) a swing of the bat to hit the ball (see Figure 1.2). The first phase relies on the anticipation of ball-flight characteristics from both pre- and post-ball release visual information for the batter to move to a suitable position from which to hit the ball. The second phase (which can occur either concurrent with or following body positioning) involves a swing of the bat to hit the ball in the desired direction. This dissociation of movement phases is similar to the dissociation of approach and terminal phases demonstrated in catching (see Chardenon, Montagne, Buekers, & Laurent, 2002; Michaels & Oudejans, 1992), and reflects the actions produced in many hitting sports including tennis, baseball, and field hockey.

There is considerable evidence to suggest that the initial body positioning movements of the batter (Phase 1) are modified according to online visual information. Hubbard and Seng (1954) examined baseball batting, a task similar to cricket batting, where an initial stepping movement precedes a subsequent bat-swing. Hubbard & Seng found that the stepping movement was initiated according to the time of ball-release by the pitcher, with step duration regulated by ball-velocity (see Ranganathan & Carlton, 2007 for more recent evidence). The separate control of body positioning and bat-swing movements in baseball batting has been proposed to extend to cricket batting (Abernethy, 1981; Gibson & Adams, 1989), with recent experimental evidence supporting this claim. Thomlinson (2009) examined the stepping behaviours of highly-skilled cricket batters hitting balls which bounced at different distances (lengths) from the batter. The initial stepping movement was found to occur 80-100 ms after ball-release, with the step distance and duration tailored specific to ball

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2 Ball-flight characteristics vary primarily on two dimensions: line and length. Line refers to the direction of the ball either towards (on-side), or away from (off-side), the batter’s legs. Length refers to the proximity with which the ball bounces to the batter, with a full delivery bouncing close to, and a short delivery bouncing far from, the batter.
Figure 1.2. Kinematic progression of an exemplar cricket shot (the on-drive). Upper panel (a) visually demonstrates a sequential progression (in six increments equally spaced in time) of movement from ball-release (0 ms) to bat-ball contact (620 ms). Lower panel (b) provides a graphical illustration of the onset and duration of the two phases of batting movement for this exemplar shot (vertical grey lines indicate 100 ms progressions in time).
length, and occurring independent of the bat-swing movement. Thomlinson (2009) concluded that the initial length-specific body-positioning movement was based on pre ball-flight information, though it appears plausible to alternately conclude that very early ball-flight may also be used to initiate and regulate this movement.

The mechanisms for visual-motor control of the second phase in batting - the bat swing - are less clear. Whilst the time-course for the down-swing of the bat is in the order of 150-200 ms (Stuelcken, Portus, & Mason, 2005; Weissensteiner, 2008), McLeod (1987) demonstrated that the visual-motor delay in cricket batting is almost 200 ms. This delay is considerably larger than the generally accepted visual-motor delay (55-130ms; Bootsma & van Wieringen, 1990; Lee et al., 1983), most likely reflecting the additional time required to overcome the substantial moment of inertia generated in the swing of a 1.1-1.4 kg bat. In other words, not only is there a delay in the time for the neural signal to initiate a change in the movement, but also a further delay due to the time it takes for sufficient force to be generated to change the path of the bat-swing. When taking the duration of a typical downswing into consideration (150-200 ms), the implication is that modification of the bat-swing may not be possible once initiated, supporting a predictive rather than prospective type of control for this second phase of batting. Even if the visual-motor system is capable of detecting ball-flight changes which require movement modification, the considerable moment of inertia produced by the high-velocity bat swing makes it difficult to respond to major alterations in ball trajectory. The possibility that skilled batters may produce relatively minor changes during bat swing (such as wrist rotation to change the angle of the bat-face) - which are less impeded by the considerable moment of inertia of the bat - have not been explicitly examined. Tresilian (2005) proposed that a pre-programmed control mechanism is adopted under particular task constraints, particularly those used for rapid hitting tasks. Accordingly it seems plausible that cricket batting may adopt a hybrid-type of motor control: one where the initial (body-positioning) phase relies upon online motor control, whilst the second (bat-swing)
phase is more predictive in nature. Further work is required to clarify the control mechanisms implicated with batting. Most importantly for this thesis it is apparent that all of the visual information 200 ms prior to bat-ball contact may be functional in producing and modifying batting interceptive movements.

1.2.1.2.2 Visual search behaviours.

Evidence from the analysis of visual search behaviours in cricket batting - although limited - provide further insights to the critical visual information underpinning skilled performance. Land and McLeod (2000) recorded the eye movements of three cricket batters of varying skill levels who were required to hit balls projected from a bowling-machine at 25 m/s (ball-flight duration = 650-750 ms).^{3} Land and McLeod (2000) found that batters did not track the ball for the entirety of its flight-path (indeed at this velocity the human eye may be incapable of doing so), rather the batters exhibited more strategic patterns of eye movements (consistent with work in baseball by Bahill & LaRitz, 1984). The skilled batter was found to anchor his vision where the ball emerged from the projection-machine, with gaze remaining at this location for 100-150 ms after release, following which a predictive saccade was made to the anticipated location of ball-bounce.^{4} Furthermore, Land and McLeod (2000) found that after bouncing, the skilled batter produced a pursuit movement to visually track the ball for 100-200 ms. At this point, with the ball in the vicinity of 50 ms (1-1.5 m) away from the batter, the position of gaze started to lag behind the path of the ball. The ball appeared not to be centrally fixated as it contacted the bat, supporting the findings of Hubbard and Seng (1954) that baseball batters do not visually track the final 2.4-4.5 m of ball-flight, and that this visual

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^{3} Ball projection-machines are commonly used in an experimental context to impose tighter methodological control and to decrease bowler workload. They are designed to replicate the ball-flight characteristics of those produced by bowlers.

^{4} A saccade is a ballistic eye movement performed to change the position of gaze from one target to another. In contrast a pursuit eye movement is one which maintains gaze on a moving target.
information may not be functionally important considering that the final 200 ms of ball-flight appears to be ineffective for the regulation of movements (McLeod, 1987).

An important component of batting expertise - implicated by the results of Land and McLeod (2000) - is the ability to detect and respond to anticipated ball-flight characteristics based on early ball-flight information. The predictive saccade produced in batting was shown to alter according to ball length, with shorter balls (when compared to a full ball) resulting in an earlier predictive saccade moving gaze to a position on the pitch further away from the batter. It is unclear at this stage whether these eye movements play a role in constraining the action produced by the batter, or whether the eye and body movements are independent of each other. In other words, it is not known whether this predictive eye movement may be the cause, effect, or unrelated to the selected batting response. When comparing the visual search behaviours of the individual batters of different skill levels, key differences were found. Concurrent with increments in skill level, earlier trajectory-specific saccades were generated following ball release, a finding interpreted to reflect the skilled batter’s ability to generate a faster synopsis of anticipated ball length. Skilled batters are better able to make use of this early ball-flight information, facilitating earlier gross body movements which place them in appropriate positions as early as possible. A suitable bat-swing is subsequently produced in accordance with the ensuing visual information. Although subject to verification, if expertise in batting is underpinned in part by an earlier predictive saccade affording timely and accurate body positioning, it stands to reason that a delay in the initiation of the predictive saccade may result in decreased batting performance.

Some degree of caution is warranted when extrapolating Land and McLeod’s findings to those which would be found facing a bowler rather than when facing a projection-machine. Although projection-machines are useful for imposing tight experimental control, it has been demonstrated that when compared to trials from in-situ bowlers, skilled batters produce different movement coordination patterns when facing a projection-machine (Renshaw,
Oldham, Davids, & Golds, 2007). Furthermore, Barras (1990) recorded the visual search patterns of skilled cricket batters observing an approaching bowler and reported that the observation of the impending action sequence of the bowler led the batter to important pre-release information such as the time and location of ball-release. Although the results of Land and McLeod (2000) provide useful insights to the mechanisms underpinning skilled anticipation, it is important that future studies look to replicate this work in the more realistic scenario facing in-situ bowlers rather than a projection-machine.

Land and McLeod’s (2000) study, despite its limitations, underscores not only the key role of early ball-flight information, but also the information apparent at and following ball-bounce. Müller at al. (2006a; 2009) have shown using a visual occlusion paradigm that removing visual information apparent after ball-bounce adversely affects the ability to produce appropriate bat-ball contact, though it has no effect on body positioning movements which may by this time be at (or close to) completion. Tracking the ball at and following its bounce appears important to facilitate successful interception. Future studies are necessary to verify whether Land and McLeod’s findings extend to a wider range of batters (rather than just for case studies), whether they extend to when facing a bowler rather than a bowling-machine, and to further examine the role of peripheral vision in guiding movements when the ball is not centrally fixated.

1.2.2 Pre ball-flight information

Research into anticipation (based on pre ball-flight information) first emerged as a result of the incongruence between the supposed physiological limitations to reaction time, and the interceptive performance observed in the natural setting. Chronometric analyses (which dominated the theoretical approach in the late 1970’s/early 1980’s; see Section 1.2.1.2.1, p. 15) demonstrated that skilled performers in ball sports may have been predicting event outcomes and initiating their chosen movement prior to the availability of ball-flight
information. As a result studies examining anticipation based on pre ball-flight information found (and have consistently confirmed) that experts are better able to use advance information to foretell elements of ball-flight characteristics (Abernethy & Russell, 1987a; Jones & Miles, 1978). Considerable work over the past 30 years has furthered our understanding of what visual information underpins this skill, and how this information may be used to facilitate performance.

The temporal occlusion paradigm has been the predominant methodology employed to examine anticipatory skill. For laboratory-based examinations of anticipation, participants predict an event outcome based on video footage which is occluded at a critical point in the event sequence. For example, video footage showing a penalty kick recorded from the perspective of a football goalkeeper may be shown up to the point of foot-ball contact, after which the display is occluded and the participant predicts the direction in which the ball would have been kicked. Expert participants consistently outperform novices in this paradigm, with superior anticipation demonstrated across a wide variety of sports including badminton (Abernethy, 1988b; Abernethy & Russell, 1987a), squash (Abernethy, 1990a, 1990b; Howarth et al., 1984), tennis (Goulet, Bard, & Fleury, 1989; Jackson & Mogan, 2007; Jones & Miles, 1978; Pollick, Fidopiastis, & Braden, 2001; Rowe, Horswill, Kronvall-Parkinson, Poulter, & McKenna, 2009; Shim et al., 2005), baseball (Ranganathan & Carlton, 2007), rugby union (Jackson, Warren, & Abernethy, 2006), cricket (Abernethy & Russell, 1984; Müller, Abernethy, & Farrow, 2006; Renshaw & Fairweather, 2000), and soccer (Helsen & Pauwels, 1993; Savelsbergh, Van der Kamp, Williams, & Ward, 2005; Savelsbergh, Williams, van der Kamp, & Ward, 2002; Williams, 2000; Williams, Davids, Burwitz, & Williams, 1994).
1.2.2.1 The nature of skilled anticipation

When combined with temporal occlusion, a number of additional experimental paradigms have been employed to further the understanding of processes underpinning expert anticipation.

1.2.2.1.1 Progressive temporal occlusion.

Using this methodology, a systematic progression of occlusion times is chosen and presented using temporal occlusion, resulting in experimental trials which occlude footage at time-points which are chosen relative to a key event (e.g., foot-ball contact in the soccer penalty kick). Anticipation is tested at each of these critical time-points, with results typically demonstrating that not only are experts better able than novices to predict outcomes, but they are better at doing so based on information presented earlier in the event sequence (e.g., Abernethy & Russell, 1987a; Farrow & Abernethy, 2003; Jackson et al., 2006; Müller et al., 2006; Renshaw & Fairweather, 2000). The ability to use information apparent at a relatively earlier point in the action sequence may afford the skilled performer additional time to execute an appropriate response – a distinct advantage in time-stressed tasks.

1.2.2.1.2 Spatial occlusion.

The systematic exclusion of display features (when combined with temporal occlusion) provides insights to the specific locations of information that underpin expert anticipation. Early studies using spatial occlusion edited video footage to mask specific features in the display - typically body segments or hitting implements (e.g., Abernethy, 1990a; Abernethy & Russell, 1987a; Williams, Davids, & Burwitz, 1995); a more recent approach has been to use video editing software to remove rather than mask this information (Müller et al., 2006). Spatial occlusion has demonstrated that experts - when compared to novices - rely on information from body segments which are more remote from the end effector; for example when observing a badminton serve, expert players primarily base their decisions on
movements of the playing arm and racquet, whereas novices rely on the racquet head alone (Abernethy & Russell, 1987a). On the basis of the kinematic chain, this finding is in accordance with experts making decisions earlier in the event sequence; the movement pattern of segments more proximal to the body core will precede those located more distally, hence providing a temporal advantage for those able to attune to more proximal body information. When examining the anticipatory ability of cricket batters, Müller et al. (2006) used spatial occlusion to selectively present different body segments of bowlers, demonstrating that skilled batters could not predict ball-flight characteristics based independently on the bowler’s hand or arm alone, rather it was the position of the hand relative to the arm that specified event outcomes.

1.2.2.1.3 Visual search.

Like spatial occlusion, visual search can provide insights to the sources of information experts rely on for the anticipation of event outcomes. Visual search patterns have supported the results of spatial occlusion studies, demonstrating a skilled performer’s advantage in extracting meaning from kinematic information more proximal to the body core; experts spend relatively more time than novices focussing on events which occur earlier in the kinetic chain. For example, more time is spent by a skilled tennis player observing the shoulder rather than the racquet of a server (Goulet et al., 1989; Williams, Ward, Knowles, & Smeeton, 2002), or by a soccer goalkeeper on the non-kicking leg rather than the kicking leg of a penalty taker (Savelsbergh et al., 2005; Savelsbergh et al., 2002). McRobert et al. (2009) recently examined the visual search patterns of skilled and less-skilled cricket batters who anticipated ball-flight characteristics based on video footage of cricket bowlers. It was found that - consistent with findings from other sports - skilled batters spend more time than lesser-skilled batters fixating on the more central body parts such as the bowling arm, head/shoulder, and trunk/hips. The
lesser-skilled batters spent relatively more time observing the ball and bowler’s hand (the end effector).

Two important limitations must be addressed which restrict the usefulness of visual gaze measurements to further our understanding of visual anticipation. Firstly, recordings of visual search patterns only provide an indication for the location of central vision; there is no assessment of any concurrent role for peripheral visual information. It is conceivable that (in particular) skilled observers could make use of information peripheral to the location of central fixation; yet visual search patterns are not capable of revealing this information. Secondly, a number of experiments have been performed which demonstrate clear skill-related differences in anticipatory skill, yet this advantage for experts is not necessarily matched by differences in gaze behaviour (Abernethy, 1990b; Abernethy & Russell, 1987b).

1.2.2.1.4 Point-light displays.

The point-light paradigm popularised by Johansson (1973) has been combined with temporal occlusion to examine the specific role of kinematic movement patterns in the expert advantage for anticipation. Point-light displays purvey a kinematic sequence where video footage of the object/s of interest are replaced by a series of isolated points of light at the location of critical information sources (in the case of a person or animal, critical joint centres are replaced by a point of light). Figural and facial cues, plus contextual information including shape, contour and colour are removed; only the essential kinematic information remains to purvey the underlying movement pattern. If expert anticipation is based purely on essential kinematic information, then the expert-novice difference evident of video simulations would be expected to remain for a point-light display - a proposition supported by most (Abernethy, Gill, Parks, & Packer, 2001; Abernethy & Zawi, 2007; Abernethy, Zawi, & Jackson, 2008; Shim, Carlton, & Kwon, 2006; Ward, Williams, & Bennett, 2002), but not all (e.g., Shim et al., 2005) studies using point-light displays.
Establishing the kinematic foundation for anticipation has been an important advance both theoretically and methodologically, affording a powerful and controllable means of systematically manipulating movement patterns. Joint centre kinematics are useful in revealing the informative details discriminating movement patterns; expert-novice differences in anticipation have been demonstrated for manipulations of key pattern discriminators revealed through averaged kinematic patterns (Pollick et al., 2001), and more recently by principal component analysis (Huys, Smeeton, Hodges, Beek, & Williams, 2008). Moreover, targeted manipulations of point light displays have implicated common coding (Prinz, 1997) as a potential means of underpinning skilled anticipation (Abernethy et al., 2008), with fMRI used to demonstrate that perception in these tasks may share a neurological basis with the mirror neurone system also responsible for action production (Wright, Bishop, Jackson, & Abernethy, 2010; Wright & Jackson, 2007).

1.2.2.2 Ecological validity in the examination of anticipation

Rigorous scientific paradigms require the imposition of tight experimental control, a particularly challenging concept for many aspects of sport and exercise science. Studies of anticipatory skill have been advantageous in affording considerable experimental control, yet two particular assumptions have been made in the process (Abernethy, Thomas, & Thomas, 1993); (i) that the video-simulation used as the stimuli for response (usually as a small two-dimensional screen-based display) accurately purveys the same information available in-situ, and (ii) that the highly perceptual responses (most commonly verbal or pen-and-paper) accurately reflect those produced as action responses in-situ. These potential limitations may have resulted in paradigms which lack ecological validity (Neisser, 1976), an abstract measure for how closely the task reflects the conditions that would occur in the natural environment. Relying on highly perceptual judgements when observing video-simulations may fail to accurately represent both the perceptual-motor system and the potential sources of
information relied on in the performance environment – each a critical issue worthy of consideration. A representative task design (Brunswick, 1956) will closely simulate these real-world conditions; albeit through improvements in either the display stimuli or the response characteristics.

1.2.2.2.1 Display Stimuli.

Video simulations provide an ideal means for presenting repeatable and reliably occludable stimuli, though potentially they may decrease the quality of information available to discriminate movement patterns. Early studies of anticipation used small video screens for the display of stimuli; conceivably diminishing the relative size, contrast, and depth information that would be available from an opposing player in-situ. In spite of these potential reductions in the quality of perceptual and sensory information, differences in anticipatory skill have consistently been reported for expert-novice comparisons (e.g., Abernethy & Russell, 1987a; Jones & Miles, 1978; Savelsbergh et al., 2002). Abernethy et al. (1993) proposed that the progression towards real-world stimuli should further increase the effect size found when examining anticipation across levels of skill; expertise in any given domain tends to be highly task specific (e.g., Chase & Simon, 1973), and reductions in task specificity will result in decreased manifestations of skill. More specifically, Abernethy et al. (1993) hypothesised that stimuli which are more specific to the task it represents would: (i) enhance the experiential basis of the skilled player’s expertise; (ii) decrease potential floor effects in measurement; and (iii) result in responses which are more likely to be produced by the specific dedicated processors relied on in the performer’s natural setting.

Commensurate with the accessibility of audio-visual technologies, studies of anticipation have evolved to more closely replicate the stimuli inherent of real world scenarios. Rather than presenting stimuli on small video or computer screens, accessibility to digital video projectors has enabled testing to take place with life-size two-dimensional displays (e.g.,
Savelsbergh et al., 2002; Williams et al., 1994). Three-dimensional video simulations allow the inclusion of stereoscopic depth information yet, to date, relatively few attempts have been made to make use of this technology (see Ranganathan & Carlton, 2007 for a possible exception). Farrow, Rendell and Gorman (2006) used a three-dimensional display to examine decision-making in basketball, but found only limited evidence for enhanced decision-making based on the addition of stereoscopic information.

PLATO liquid crystal occlusion goggles (Milgram, 1987) have enhanced the ecological validity of studies seeking to examine anticipation, allowing the examiner to occlude vision of in-situ display stimuli. Starkes et al. (1995) were the first to examine anticipatory skill by means of occlusion goggles. They employed a verbal response paradigm to confirm the expert-novice differences previously reported using video simulation stimuli. Abernethy et al. (2001) incorporated movement into an in-situ occlusion paradigm, with squash players required to move, following occlusion, in the anticipated direction of the ball. This once again confirmed the previous laboratory-based findings of an expert advantage in anticipation.

Liquid crystal occlusion goggles have become increasingly popular, with a growing number of studies examining anticipatory skill whilst observing in-situ display stimuli (e.g., Farrow & Abernethy, 2003; Müller & Abernethy, 2006a; Müller et al., 2009). By allowing testing to take place in the performance setting rather than in the laboratory, these studies offer a marked advantage in enabling the use of a real stimulus which possesses full stereoscopic, size, and contrast features. Whilst clearly desirable, in-situ designs present significant logistical challenges, particularly in imposing heavy workloads on players recruited to act out the stimuli. Moreover, the advantages afforded by occlusion goggles have come about at the expense of experimental control; potentially compromising both how replicable the movement pattern stimulus is between participants, and the degree of temporal precision possible for the exact moment of visual occlusion (Farrow, Abernethy, & Jackson, 2005).
The majority of studies using occlusion goggles have relied on a manual trigger for occlusion, with an experimenter required to press a button to initiate occlusion. Appropriate controls have been put in place to account for this imprecision, including the post-hoc analysis of occlusion time to evaluate suitability for inclusion, and a corresponding increase in the number of trials to compensate for those excluded post-hoc. Rather than being able to accurately occlude footage at a single point in time, post-hoc sorting has resulted in the inclusion of occlusion windows in excess of 300 ms to represent this single moment (Farrow & Abernethy, 2002; Müller & Abernethy, 2006a; Müller et al., 2009). This has resulted in occlusions that may have occurred up to 300 ms prior to the desired point being included for analysis, with these earlier occlusions denying participants potentially useful visual information to inform their decision. If this is compared with a video simulation, where the same movement pattern and occlusion points can be reliably presented to all participants, it is clear that an in-situ experimental design using occlusion goggles compromises the degree of experimental control that is possible.

An automated means of in-situ occlusion control is desirable to overcome the limitations of manual triggering, yet very few attempts have been made to implement an event-related mode of control. Oudejans & Coolen (2003) presented one exception; they performed an online registration of kinematic movement patterns to occlude the vision of basketball jump shooters. This system used an Optotrak motion detection system in conjunction with a specifically written computer program to provide individualised pattern recognition as a trigger for occlusion - as a result enhancing the precision for the time of occlusion. This potentially useful methodology imposes its own unique limitations though, as online kinematic analyses necessitate considerable demands in terms of equipment and expertise, particularly in the development of appropriate algorithms for the detection of movement patterns. Furthermore, this equipment may not function outdoors, limiting the applicability of such a paradigm in field studies. Clearly there exists sufficient motivation in the
examination of anticipation to replicate real-world scenarios as closely as possible, with a considerable gap in methodology available to do so with relative ease and experimental control.

To date very few studies have examined whether improvements in the ecological validity of the display stimuli used to test anticipation results in commensurate improvements in the discrimination of expert and novice observers. Mann, Williams, Ward & Janelle (2007) considered this issue within a meta-analysis of perceptual-cognitive skill in sport. They examined the expert-novice differences reported across a variety of studies of sporting expertise, reporting a larger effect size for those studies performed in-situ compared to those using video simulations. Further evidence supporting the use of enhanced display fidelity was provided by Shim et al. (2005), who examined the on-court anticipation of a tennis stroke when participants observed each of a point-light video simulation, a normal video-simulation, and an in-situ hitter. Shim et al.’s (2005) results were in line with the propositions of Abernethy et al. (1993), demonstrating that skilled anticipation was enhanced commensurate with improvements in display fidelity. Interestingly, Shim et al. (2005) reported that in contrast to the effect of display fidelity on skilled tennis players, the performance of novice observers decreased with enhanced display fidelity. It was concluded that the increased display complexity resulting from enhanced fidelity may have either been distracting, or resulted in an overload of information - each a potentially viable explanation for a decrease in novice performance.

1.2.2.2 Perception-action coupling.

Traditional studies of anticipation have relied on participants to make perceptual-cognitive responses (e.g., verbal or pen-and-paper) which may fall short of accurately representing the outcome produced by a movement response in the natural setting. Decoupling action from perception facilitates experimental convenience but has been
criticised as missing an important element of expert performance (Abernethy et al., 1993; van der Kamp, Rivas, van Doorn, & Savelbergh, 2008). The interdependency of perception and action has been highlighted in particular by Gibson (1979; see Section 1.2.1.2), who proposed that separation of these systems fails to accurately depict the true essence of expertise. From this perspective, perception informs action and conversely action guides perception; any manipulation of one will inevitably influence the other.

The theoretical rationale for the inclusion of movement into testing paradigms is supported by studies of decision-making which show that the incorporation of movement can enhance the suitability of action-based judgements. Oudejans et al. (1996) found that participants who were free to move were more likely to appropriately judge whether a fly ball was catchable than for those participants who were stationary. Similarly, an examination of road-crossing behaviour (Oudejans, Michaels, van Dort, & Frissen, 1996) demonstrated that pedestrians already in a walking motion were more accurate in their road-crossing behaviours (i.e., judging the appropriateness of gaps between cars) than those who were stationary. In both examples, the inclusion of action in the response enhanced decision-making accuracy, or conversely the removal of action was detrimental to decision-making behaviour. Evidently theoretical and experimental evidence exists to support the development of more representative task designs which preserve the degree of perception-action coupling that exists in the performance environment.

The dual pathway theory of vision (Milner & Goodale, 1995; see Section 1.1, p. 3) provides neuropsychological support for the incorporation of movement into response paradigms testing decision-making. According to this theory of independent but interacting pathways, skilled athletes are most likely to depend on the dorsal system for the production of online movements in the performance environment. Accordingly, to obtain the best possible representation of skilled performance, it is desirable to test the dorsal pathway, yet the most commonly reported responses in tests of anticipation and decision-making rely on highly
perceptual judgements which are most likely to be the result of ventral processing. Van der Kamp, Rivas, van Doorn & Savelsbergh (2008) persuasively argued that - to date - the majority of studies examining visual anticipation in sport have tested the ventral rather than the dorsal pathway; the removal of movement has resulted in a somewhat limited knowledge base biased towards conscious perceptual processing. Van der Kamp et al. placed a strong emphasis on the interaction between the two systems (see also Creem & Proffitt, 2001; Goodale & Haffenden, 2003; Goodale et al., 2004), with contributions from the ventral pathway important for both the identification of appropriate actions, and for some aspects of movement control; in turn it aids the dorsal system for the online visual guidance of action.

Within the framework presented by van der Kamp et al. (2008), the relative contribution of the two pathways alters across the time-course of an interceptive action. Consider, for example, a tennis player receiving serve from an opposing player. This framework proposes that the ventral system provides the predominant contribution as the service action begins, however the ventral involvement progressively decreases whilst the dorsal contribution increases until the dorsal system dominates control following racquet-ball contact (see van der Kamp et al., 2008; Figure 3, p.109). An important consequence of this proposition is that it foresees a role for the dorsal system prior to - and for the ventral system following - the appearance of ball-flight information.

It has become increasingly common for studies of anticipation to require participants to make movements rather than verbal responses. Williams and Davids (1998) for example instructed participants observing a life-size video display to move in the anticipated direction of a soccer pass rather than to simply verbalise their response. Results replicated the expert advantage reported previously in examinations of anticipation using verbal responses. Despite important enrichments in ecological validity for both display and response characteristics, participants are rarely required to actually intercept a target, primarily a result of methodological (e.g., the use of video simulations) and ethical (e.g., concern for participant
safety) limitations (for exceptions, see Farrow & Abernethy, 2002; Müller & Abernethy, 2006a; Müller et al., 2009). Simulated or shadowed movements are more commonly required to best simulate the real-world interceptive response.

The dual-pathway theory of vision has been cited by a number of studies as justification for the incorporation of a movement-based response when testing anticipation (e.g., Cauraugh & Janelle, 2002; Farrow & Abernethy, 2003; Keil & Bennett, 2002; Ranganathan & Carlton, 2007; Shim et al., 2005), with these studies seeking to more accurately elicit outcomes of the visual-motor pathway relied on in the performance setting. Recent evidence suggests however that rather than a simulated movement being sufficient, an actual opportunity for interception may be required to accurately test responses generated by the dorsal pathway. Króliczak, Heard, Goodale and Gregory (2006) presented a hollow-face illusion to participants - an instrument which contained a sculptured face that gave the illusory appearance of possessing depth towards (but in reality was in depth away from) the observer. They used this illusion to elaborately examine the type of movement controlled by the dorsal visual system. The hollow-face illusion was adopted under the assumption that a perceptual interpretation which relied on the ventral system would be deceived by the illusion, and as a result ventral processing would interpret the face as being in depth towards the participant. Rather than producing conscious perceptual interpretations, the dorsal system acts egocentrically (Goodale & Milner, 1992), with the expectation that responses relying on this system would be impervious to perceptual illusions, and as a result the depth in the illusion would be interpreted as being away from the participant. Króliczak et al. (2006) placed small markers on the hollow-face, with participants required to draw, point towards, or flick at the position of the marker. Occlusion of vision was initiated at the onset of movement to prevent visual regulation of the goal-directed actions. The flicking response, reasoned to be an online visual-motor action, was executed at the actual position of the marker - in other words, it was not deceived by the illusion. In contrast, the marker was incorrectly perceived to be located in
depth towards the participant for both the drawing and pointing conditions, suggesting that these incorrect responses were ventral in nature. The important implication arising from this study is that a real-time movement does not necessarily reflect and/or test processing of the dorsal visual system. Pointing - although clearly a visually-guided movement - appears to be mediated by the ventral stream. In Króliczak et al.’s (2006) study, an online motor response with intention to intercept was required before the dorsal system was engaged for visual-motor control. The consequence for studies of interception is that simple simulated movements may fail to test the visual-motor pathway relied on in the real-world performance setting. An opportunity for interception may be required to effectively elicit the naturally occurring response.

The prediction of improved expert anticipation as the mode of response more accurately replicates that produced in the real-world may have a sound theoretical basis, yet there is limited empirical evidence to suggest that this actually happens. Farrow & Abernethy (2003) have reported one exception, demonstrating that skilled tennis players observing in-situ tennis servers were better when moving towards (coupled response), than when verbally predicting (uncoupled response), the anticipated direction of the serve. This advantage for a coupled-movement was found when some ball-flight information was available, but not replicated when anticipation was based exclusively on pre ball-flight information. Conversely, Ranganathan & Carlton (2007) reported that skilled baseball batters observing a virtual display were disadvantaged when responding in a coupled fashion, both when ball-flight information was and was not available. It was speculated that this coupling-induced decrease in performance may have been attributable to a combination of both increased task difficulty when swinging a baseball bat, and the earlier response initiation required for movement (when compared to a verbal response). A further explanation appears plausible based on differences in the fidelity of the display information. The stimulus used in the Ranganathan and Carlton (2007) study - a simulation using a point-light display - represents a marked
decrease in ecological validity. It is possible that the task may have become too artificial to accurately represent the tasks for which skilled batters had developed their expertise. In light of the requirement for a realistic opportunity for interception to elicit a response of the dorsal visual system (Króliczak et al., 2006), it is plausible that an artificial video simulation is incapable of engaging the most appropriate motor pathway, no matter how specific the movement may be.

It is readily apparent that there still exists much to learn about the effect of perception-action coupling on anticipatory performance. There is sufficient reason to expect that increases in anticipatory performance should be found commensurate with increases in the coupling between perception and action, yet little is known of this relationship, and evidence to support that such an effect exists is equivocal. There appear to be two serious gaps in the current knowledge base: firstly whether increased coupling results in increased anticipatory performance, and secondly whether such a result is contingent on the presence of ball-flight information. Moreover, in denying a realistic opportunity for interception, the majority of existing studies incorporating movement as a response may have failed to accurately engender responses of the dorsal visual system (Króliczak et al., 2006; van der Kamp et al., 2008). Despite citing the dual-pathway theory of vision as reason for the incorporation of a coupled response, many of these studies may have inadvertently elicited ventral stream responses, with the provision for an opportunity to intercept necessary to demonstrate a full effect of coupling. Furthermore, there is no indication whether performance differences based on increases in perception-action coupling are possible when observing a video simulation; it may be that an in-situ design is required to demonstrate any effect for perception-action coupling.


1.2.2.3 *Anticipation and the facilitation of sporting performance*

A considerable body of evidence has evolved over the last 30 years examining anticipatory skill yet a surprisingly small proportion of these studies have sought to establish whether this skill translates to enhanced interceptive performance. The expert superiority in anticipation is clear (Mann et al., 2007), yet little effort has been made to discern cause and effect: whether this skill is a necessary component - or simply a by-product - of expertise. Early evidence demonstrated that anticipation may lead to enhanced movements by skilled squash players in competitive situations (Howarth et al., 1984), though the mediating effect of situational probabilities (Abernethy et al., 2001) may have tempered the validity of any conclusion that this may be evidence for anticipation based on kinematic movement patterns alone. More recently Shim et al. (2005) concluded that the availability of pre ball-flight kinematic information significantly enhanced reaction latencies when returning tennis strokes from in-situ players. A number of studies have also reported that the removal of advance information results in significant adaptations in coordination dynamics (Pinder, Renshaw, & Davids, 2009; Renshaw et al., 2007), advocating the importance of advance information being available for optimal learning in the training environment.

In many interceptive sporting tasks ball-flight information alone may be sufficient to facilitate successful interception, and the role of advance information may be more subtle in offering fine temporal advantages. In an interceptive task, advance information may play an important role for early and appropriate body positioning, with ball-flight information necessary for actual interception (Abernethy, 1981; Hubbard & Seng, 1954). For example, pre ball-flight kinematic information is used by a baseball batter to facilitate pitch-specific lower-body positioning movements, with bat-swing characteristics related to ball speed (Ranganathan & Carlton, 2007). Early body positioning allows a stable base to be established as quickly as possible, making possible a wider range of responses which are less likely to be constrained by temporal demands.
1.3 VISUAL FUNCTION AND INTERCEPTIVE ACTIONS

1.3.1 Vision and Sporting Performance

It is readily apparent that vision is critically important not only for the essential coupling of perception with action for successful interception (Bootsma & van Wieringen, 1990), but also for the perception of advance kinematic information used to facilitate skilled interception (Jones & Miles, 1978; Shim et al., 2005). The remarkable ability of skilled athletes to overcome the excessive spatial and temporal demands of fast-paced interceptive tasks has naturally led many to ponder whether these achievements are underpinned by some sort of extraordinary visual ability. Vision is unmistakably important for the successful execution of many forms of interception, and for this reason it may be intuitive to infer that superior vision may lead to superior interceptive performance. A demonstration that accomplished athletes possess superior visual skills (such as visual acuity and contrast sensitivity) would advocate both the inclusion of these assessments in talent identification testing batteries, and for these skills to be trained to improve on-field sporting performance.

An evaluation of visual function encompasses a wide variety of attributes, many of which are predominantly dependent on the anatomical and physiological properties of the eye. Throughout this thesis these characteristics are termed primary visual attributes, reflecting their origins at the level of the eye, rather than being a result of secondary cognitive processing. Such attributes have at various points been called general visual measures (e.g., Abernethy, Neal, & Koning, 1994), visual hardware (e.g., Starkes & Deakin, 1984), or basic visual functions (e.g., Abernethy & Wood, 2001). They include (but are not limited to) characteristics such as visual acuity (VA), contrast sensitivity, ocular-motor properties, and peripheral vision. Each of these are measurable as separate characteristics, and conceivably a strong case could be built for each of these factors to play a critical role in most sporting tasks (Loran & MacEwen, 1995). The training of primary visual attributes has received considerable
interest in the optometric literature; firstly addressing whether improvements are possible from vision training, and secondly whether any training effect may transfer to a measurable improvement in the performance of visually-regulated tasks. Despite suggestions to the contrary (e.g., Williams et al., 1999), it is well established that vision training can improve numerous visual skills (Erickson, 2007; Scheiman et al., 2005; Scheiman & Wick, 2008) including central acuity (Balliet, Clay, & Blood, 1982; McKee & Westheimer, 1978), peripheral acuity (Johnson & Leibowitz, 1979; Saugstad & Lie, 1964), contrast sensitivity (Mayer, 1983), and vergence eye movements (Daum, 1982). Improvements in these skills have been demonstrated to result in enhanced task performance for skills such as reading (Chung, Legge, & Cheung, 2003), and computer use (Irving & Woo, 1988). Importantly, though, these attributes have been trained in people who demonstrate deficiencies, usually children who are in important developmental stages of their life. It is rare for these skills to be trained to enhance those with normal vision to a ‘supra-normal’ level - indeed there is rarely considered a need to do so.

A common approach when seeking to test the theory that skilled athletes possess superior visual attributes has been to measure and compare these characteristics between athletes with different levels of sporting expertise. The supposition that skilled athletes are characterised by superior visual attributes was supported by early experimental evidence (e.g., Beals, Mayyasi, Templeton, & Johnston, 1971; Graybiel, Jokl, & Trapp, 1955; Olsen, 1956; Spurgeon, French, Rivers, Bailey, & Ellisor, 1989; Williams & Thirer, 1975), yet a growing number of more recent studies have failed to support this view (Abernethy & Neal, 1999; Starkes, 1987; Ward & Williams, 2003). Table 1-1 presents a synopsis of the published studies which have examined visual characteristics across levels of sporting skill, with findings presented for six of the most commonly examined primary visual attributes. A relatively equal number of studies are apparent which either do or do not support these attributes as being able to differentiate players of contrasting skill levels. A comparison of the date of publication
for these studies reveals that those supporting skill-based differences in primary visual attributes are relatively older than those failing to find any differences. The average year of publication for studies finding a skill difference (1981 ± 19 years) is older than the average year of those publications which did not find any differences (1989 ± 14 years). This in some ways may reflect the relatively more recent literature on expertise which is considered from a more holistic perspective rather than just an optometric one. Although for some there is a prevailing view that skilled athletes are characterised by superior primary visual attributes (Erickson, 2007; Gregg, 1987; Loran & MacEwen, 1995), there appears to be an increasing recognition that the variance caused by differences in visual attributes explains a low proportion of skill (Abernethy & Wood, 2001), and that skilled athletes are better characterised by sport-specific measures of perceptual-cognitive skill (Abernethy et al., 1994; Ward & Williams, 2003).

Expert sportspeople have consistently been demonstrated to possess superior skills in domain-specific tasks such as anticipation (Abernethy & Russell, 1987a; Jones & Miles, 1978; Starkes et al., 1995), pattern-recall (Allard & Burnett, 1985; Allard, Graham, & Paarsalu, 1980; Starkes, 1987), decision-making (Helsen & Pauwels, 1993; Starkes & Deakin, 1984; Thiffault, 1980), and situational probability (Abernethy et al., 2001; Alain & Proteau, 1980; Caserta & Singer, 2007). Rather than these skills being dependent on anatomical and physiological structure (like primary visual attributes), they are cognitively based and develop across many years of task specific practice (Abernethy & Russell, 1987a; Ericsson & Kintsch, 1995; Williams et al., 1999). A number of multi-disciplinary examinations of sporting expertise have sought to evaluate the relative contributions of the primary visual attributes and perceptual-cognitive skills (Abernethy et al., 1994; Helsen & Pauwels, 1993; Starkes, 1987; Ward & Williams, 2003). Using multivariate analyses, each of these studies have concluded that domain-specific perceptual skills were better than primary visual attributes in their ability to discriminate between levels of expertise. In other words, these secondary perceptual skills are more likely than the primary visual skills to be associated with sporting success. The general conclusion
<table>
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<th>Definition</th>
<th>Skill difference</th>
<th>Literature supporting</th>
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<tr>
<td><strong>Static visual acuity</strong></td>
<td>The ability of the eye to resolve detail in a stationary target</td>
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<td>Fremion, et al. (1985)*</td>
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<td>Laby, et al. (1996)*</td>
<td>Spurgeon, French, Rivers, Bailey, &amp; Ellisor (1989) – baseball batting*</td>
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<td><strong>Dynamic visual acuity</strong></td>
<td>The ability of the eye to resolve detail in a moving target</td>
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<td>Hughes, Blundell, &amp; Walters (1993)*</td>
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<td>Whiting &amp; Sanderson (1974)</td>
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<td><strong>Contrast sensitivity</strong></td>
<td>The ability of the eye to resolve differences in luminance</td>
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<td>(reflection or emission of light)</td>
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<td><strong>Peripheral visual field</strong></td>
<td>The visual sensitivity of the eye to objects located in an extent of space</td>
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<td></td>
<td>Hughes, Blundell, &amp; Walters (1993)*</td>
<td>Abernethy, Neal, &amp; Koning (1994)</td>
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<td></td>
<td></td>
<td>Stroup (1957)</td>
<td>Clark &amp; Warren (1935)</td>
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<td></td>
<td></td>
<td>Williams &amp; Thirer (1975)</td>
<td>Deshaies &amp; Pargman (1976)</td>
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<tr>
<td><strong>Depth perception</strong></td>
<td>Perception of the relative distance between two objects</td>
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<td></td>
<td></td>
<td>Blundell (1984)*</td>
<td>Abernethy, Neal, &amp; Koning (1994)</td>
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<td>Winograd (1942)</td>
<td>Hughes, Blundell, &amp; Walters (1993)*</td>
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<tr>
<td><strong>Colour vision</strong></td>
<td>The ability of the eye to resolve objects based on wavelength of light</td>
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<td></td>
<td>(reflected or emitted)</td>
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<tr>
<td></td>
<td></td>
<td>Harris &amp; Cole (2007)*</td>
<td>Abernethy, Neal, &amp; Koning (1994)</td>
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*Note: Starred items (*) indicate studies of hitting/striking sports*
from studies of sporting expertise appears to be that there is not a clear and compelling case for athletes to possess primary visual skills which are superior to those of the general population (Abernethy & Wood, 2001; Beckerman & Hitzeman, 2001; Fremion et al., 1985; Wood & Abernethy, 1997).

1.3.2 Vision as a limitation to sporting performance

The inability of primary visual attributes to systematically differentiate levels of expertise in studies of expert performers in sport (see Table 1-1) may in many cases be a result of ceiling effects. Anatomical limitations exist for most of the primary visual attributes: in a young healthy population VA, for example, is limited by retinal photoreceptor density, and the extent of the peripheral visual field is limited by the structure of the face and orbit. In each of these (and other) attributes, there is very little variation amongst a young healthy population, with the majority of eyes expected to function optimally when corrected (Grosvenor, 1996). On this account it is not surprising that the majority of studies fail to demonstrate differences across populations matched for age.

It is not uncommon to read reports or hear anecdotal stories of elite athletes who achieve their remarkable feats on-field despite being shown to have below-normal levels of vision (e.g., Brown, 2008; Harris & Cole, 2005; Williamson, 2006). Testing has questioned the quality of vision even for some of the world’s greatest athletes including baseballer Babe Ruth (Voisin, Elliott, & Regan, 1997) and cricketer Don Bradman (Hutchins, 2002), each of whom later in their life were shown to possess vision below normal levels. It is possible that for these athletes their respective sporting accomplishments were achieved despite these apparent visual disadvantages.

Epidemiological studies have typically found that the prevalence of visual problems is similar in sporting groups to what would be found in the general population (Bausch & Lomb, 1995; Beckerman & Hitzeman, 2001; Garner, 1977; Sherman, 1980). These results can be
interpreted to infer that athletes do not require normal levels of vision, though caution is warranted in making such a conclusion; the athletes included in these studies either were of low skill levels (e.g., Beckerman & Hitzeman, 2001), or were participants in sports which would not necessarily considered to be visually demanding (e.g., Bausch & Lomb, 1995).

A vision specialist (such as an Optometrist or Ophthalmologist) engaged to screen the vision of athletes will do so with the goal to detect - and subsequently correct or manage - perceived visual deficiencies. These professionals will have their own interpretation of the requirements for ‘normal’ operation of the visual system, and will typically take action to rectify any characteristic of vision judged to be functioning at a level below normal expectations. What is relatively unknown however is what the level of functioning may be that is necessary for normal performance across a variety of different sporting tasks. That is to say, what is the necessary level of visual function below which performance will be adversely affected? Reference tables are published to guide the practitioner towards the criticality of different visual skills across a wide variety of sports (e.g., Gardner & Sherman, 1995), however these tables are based on intuition rather than being guided by empirical evidence. This represents a potentially serious flaw in clinical procedures, with no firm evidence available to guide professional decision-making.

There is little evidence to suggest whether athletes must function at normal levels for most favourable performance, or conversely that they can be successful with sub-normal vision. Put simply, it is not known if, and if so at what point, vision is a limitation to skilled sporting performance. It is reasonable to suggest that any of the primary visual attributes addressed here are, at some point, capable of being a limitation to sporting performance. If VA for example is systematically decreased through to the point of practical blindness, clearly at some level performance must decrease (see Figure 1.3). What is interesting, and at the heart of the debate on sports vision, is where this point of limitation lies. Evidence presented here (e.g., Abernethy & Wood, 2001; Beckerman & Hitzeman, 2001; Williams et al., 1999)
appears to suggest that for most visual skills, this limitation lies at a level below the expectation of normal functioning (see Figure 1.3a). The optometric perspective generally (though not unconditionally) would suggest that levels of normal function - as guided by population norms - reflects the point of limitation (Applegate & Applegate, 1992), with anything below this likely to result in a decline in performance (see Figure 1.3b). A small subsection of sports vision specialists infer that there is no limitation, with performance continuing to increase commensurate with improvements in visual function (see Figure 1.3c).

**Figure 1.3. Hypothetical changes in interceptive performance where (a) the visual limitation to performance lies at a level worse than normal visual acuity, (b) the visual limitation to performance is at the level of normal visual acuity, and (c) performance continues to improve commensurate with improvements in visual acuity. Normal visual acuity is denoted as 6/4.3 (18-34 yr population; Elliott, Yang, & Whitaker, 1995), and the x-axis progresses from left-to-right according to increments in the VA denominator (following optometric convention).**

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Visual acuity is typically denoted by the Snellen fraction (e.g., 6/12); in this fraction the numerator represents the test distance (conventionally 6 m), whilst the denominator is the distance (in metres) at which the smallest detail subtends 1 min of arc, or more commonly explained (though not completely correctly) as the distance at which a person with ‘normal’ vision could resolve such detail. Accordingly, a VA of 6/60 can be loosely interpreted to mean that the person needs to be at 6 m to see what another person with ‘normal’ VA could see at 60 m.
The current problem which makes this discordance difficult to resolve is that the point of limitation has not been empirically verified for the variety of visual attributes which may impact on performance in different sporting activities. Hence it may be useful to examine whether skilled athletes can maintain their performance if vision is below normal capacity. This may provide a better indication for whether vision is a limitation to performance. If performance can be maintained despite the imposition of below-normal levels of visual function, then it seems reasonable to conclude that the normal level of vision is not a necessity for optimal performance.

1.3.3 Visual Blur and Interceptive Performance

Visual acuity is the standard and often sole assessment of visual function (Elliott et al., 1995). It measures the ability of the retinal photoreceptors to resolve detail, and reflects the minimum angle over which two points can be recognised as being separate (Grosvenor, 1996). An assessment of VA is the first test performed in an optometric or ophthalmological consultation, and is the key measure used to determine suitability for numerous occupations and activities such as driving (Charman, 1997) and aviation (Campbell & Bagshaw, 2002). In an examination seeking to assess the relationship between visual function and task performance, VA stands out above all others as being the key measure used for assessment.

Static visual acuity, typically measured using a Snellen or Bailey-Lovie letter chart, provides an account of the resolving ability of the eye under conditions of optimal contrast. This measure has been criticised as lacking the construct validity necessary to be an effective measure of performance in sport, as the observation and recognition of letters does not correspond with the type of images observed in a sporting environment (Williams et al., 1999, p.84). Such a view perhaps fails to understand the anatomical underpinnings of the test; resolvable detail directly reflects the properties of the image formed on the retina, and the ability of the photoreceptors to resolve detail in such an image (see Grosvenor, 1996 for more...
The use of numbers, letters or pictures is generally irrelevant; VA is a test of the minimum detail resolvable by the anatomical features of the eye.

The equivocal findings to support VA being an important characteristic of skilled sportspeople (Table 1-1) may in some respects reflect a ceiling effect; VA is limited by photoreceptor density, with very little variability found in the anatomical structure of the retina across a young population. When corrected, the average VA for the 18-34 yr old population is 6/4.3, and it demonstrates low variance (SD of denominator = 0.9; Elliott et al., 1995). On this basis, there is very little scope for supra-normal acuity, and a low probability of sub-normal VA (when corrected). There is little reason to suggest there would be a difference across groups of expertise within this age population. In taking a different approach to outline the importance of VA in sporting tasks, Sherman (1980) states that “If we include the increasing number of athletes wearing spectacle lenses during participation in football, baseball, tennis, golf, and basketball it is obvious that clear vision at the very least is important for peak performance” (p. 663). Indeed it may make good sense for athletes to be fully corrected for athletic participation; however a relatively high incidence of athletes wearing visual correction is in no way proof that clear vision is a necessity for peak performance. Gregg (1987) states in reference to sports performance “exactly how good acuity must be has not been proven, at least in a statistically significant sense” (p. 18). There is very little indication for the minimal requirements of VA for the execution of sporting tasks, with only inferences being made based on population-based data. This poses an interesting question worthy of consideration - how poor can VA be before it becomes a limitation to sporting performance?

For the range of ages most likely to be represented by athletes participating in elite sport (15-40 years), myopia (or short-sightedness) is the most frequent cause of decreased VA (Grosvenor, 1996). Myopia is caused by a lengthening of the eyeball such that it is in discordance with the refractive power of the eye; this results in poor distance (but generally clear near) vision. A strong relationship exists between myopia and VA, with increasing
myopia resulting in commensurate decreases in acuity (Hirsch, 1945). Decreasing VA via the simulation of myopia may be an appropriate means to test whether acuity is a limitation to sporting performance. Myopia (and hence visual blur) can be simulated through the addition of refractive power to the eye; achieved either by the use of spectacle lenses in front of, or a contact lens placed onto the surface of, the eye.

Very few studies have examined the effect of visual blur on visual-motor performance, either within or outside of the sporting domain. One of these few was a study by Heasley et al. (2004), who examined the effect of blur on the walking behaviours of a geriatric population. Visual blur has previously been associated with an increased risk of falls in the elderly (Ivers, Cumming, Mitchell, & Attebo, 1998; Lord, Clark, & Webster, 1991; McCarty, Fu, & Taylor, 2002), an issue with profound health and economic implications (Cripps & Carman, 2001). Heasley et al. (2004) used spectacle lenses to induce a low level of refractive blur in elderly subjects (decreasing VA from 6/5 to 6/8), finding distinct safety-driven adaptations in stepping behaviour. In this case even a low level of blur produced movement adaptations to minimise the chance of falls, but these adaptations ensured that there was no change in the incidence of falls.

Visual problems account for only a small proportion of motor vehicle accidents (1%; Burg, 1967; Decina & Staplin, 1993), although this has been attributed to both the effective use of exclusion criteria to screen those with poor vision from driving (Higgins, 1996), and the impact of other factors such as cognitive deficits, attentional distractions, alcohol, experience, illicit drugs, and age (e.g., Ball, Owsley, Sloane, Roenker, & Bruni, 1993; Peden et al., 2004). Higgins, Wood, and Tait (1998) assessed the driving ability of participants wearing spectacle lenses to induce four different levels of visual blur (VA: 6/6; 6/12; 6/30; 6/60). They found immediate blur-induced decreases for each of road sign recognition, road hazard avoidance, and total driving time; yet there was no effect on participants’ ability to judge driving interceptions through targets. In this case, perceptual judgements (detecting signs and
hazards) were heavily impacted; yet even for a VA of 6/60, movement-based judgements (including gap clearance and movement through a slalom course) were relatively unaffected. Norman (2002) somewhat controversially interpreted this as being evidence for visual blur affecting a ventrally-based but not dorsally-based task. Indeed the resilience of the motor (but not perceptual) task is in accordance with the proposed resilience of the dorsal (but not ventral) system to visual blur (see Section 1.1). Importantly though, Higgins et al. (1998) reported that movement adaptations were made to maintain performance; in this case decreased driving velocity may have afforded visual information to be detected closer to the object, with more time available to react accordingly. Across both the stepping and driving paradigms, maintained performance appears to have been made possible through adaptations in motor behaviour.

Despite an exhaustive search throughout the available literature prior to commencement of this thesis, only one study was evident which has investigated the effect of blur on visual-motor skills within the sporting domain. Applegate and Applegate (1992) used spectacle lenses to examine the effect of decreased VA on the free-throw shooting performance of novice basketballers. Applegate and Applegate found that, even for the highest level of blur (reducing VA to 6/75), there was no decrease in free-throw shooting performance. From an optometric perspective, where decreases in acuity are consistently related with a decrease in visual performance and an increase in the frequency of reported symptoms, these results were in contrast to “common sense” or what would be “commonly assumed” to be the case (Applegate & Applegate, 1992, p.765). Although this study demonstrated a considerable task-specific resilience to blur, the skill examined could hardly be classified as being visually onerous. The target (a basketball ring and backboard) was stationary, and when considered in conjunction with the size of the ball, both objects were evidently quite large and as a result the test was unlikely to be reliant on clear visual information. Moreover, the relatively poor performance of the novice participants may have
resulted in a floor effect, with blur having little influence on participants who lacked the well-refined perceptual-motor coupling skills characteristic of more expert performers. Whilst this study presents results which may be considered interesting and perhaps surprising, performance in this case was maintained in a task which was far from testing the limits of the visual-motor system.

It is apparent that performance in a small number of interceptive tasks (both within and outside of the sporting domain) appears to maintain some degree of resilience to visual blur, a finding which is in conflict with what may be expected from an optometric viewpoint. There appears to be discordance between the apparent prevalence of expert sports performers with below-normal visual function, and the expectation that optimal visual function is a necessary requirement for skilled sporting performance. The lack of evidence for the requirement of most favourable visual function (in this case clear vision) represents a serious shortcoming in the manner with which some vision specialists practice. Furthermore, the resilience of a selection of motor tasks to visual blur appears to be consistent with the neurophysiological expectations of the dual-pathway theory of vision. Evidently, there is much to learn about how visual blur affects sporting performance, and more specifically, how blur may affect the successful execution of a highly-demanding interceptive task.

1.4 THESIS OUTLINE

1.4.1 Rationale for research

Vision clearly plays a crucial role in the execution of challenging interceptive actions in sport. The correction and training of primary visual skills to enhance sporting performance is based on the premise that vision must be a limitation to performance, and that improvements in their function will transfer to enhanced on-field results. On the contrary, the extensive body of research examining the development of expertise in sport suggests that perceptual
attributes such as anticipation and pattern perception are more likely than primary visual skills to be key factors in the characterisation of skill. This is a serious discordance which warrants further investigation. The evidence to suggest that skilled sportspeople possess superior primary visual skills is often cited to be equivocal at best, though this traditional means of examination is limited by the low variation seen throughout the population in many of these visual attributes. An alternate approach may be to ask, how good must vision be to sustain optimal sporting performance? What would happen to interceptive performance if vision was decreased? Decreases in performance commensurate with any reduction in visual clarity would suggest that vision is a key and critical precursor for optimal performance. On the other hand, if performance were to be maintained despite patent reductions in visual quality, there is good reason to conclude that vision is unlikely to be a limiting factor for performance in that task.

There are many different measures used to assess visual function, nonetheless it has been outlined that visual acuity is the fundamental measure used most frequently to evaluate vision. VA is simple to manipulate via the use of refracting lenses which blur vision. As a result, simple manipulations can be applied to blur the vision of skilled performers to examine the effect of decreased VA, and accordingly whether this element of vision is a limitation to interceptive performance. Very little is known about the effect of blur on an interceptive action, and there is no evidence to suggest whether blur affects performance when this action is one for which the visual demands would be considered to be highly challenging. The dual-pathway theory of vision would appear to suggest that clear vision should not be a necessary precursor for the performance of a dorsally-based task, yet there is insufficient empirical evidence to verify this claim.

Skilled performance in high-speed interceptive tasks is underpinned by enhanced anticipation of event outcomes based on the judicious observation of a pre-release event sequence. It is conceivable that interception itself may retain some degree of resilience to
blur, yet this important advance information may be more susceptible to blur-induced decreases in performance. This anticipatory skill has particularly been of interest recently when interpreted from the perspective of the dual-pathway theory of vision, with considerable speculation that skilled performance may rely on a combination of ventral and dorsal processing. Numerous studies have used this rationale to justify the inclusion of movement-based responses in their examination of anticipatory skill, yet at this stage there is no evidence to demonstrate that the inclusion of movement provides any advantage when decisions are based solely on pre ball-flight information. Is a movement-based processor capable of acting on this pre ball-flight information? Or must ball-flight be present to engage the dorsal ‘vision-for-action’ system? It is not known whether visual clarity is a critical precursor for this important component of interceptive skill in sport; albeit in the more traditional (uncoupled) manifestation of anticipation, or for the more realistic coupled response that skilled sportspeople are likely to rely on in the natural setting.

1.4.2 Scope of experimental research

Cricket batting has been chosen as the skill to be examined throughout the research in this thesis; it is a highly demanding interceptive task, where an implement must be effectively manipulated to strike a moving target in very specific directions. This task has been chosen as skilled batters are able to overcome remarkable spatial and temporal constraints which have
been reported to approach the limits of the human visual-motor system (see Section 1.2, p.9). Furthermore, the growing body of research available for cricket batting ensures that a considerable degree of knowledge is readily available for how successful batting occurs.

Expertise in batting bears considerable similarities to that for other time-stressed interceptive sports such as tennis, hockey and baseball; successful execution relies upon not only on finely developed perceptual-motor processes capable of coupling movements to rapid ball-flight information, but also on the ability to anticipate ball-flight characteristics based on pre ball-flight kinematic information from the bowler’s movements.

Sporting expertise is increasingly understood to be highly task specific (Abernethy et al., 1993; Starkes & Deakin, 1984); accordingly it was considered most meaningful to conduct testing in conditions replicating the performance environment as closely as possible. Experimentation took place in a highly applied setting in an attempt to best replicate the conditions in which the interceptive ‘experts’ have developed their skill. This increase in face validity does come at the cost of experimental control; a limitation acknowledged but accepted in an effort to best simulate performance conditions.

Finally, a clear argument has been put forward to demonstrate that there are many different means of evaluating vision, yet the research performed in this thesis will focus solely on visual acuity. Although this is widely acknowledged to be the most common measure of visual performance, many others such as contrast sensitivity, depth perception, and binocular alignment may also be critical factors in sporting performance (see Section 1.3.2, p.41). It is acknowledged that these factors may independently act as limitations to performance, however the research here will comprehensively focus on the attribute most commonly associated with visual performance.
1.4.3 Thesis structure

The research reported here is presented in two phases, each phase containing two separate experiments. The four separate experimental chapters have been written and reported in a format suitable for submission to peer-reviewed journals, based on the recommendation of the UNSW School of Optometry and Vision Science Postgraduate Review Panel. This may result in a considerable degree of repetition across the experimental chapters; however it allows the chapters to be ‘stand alone’ entities, aiding in the dissemination of research findings.

Phase I of the experimental research examines the effect of visual blur on bat-ball interception. A high degree of resilience to blur has been demonstrated for an interceptive action with relatively low demands of the visual system; however does this resilience to blur extend to a much more demanding visual spatial task? Experiment I (Chapter 2) seeks to establish a baseline relationship between blur and interceptive performance, isolating ball-flight information in a controlled environment using a ball projection-machine. Experiment II (Chapter 3) seeks to replicate these findings in conditions which more accurately represent the circumstances inherent in the natural environment, and for temporal demands which approach those experienced at the upper levels of competition. Sources of information known important for effective movement-coupling are manipulated to examine whether visual clarity is a limiting factor for performance in the natural setting.

Phase II investigates whether visual blur affects anticipatory skill; an attribute shown to be an important component of expert anticipation. The majority of existing investigations into skilled anticipation rely on uncoupled cognitive responses rather than coupled motor responses, but does this accurately reflect the anticipatory skill used in the natural setting? Furthermore, will visual clarity be a critical precursor for successful performance in this critical element of interceptive skill? Experiment III (Chapter 4) sets out to establish the experimental conditions necessary to examine skilled anticipation in the performance environment.
Following this, Experiment IV (Chapter 5) uses the methodology developed in Experiment III to evaluate whether visual blur affects anticipatory skill in the natural setting (with strong coupling omnipresent between perception and action), and furthermore how this relationship differs if anticipation is based on the more conventional lab-based response (where the relationship between perception and action is diminished).

Finally, Chapter 6 evaluates the experimental results individually and collectively, bringing together the findings to assess the impact of refractive blur on interceptive skill. Implications will be outlined for both research and practice, along with important future considerations which may prove to be useful in enhancing skilled sporting performance.
PHASE I

BLUR AND INTERCEPTION
CHAPTER 2

IS OPTIMAL VISION REQUIRED FOR THE SUCCESSFUL EXECUTION OF AN INTERCEPTIVE TASK?

‘Common sense is the collection of prejudices acquired by age eighteen.’

Albert Einstein
2.1 INTRODUCTION

Everyday interceptive tasks such as shaking hands, jumping rope, or hitting a tennis ball rely on vision to play an essential role for their successful execution. These tasks require the perception of relative motion with, and producing a response to, a targeted object. In order to achieve the desired goal, the visual system must provide a rapid and accurate assessment for the parameters of the task at hand. It is unclear however whether optimal visual function is required for most favourable performance in these tasks. This is particularly the case in sports such as field hockey, squash and cricket where there is a high demand for spatial and temporal accuracy.

Whilst vision is an indispensable component of the perceptual system required to produce an interceptive response, it is less clear whether optimal visual functioning is required for the successful execution of this action. A useful method of investigating the optimal function required for a task is to examine differences in visual attributes between expert and novice performers of the required skill. This is commonly carried out in a sporting context as one can access a wide spectrum of expertise on a number of different but all highly demanding interceptive tasks. Despite early evidence that experts in a sporting context possess superior primary visual attributes such as visual acuity (VA) and depth perception (Hoffman, Rouse, & Ryan, 1981; Sherman, 1980; Watanabe, 1983), the weight of evidence within the literature suggests that these visual functions are typically not a limitation to sporting performance (Abernethy & Wood, 2001). Elite athletes do not appear to have enhanced primary visual functioning (Abernethy, 1987; Starkes & Deakin, 1984), but rather may be more accustomed to recognising and utilising task relevant visual information to aid in facilitating performance (Abernethy & Russell, 1984, 1987a; Jones & Miles, 1978).

A limited number of studies have looked to examine how decreasing the quality of visual input may affect performance. In a training study, Bennett, Davids and Button (1996)
have demonstrated that the removal of visual information can actually improve motor learning in an interceptive task. In their study three groups of inexperienced catchers were taught to catch tennis balls one handed. The first group learned to catch with vision of the catching arm occluded, whilst the second group learned with no occlusion of vision. After a phase of 120 trials, subjects crossed over to the opposite condition for a second (transfer) phase. The third group simply participated in two phases of vision with no occlusion. Perhaps surprisingly (and in contrast to the specificity of learning hypothesis), learning without vision of the catching limb was found to enhance catching performance in the normal viewing condition. That is to say that, despite the removal of seemingly essential visual input, proprioceptive information may have been enhanced in order to aid, and improve learning. Superior attunement to this spatial information appears to have afforded superior learning in a task, and as a result performance, through the manipulation of the visual information available.

Whilst it is not a single all-encompassing measure of visual function, visual acuity is clearly a key measure of optimal function. It provides a determination of the resolving ability of the eye in terms of a minimum angle of resolution, although it is typically denoted as a Snellen fraction. Sub-optimal visual acuity denotes sub-optimal visual function. Over 70 years ago it was first reported that many high-level performers in a range of ball sports exhibit below normal visual acuity (Bannister & Blackburn, 1931), a finding later supported in a sample of baseball players (Winograd, 1942). In a survey of athletes across varying levels of ability, Beckerman and Hitzeman (2001) found that 28% of their cohort possessed a habitual corrected VA worse than 6/7.5, a level considered to be below normal expectations for the general population. About 10% of the high-level athletes in this cohort exhibited short-sightedness, long-sightedness, or other visual complications, a rate similar to that found in the general population. It appears that the traditionally key measure of visual function may not actually provide a true reflection of sporting ability.
The most common cause of decreased VA from childhood through to early adulthood is short-sightedness, or myopia (Grosvenor, 1996). Myopia occurs when light is focussed in front of the retina, and hence distant objects appear blurred. In vivo this typically occurs due either to the eye possessing too much refractive power, the eye ball having lengthened, or possibly by a combination of both of these factors (Grosvenor, 1996). Myopia can be simulated through the addition of refractive power to the eye, a ‘positive over-refraction’. This may be achieved through the use of spectacle lenses, or by using contact lenses. When introducing refractive blur to basketball players through the use of spectacle lenses, Applegate and Applegate (1992) found that a decrease in VA to 6/75 produced no significant decrease in set shot shooting performance. Whilst this study is of interest in demonstrating a lack of dependence on clear vision in a more static task, it provides little indication of what would occur in a highly demanding interceptive task where there is relative movement between the actor and targeted object.

The purpose of this study was to determine whether optimal vision is required for the successful completion of an interceptive task. Tasks such as returning a serve in tennis, saving a penalty shot in football, or catching a fly ball in baseball are assumed to be visually demanding (Gardner & Sherman, 1995), necessitating perception of movement between the object and actor. Williams, Davids and Williams (1999) have highlighted the need for greater ecological validity in studying visual perception in a sporting context, with a need to embed perceptual research in a real-life setting. Many tasks such as cricket batting or passing in football present situations where there may be a desired outcome (for example to score runs or score a goal), yet there are many different degrees of freedom in the problem, and as a result many potential responses which could result in successful attainment of the goal. Allowing for this multitude of potential responses is challenging, and sport science research has traditionally found it difficult to adequately assess performance for these types of tasks.
Myopic blur was induced in skilled cricket batters to determine whether it had any effect on cricket batting performance. Cricket batting was chosen as it provides a highly demanding interceptive task, yet with the ethical concerns of decreasing the quality of the visual input, cricket fortunately provides an environment where players wear extensive protective equipment in their habitual setting which helps to decrease the likelihood of injury to participants.

It was hypothesised that refractive blur would be tolerated to some degree with no decrease in performance, as visual clarity is unlikely to be a limiting factor in the successful execution of a highly demanding interceptive task. If optimal vision was required then it would be expected that batting performance would decrease with the introduction of any myopic blur.

## 2.2 METHODS

### 2.2.1 Participants

Eleven skilled male cricket batters (mean age 24.1 ± 3.6 years) participated in the study. Participants were recruited either as players in clubs participating in the Sydney Grade Cricket Competition, or as having played as a junior state or first grade country representative within the previous five years. Each participant gave written informed consent according to the appropriate institutional ethical guidelines.

### 2.2.2 Session construction and design

Each participant attended for two sessions. The first session involved a routine optometric consultation held at a University Optometry Clinic. The consultation comprised an assessment of VA, ocular prescription (refraction), corneal curvature (keratometry), an anterior eye examination, and a fitting of appropriate soft contact lenses. Participants who
had a corrected VA worse than 6/6 in either eye, or those who could not adapt to contact lenses, were omitted from the study.

The second session was held at the Cricket NSW Indoor Centre. Participants faced a bowling-machine (Jugs Cricket Bowling Machine; Cheltenham, Victoria) located ≈17.7m from the batter’s location of stance, set to project balls at a velocity of approximately 105-115 kph. These parameters were set to simulate the release position and velocity of a medium paced right-arm cricket bowler. Vision of the bowling-machine was set against a white background, similar to that experienced in an actual cricket match.

A bowling-machine was used in preference to actual bowlers for two reasons. First, this provided a degree of control over the projection parameters such as ball direction and velocity. Second, the use of a bowling-machine allowed the isolation of ball-flight information, as it was anticipated that if actual bowlers were used the blur may have provided a confounding effect on the ability to perceive the pre-release information inherent in the action of the bowler (Abernethy & Russell, 1984; Müller et al., 2006; Penrose & Roach, 1995). The interest of this particular study was primarily in establishing any effects of blur on interception based on ball-flight information alone.

Bowling-machines offer considerable experimental control in terms of ball direction (Figure 2.1) and velocity; however one of the hindrances in a study such as this is the difficulty in presenting inter-trial variability. Newer projection-machines are capable of highly repeatable and easily manipulated projection directions which can be changed between trials; however equipment of this type was not available at the time of the study. For the older instruments such as the one used in this study, altering the ball-direction is more difficult, and as a result safe and repeatable changes require a very time consuming process. Rather than

1 Cricket bowlers are often classified according to bowling-velocity as: slow (≈ 60-90 kph); medium (≈ 90-120 kph); and fast (≈ 120-150 kph). Ball-velocities recorded in the laboratory tend to be approximately 10% lower than those reported on television broadcasts.
altering the location of ball-bounce after every trial, an older projection-machine was chosen from those instruments available as pilot testing with this particular machine demonstrated that even without any change in projection direction, there was a moderate degree of variation in the location that the ball bounced (i.e., the location varied within the order of 1 m). It was hoped that the greater variability of this machine would decrease the batter’s ability to predict the exact bounce location within each testing block.

2.2.3 Procedures

Batters faced the bowling-machine whilst under a maximum of five different refractive blur conditions: wearing no correction (habitual vision; for those subjects whose uncorrected
VA in each eye was 6/6 or better); contact lenses of the patient’s correct prescription (the ‘plano over-refraction’ condition to control for the simple effect of wearing a contact lens); and contact lenses of +1.00, +2.00, and +3.00 dioptric (D) blur over-refraction. Each of these conditions was presented in a randomised fashion as a control for the effects of practice and fatigue, with five minutes rest allowed between conditions.

Figure 2.2 demonstrates both the appearance of the bowling-machine, and how a bowler would appear to a batter for each of the four refractive blur conditions common to all participants. Compared to an expected habitual VA of 6/4.3 for all participants (Elliott et al., 1995), a +1.00 over-correction would on average reduce VA to approximately 6/18 (Grosvenor, 1996). Likewise, with a +2.00 over-refraction acuity would be expected to decline to the vicinity of 6/40, and with a +3.00 over-refraction the acuity would decrease further to approximately 6/60. In Australia, Great Britain, and the USA, 6/60 represents the level of VA which constitutes legal blindness (Department of Family and Community Services, 1996; Farrall, 1991; Grosvenor, 1996). In this study it was chosen to blur batters by a certain refractive amount rather than to a set level of VA (as Applegate & Applegate, 1992 did), as the accurate measurement of threshold VA is partially a psychological measure which depends in particular on motivation on the part of the patient. Applegate and Applegate also used spectacle lenses in their demonstration of blur on task performance; contact lenses were chosen to be used in this study as they induce less spectacle magnification, induce little or no prism when not looking in primary (straight) gaze, and contact lenses present no limitation to the wearer’s field of view (Mandell, 1988).
Figure 2.2. Simulation of the batter’s view (a) in the experimental set-up, and (b) in a game situation with plano, +1.00, +2.00, and +3.00 levels of blur.
The projection-machine produced a moderate degree of variability in the location of ball-bounce ($\approx 1\ m$), however this was deemed insufficient to adequately replicate the higher degree of variability in bounce location typically experienced by a cricket batter ($\approx 10\ m$ in depth and $2\ m$ in laterality). As a result, for each blur condition participants faced sixty trials from the bowling-machine presented in four blocks (each having 15 trials) grouped according to projection-direction (depth and laterality). These four blocks of projection-direction were classified as: short and at the off-side; full and at the off-side; short and at the leg-side; and full and at the leg-side. The natural variation of the older projection-machine provided the intra-block variation. The projection-direction of the machine was only altered after each 15-trial block, with the four blocks presented in a random order. In presenting 15-trial blocks with minimal manipulation in the direction of ball projection, there was a risk that participants were able to obtain some degree of knowledge of the location that the ball may bounce. However, a post-hoc examination of performance across the 15 deliveries in each block demonstrated that no improvement in performance took place across the progression of deliveries within each block. This provides some indication that participants did not use prior information of the location of ball-bounce to sufficiently enhance performance on subsequent trials.

Participants were provided with cricket-relevant contextual information; instructed to bat in the trials with the mindset that they were batting in the second half of a one-day limited-overs match.\(^1\) This situation necessitates the batter to score runs in a relatively aggressive manner whilst also avoiding dismissal. Each participant was videotaped whilst batting so that the footage could later be viewed by the researchers and a coach to assess performance, the footage recorded from an elevated position immediately above the location

\(^1\) Cricket matches differ according to the length of time available for each team to bat. There are three main forms of the game: a test match where teams bat in excess of two days (over 1150 balls); a one-day match where teams bat up to 50-overs (300 balls); and a Twenty20 match where teams bat up to 20-overs (120 balls). As the available time to bat is decreased, teams will tend to bat in a more aggressive manner and increase their risk of dismissal to increase the rate of scoring runs.
of the projection-machine. Videos were later edited so that each block of 15 deliveries was presented in a completely randomised order across all blur conditions to prevent judging bias as a result of order effects.

### 2.2.4 Data analysis

Performance for each trial was assessed using two independent scores: (i) a simple categorical score used to evaluate the quality of the contact (QOC) between bat and ball, and (ii) a subjective coach rating of interceptive quality given the characteristics of the trial the shot was played against. The first score used the QOC score validated by Müller & Abernethy (2008), with a trained observer making a categorical judgment of the quality of the bat-ball contact. Although this method of evaluating performance is in itself subjective, it has been demonstrated to correlate highly with an objective measure of bat-ball interception in cricket. For each legitimate trial where the batter attempted interception, a judgement was made whether the bat had contacted the ball, and whether this contact was either *good* or *bad*. Two measures of interceptive performance were calculated, firstly the percentage of trials where *any* bat-ball contact occurred, and secondly the percentage of trials where *only good* contact was made (Müller & Abernethy, 2006a). The QOC score is a useful, validated means of evaluating interception; it may be seen to fall short though of effectively assessing how successful a participant may be in achieving the primary task goal to hit the ball aggressively and score runs.

The second measure of interception required a Level 2 Cricket Coach (Australian National Coaching Accreditation Scheme) to evaluate performance for each trial, and was

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2 A *good* bat-ball contact is defined as occurring when the ball after contact travels in a direction consistent with the pre-contact plane of motion of the bat. A *bad* contact in contrast moves in a direction inconsistent with the pre-contact plane of motion of the bat. A more detailed description of this protocol can be found in Müller & Abernethy (2008).
developed in an attempt to overcome the limitations of the QOC score. The coach assessed the appropriateness and the execution of the response (shot) played by the batter for each trial considering both the quality of the delivery, and the contextual game situation the player was presented with. The *coach-rating score* was given out of ten for each trial, with ten representing the best possible response to the delivery. If the batter was deemed to be dismissed they were given a score of zero for that trial.

For both methods used to evaluate interceptive performance, if the ball was deemed to have been so far out of reach that no appropriate stroke could be played (and hence a *wide* was likely to have been judged by an umpire in a limited overs match), the trial was deemed illegitimate and excluded from analysis.

The three measures of interceptive performance (*percentage of all bat-ball contacts*, *percentage of good bat-ball contacts*, and *coach-rating score*) were evaluated for each trial. A 4 (Blur: plano, +1.00, +2.00, +3.00) x 4 (projection-direction: short & off, short & leg, full & off, full & leg) ANOVA with repeated measures on both factors was used to examine for differences in each of the three performance scores. In the event of a main effect for blur, successive contrasts were used to examine for differences across adjacent levels of visual blur. Paired *t*-tests compared performance (again using all three measures) between the no-lens and habitual contact lens conditions for those subjects who met the inclusion criteria of 6/6 VA without visual correction. An alpha level of 0.05 was considered significant for all tests, although to protect against violations of the assumption of sphericity, alpha was adjusted where necessary according to the Greenhouse-Geisser method. Partial eta squared ($\eta^2_p$) values were computed for all analyses of variance to provide the proportion of the effect + error variance that was attributable to each factor or combination of factors.
2.3 RESULTS

2.3.1 Blur and interception

2.3.1.1 Percentage of all bat-ball contacts

An examination of the percentage of all bat-ball contacts revealed a significant effect for blur (Figure 2.3a; $F(3,30) = 3.70, p < .05, \eta^2_p = 0.27$), due to a significant decrease in all bat-ball contacts from the +2.00 to +3.00 blur condition ($p < .01$). There was no main effect of projection-direction ($F(3,30) = .83, p = .49, \eta^2_p = 0.08$), however this was superseded by an interaction between blur and projection-direction ($F(9,90) = 2.77, p < .01, \eta^2_p = 0.22$). This interaction was primarily a result of a greater decrease in bat-ball contacts for deliveries directed full and at the off-side for the +2.00 to +3.00 contrast ($p < .001$, Figure 2.4a). The only other successive contrast to reach significance was the +2.00 to +3.00 contrast for short deliveries directed towards the leg-side ($p < .05$).

2.3.1.2 Percentage of good bat-ball contacts

There was no main effect of blur for the percentage of good bat-ball contacts (Figure 2.3b; $F(3,30) = 2.65, p = .07, \eta^2_p = 0.21$), however there was a main effect of projection-direction ($F(3,30) = 3.11, p < .05, \eta^2_p = 0.24$), superseded by a significant interaction between blur and projection-direction ($F(9,90) = 2.10, p < .05, \eta^2_p = 0.17$). This interaction was primarily due to a lower percentage of good contacts in the +3.00 condition for balls bouncing full and towards the off-side ($p < .01$, Figure 2.4b), with no other successive contrasts reaching the required level of statistical significance.
Figure 2.3. Percentage of (a) all bat-ball contacts and (b) good bat-ball contacts for each blur condition. Significant difference in successive contrast across adjacent levels of blur is indicated ($\Delta p < .05$). Error bars represent the standard error.
Figure 2.4. Percentage of (a) all bat-ball contacts, and (b) good bat-ball contacts for each of the four categorised projection-directions across the four blur conditions.
2.3.1.3 Coach-rating score

The coach-rating of interceptive performance revealed a main effect for blur (Figure 2.5; $F(3,30) = 3.36$, $p < .05$, $\eta^2_p = 0.25$) due to a significant decrease in performance from the +2.00 to +3.00 blur condition ($p < .05$). Table 2-1 demonstrates that seven of the 11 participants improved their mean coach-rating score from the plano to +1.00 condition, five of the 11 improved from the +1.00 to +2.00 condition, whilst only one of the 11 subjects improved from the +2.00 to +3.00 condition.

![Figure 2.5. Mean coach-rating score for each contact lens blur condition. Significant difference in successive contrast across adjacent levels of blur is indicated ($\Delta p < .05$). Error bars represent the standard error.](image-url)
Table 2-1. Mean Coach-Rating Scores (out of ten) for each of the Eleven Participants in all of the Common Contact Lens Blur Conditions

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<tr>
<th>Subject No</th>
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*Number in parentheses represents the order in which the refractive conditions were presented for each participant.

A significant main effect was revealed for projection-direction (Figure 2.6; $F(3,30) = 9.41$, $p < .001$, $\eta^2_p = 0.49$) due to significantly greater performance for trials bouncing short and towards the off-side compared to all other ball-bounce locations (all $ps < .001$). There was no significant difference between any of the other pair-wise comparisons for projection-direction (trials towards the leg-side, short vs. full, $p = 0.33$; full trials, leg vs. off, $p = 0.99$; and short towards the leg-side vs. full towards the off-side, $p = 0.34$). The interaction between blur and projection-direction was not significant ($F(9,90) = 1.37$, $p = .22$, $\eta^2_p = 0.12$).
2.3.2 Effect of wearing a contact lens (of habitual correction)

Five participants were found to have a VA of 6/6 or better in each eye without visual correction; as a result they batted both without correction, and with contact lenses of minimal (or no) visual correction. No change in performance was found for any of the three performance measures when comparing batting without lenses to batting with lenses of habitual correction: percentage of all bat-ball contacts (no-CL vs. habitual-CL = 88.7 ± 6.7% vs. 84.7 ± 6.0%; \( t(5) = -1.32, p = .26 \)); percentage of good bat-ball contacts (no-CL vs. habitual-CL = 70.5 ± 12.1% vs. 66.0 ± 10.9%; \( t(5) = -1.93, p = .13 \)); and coach-rating score (no-CL vs. habitual-CL = 6.0 ± 0.6 vs. 5.8 ± 0.5; \( t(5) = -1.85, p = .14 \)).
Chapter 2  Blur and interception

2.4 DISCUSSION

The purpose of this study was to examine the effect of induced myopic blur on an interceptive task. It was hypothesised that visual clarity is unlikely to provide a limitation to interception, and as a result performance would demonstrate some degree of resilience to visual blur. Consistent with this hypothesis, it has been demonstrated that skilled cricket batting does not require optimal vision for successful execution. Rather, in this study batters were able to tolerate relatively high levels of blur before there was any measurable decrease in batting performance. This is an intriguing and perhaps counterintuitive finding which raises many questions in seeking to further our understanding for how interceptive actions are performed.

Research into sporting expertise appears to have converged to a relatively common viewpoint that superior vision is not required for optimal athletic performance (Abernethy & Wood, 2001; Garner, 1977; Starkes & Deakin, 1984), yet it still may be surprising that participants in this study required blur to the point of legal blindness before there was any decrease in performance. Although Applegate and Applegate (1992) were able to blur their subjects beyond legal blindness without any decrease in basketball free-throw shooting performance, the closed and simple visual nature of their task was much different to the visual demands of the task examined here. The findings of this study may be interpreted to support those found for the free-throw, however more importantly it has expanded on those findings in two ways. Firstly, a level of blur has been demonstrated where performance decreases, implying that a range of myopic blur exists where there is no measurable decrease in performance. Secondly, this range has been demonstrated in a dynamic open skill where there is relative movement between the actor and their target.

A possible explanation for the moderate level of blur tolerated in the batting task may lie in the nature of the visual information sourced by the neural pathway which produces
online interceptive responses. According to the dual-pathway theory of vision outlined by Milner and Goodale (1992; 1995), real-time interceptive actions are produced by the dorsal visual pathway which are distinct from the perceptual interpretations of the ventral pathway. The magnocellular visual information sourced by the dorsal pathway is known to be relatively insensitive to blur yet sensitive to contrast and movement (Milner & Goodale, 1995; Shapley, Kaplan, & Soodak, 1981). This is in contrast to the ventral pathway which sources both parvo- and magno-cellular information, with the parvocellular input highly sensitive to clarity and colour. From this viewpoint it is conceivable that a dorsally- but not ventrally-based task may be moderately resistant to visual blur. Although the dorsal system may be expected to demonstrate a high degree of resilience to blur, alternately it is likely to be highly sensitive to changes in visual contrast. This proposition is consistent with the findings of Campbell, Rothwell and Perry (1987), whose simulation of the conditions experienced by a cricket batter found a rapid increase in reaction time when ambient light levels were decreased beyond the point that a cricket game would typically be stopped. This occurs despite the fact that VA at these levels is still very good (Pirenne & Denton, 1952), and the visibility of the ball is still well above the detection threshold. This differentiation between the criticality of blur and contrast may prove to be a fruitful means of differentiating the functions of the two visual streams (see Brown et al., 2005 for a similar example distinguishing the functions of the two pathways based on the sensitivity of peripheral vision).³

Interceptive quality was found to decrease in the +3.00 blur condition for two of the three measures of performance: percentage of all bat-ball contacts and the coach-rating score.

³ Blur and contrast are not completely independent visual manipulations, for example, using spherical lenses to blur an image will produce a commensurate decrease in contrast sensitivity (Marmor & Gawande, 1988). However, visual clarity can be preferentially decreased to a much greater degree than contrast, and vice-versa.
The main effect of blur for each of these two scores demonstrated similar response patterns, and similar effect sizes. This congruence between the two scores indicates that either (i) the coach subjectively judged interceptive performance based on the ability to make bat-ball contact (i.e., the scores are measuring the same factor, with the coach rating not sensitive to higher-order parameters), or that (ii) only the quality of bat-ball contact changed across the levels of blur, with no change in the way batting was executed. Although the similar finding for the QOC and coach-rating in some respect validates the use of the coach-rating to evaluate interceptive performance, it also highlights the short-comings of this score in lacking a strong and definable operational definition. Future studies seeking to evaluate striking performance may look to overcome this potential shortfall by more explicitly appraising the batting behaviours of interest.

It has been demonstrated that visual blur can produce manipulations in motor task execution in an attempt to maintain levels of performance (Heasley et al., 2004; Higgins et al., 1998), and as such it is possible that batters implemented a more defensive strategy with the introduction of blur to maintain interceptive quality. That is to say that participants may have sacrificed the forcefulness of their strike (i.e., they were less aggressive) to maintain bat-ball contact. A less aggressive bat-swing allows a later stroke to be played (which allows more time before an appropriate decision must be made), and decreases the bat-velocity which moderates the temporal precision required to make bat-ball contact. Unfortunately the performance measures used in this study may have been insensitive to these changes in execution.

The percentage of good bat-ball contacts was not found to differ across the different levels of blur, although this main effect for blur was close to reaching significance ($p = .07$). It appears that the score for good contacts may be less sensitive to changes than the score for all bat-ball contacts. It is conceivable that the participants were not able to make bat-ball contact
for challenging trials in the +3.00 condition, whereas some degree of contact was achievable for the lower levels of blur.

The examination of performance differences which occur between contrasting ball-machine projection-directions provides a further insight to the sensitivities and biases of the different methods of performance evaluation. For both of the QOC scores, the lack of a main effect of projection-direction indicated that participants were able to maintain similar levels of bat-ball contact for each of the different ball directions. For both scores, however, an interaction occurred between blur and projection-direction, with the decreased performance in the +3.00 condition occurring as a direct result of the poorer bat-ball contact for trials directed full and towards the off-side (Figure 2.4). When considering this effect, the successful interception of trials directed in this location requires the participant to move forward, and to meet the ball away from their body. This may present conditions which are difficult to overcome with blur because (i) moving forward affords the participant less time to execute their response before the ball arrives, and (ii) it may be more difficult to detect the parameters for a ball directed away from the body than for one which is approaching towards the body and therefore towards the batter’s line of sight (as would occur for trials directed towards the leg-side).

Batting performance for the coach-rating scale was superior for trials bouncing short and towards the off-side; the absence of any interaction with blur indicates that this was a consistent effect across each of the refractive blur conditions. It has already been established that the QOC is not different across the different projection-directions, yet the coach has rated performance better for balls bouncing in this location. This may be a reflection of a judging bias, such that the shots performed in response to short deliveries towards the off-side were deemed to be superior responses to those performed for other ball-bounce locations. Alternately, it is conceivable that more time should be available to intercept trials which are short and directed towards the off-side. For deliveries directed towards the leg-side,
appropriate responses tend to be played in front of the body irrespective of whether the length is short or full. For deliveries directed away from the body towards the off-side, a full ball will conventionally require the batter to move forwards to meet the ball; a shorter ball on the other hand allows the batter to move back to play their most appropriate response. As a result more time is available for responses to short trials towards the off-side, resulting in good reason to expect superior performance as both (i) relatively later shot manipulations could be made, and (ii) more time is available to produce a larger backswing and a more aggressive response (which is more likely to result in runs). In this sense the coach-rating may be adding something above and beyond the QOC score, potentially evaluating the greater likelihood that responses will result in runs in a match situation. The lack of interaction between blur and projection-direction does suggest however that any extra time advantage provided by these deliveries is not a relative benefit with the introduction and progression of visual blur.

The introduction of a correcting contact lens to those participants with an uncorrected acuity of 6/6 or better was not expected to cause any measurable change in performance; any improvement in vision would be very minor (or negligible), and modern contact lenses are very comfortable and unlikely to cause a distraction (even for new wearers). For those five participants who met the inclusion criteria to bat both with and without contact lenses, no significant differences were found for any of the three performance evaluations when placing a contact lens on the eye. This was an important finding as many of our participants had never worn contact lenses before and it provides some evidence that the introduction of what could be seen to be a relatively invasive medical device did not adversely affect batting performance. Although this finding is tempered by the small sample size, there is little reason to believe that simply placing a non-blurring contact lens onto a participant’s eye will have any adverse affect on performance.
2.4.1 Methodological considerations

The highly applied nature of this study has helped to advance the methodologies used in the examination of visual perception in interceptive and sporting tasks. The task at hand has continued the example of Williams et al. (1993) and Farrow and Abernethy (2003) in coupling perception and action rather than by examining perception alone, an important consideration given Milner and Goodale’s (1995) assertion of different neural streams subserving different functional outcomes. Furthermore this has been the first utilisation of contact lenses in this domain, providing a more realistic manipulation of vision than can be achieved when using spectacle lenses.

When examining performance in an open interceptive task such as cricket batting, it is important to acknowledge that there is not one correct appropriate movement response for any given trial (Newell, 1986). Different participants, or even the same participant, may select very contrasting responses for any given scenario, each of which may provide an equally desirable outcome. The subjective coach-rating scale was employed in an attempt to provide a scoring method which is sensitive to this multitude of potential responses. It was designed to overcome the limitations of the QOC score, which is not sensitive to changes in interceptive execution (which may be attenuated by blur) such as the aggressiveness or the forcefulness of the bat-swing. Clearly though there are limitations to the utilisation of this rating scale, and it is acknowledged that it may not be as sensitive as an objective scale, and as a result may artificially increase the range of blur where no change in performance is reported. At this stage it is clear that either (i) blur less than +3.00D does not change the nature of the interceptive response, or (ii) that the evaluations of interceptive performance used here were not sensitive enough to detect any changes for lower levels of blur. Future attempts to assess performance in open striking tasks may look to more specifically assess changes in execution (e.g., forcefulness of bat-swing) in conjunction with the quality of bat-ball contact. This may be useful in resolving whether for lower levels of blur performers are manipulating the nature of
the interception to preserve appropriate bat-ball contact, or that there is no change in batting performance as has been reported in the current study.

Caution must be exercised when generalising these findings to suggest that athletes participating in high speed interceptive tasks do not require visual correction. A bowling-machine has been used in this study to isolate ball-flight information from the additional pre-release information that a skilled player would typically use to facilitate interceptive performance (Shim et al., 2005). At this stage it is unclear whether blur moderates the ability of skilled players to couple movements to this advance information. A further consideration is that the moderate ball-velocities experienced in this study fail to replicate the conditions experienced at the highest levels of competition. Is it possible that the high degree of resilience to blur demonstrated here may be tempered by the greater temporal demands of faster ball-velocities. Moreover, despite using a projection-machine in this study which provided some degree of variability in the location of ball-bounce, it is possible that participants were able to somewhat predict the landing location of the ball; this conceivably, in conjunction with the relatively consistent ball-speed, may have been sufficient to overcome the patent decrease in vision in order to sustain interceptive performance. This assertion would, though, be refuted, if the protocol were to be repeated with deliberate variations in the location of ball-bounce either (i) by varying the projection characteristics of the projection-machine between each trial, or (ii) by using bowlers to deliver trials (rather than a machine) to introduce greater inter-trial variability. Further research is required to establish the effect that myopic blur may have on these factors, and should aim to create an environment which more closely replicates the actual performance conditions typically experienced by the skilled performer.

A further contentious methodological issue has been the inclusion of auditory information; it could be argued that the presence of auditory cues has aided performance with the degradation of visual information. The nature of this study though was to simulate a real-
life situation as closely as possible, and the removal of alternate perceptual information would only aid in diminishing the ecological validity of the study. If a skilled performer is able to compensate for visual losses by enhancing their perception of sound, this further advances the argument that exceptional primary visual skills are not a critical precursor for superior interceptive performance.

2.5 CONCLUSIONS

Rather than being a factor which differentiates expert from lesser-skilled performers, visual clarity does not appear to be a limitation to interceptive performance in a fast striking task. Skilled performers of a spatially and temporally demanding interceptive action are able to maintain performance despite the imposition of moderate levels of visual blur. Future work will establish whether this finding is repeatable using more sensitive methods of performance evaluation, and whether it extends to conditions which more closely simulate those experienced in the skilled performer’s natural environment.
CHAPTER 3

THE RESILIENCE OF NATURAL INTERCEPTIVE ACTIONS TO REFRACTIVE BLUR

‘Human beings...are far too prone to generalize from one instance. The technical word for this, interestingly enough, is superstition.’

Francis Crick
3.1 INTRODUCTION

The successful execution of interceptive tasks, particularly the striking of objects moving at high speed, requires highly refined visual-motor skills developed across many years of extensive practice. While the skills necessary for interceptive tasks are likely to possess an important evolutionarily basis (e.g., in hunting tasks), today the limits of these skills are most frequently demonstrated in time-constrained sports such as baseball and ice-hockey. The visual system clearly plays a critical role in the successful completion of these tasks, underpinning the skilled coordination of relative movement between the hitting implement and moving target. The dependence of these tasks on vision has given rise to the commonly held assumption that optimal, or at least excellent visual function, is imperative for successful execution. Empirical evidence suggests however that this may not necessarily be the case, particularly in terms of visual acuity (VA).

One of the earliest attempts to understand the basis of expertise in striking tasks involved an examination of the visual skills of highly renowned baseballer, Babe Ruth. Fullerton (1921) reported that Ruth had above-average visual speed, although subsequent examinations later in the baseballer’s life revealed impediments to his depth perception (Voisin et al., 1997). This inconsistency in findings may be seen to reflect a debate which continues today: whether superior visual skills are essential for expert performance in tasks such as batting, or rather that these attributes are unlikely to limit performance.

3.1.1 Visual and perceptual attributes associated with sporting expertise

The measurement and comparison of key primary visual attributes across expert and novice sports performers has been a popular approach in attempting to establish how important these attributes are for skilled motor performance. Studies of this nature have sought to investigate whether superior visual skills are a hallmark of, and indeed a
requirement for, skilled performance. Accordingly if this were to be the case, below normal visual function would be a limitation for visual-motor performance. While a number of early studies reported an expert advantage on some basic measures of visual function including visual acuity and depth perception (e.g., Beals et al., 1971; Olsen, 1956; Spurgeon et al., 1989), more recent reviews have failed to support these findings as being systematic (Abernethy, 1987; Ward & Williams, 2003). Indeed anecdotal reports of elite athletes with inferior visual function are increasingly common - an observation supported by studies demonstrating a similar prevalence of visual deficiencies among expert and either non-expert performers or the general population (e.g., Beckerman & Hitzeman, 2001). Nevertheless, some significant expert-novice differences continue to be reported on select visual attributes such as dynamic visual acuity (Hughes et al., 1993; Rouse et al., 1988) and peak saccadic velocity (Morgan, in press). Consequently, debate continues whether these may be systematic and reproducible findings, and if so whether they represent an underlying cause or simply a by-product/consequence of domain-specific expertise.

Studies of sporting expertise generally appear to converge on a common viewpoint that visual-perceptual skills, based upon the ability to recognise and act on task-relevant visual information, are more likely than primary visual attributes to underpin skilled performance (Abernethy, 1987; Starkes & Deakin, 1984). In a selection of these studies, multivariate analyses incorporating visual, cognitive, and perceptual measures have been applied; typically finding that measures such as anticipatory skill and pattern recognition discriminate between levels of skill to a degree not apparent for measures of general visual attributes such as visual acuity and ocular muscle balance (Abernethy et al., 1994; Starkes, 1987; Ward & Williams, 2003). Studies of this kind suggest that exceptional levels of primary visual functioning are not necessary for expert sports performance (nor a defining characteristic of expert performers) and rather that levels of visual function at or even below population norms can sustain skilled performance.
3.1.2 Interception with sub-normal vision

The visual information relied on by the dorsal ‘vision-for-perception’ pathway provides some reason to suggest that clear vision may not be necessary for the optimal performance of online visual-motor movements. The ventral ‘vision-for-perception’ pathway represents our normal phenomenological experience of ‘vision’; a clear, colourful image of our surrounds that we use to make conscious perceptual interpretations and decisions. On the other hand, the dorsal pathway sources and acts upon visual information which is highly sensitive to movement and contrast, yet this information has relatively poor sensitivity to clarity and colour (Livingstone & Hubel, 1988; Milner & Goodale, 1995). As a result of this insensitivity to clarity in the dorsal pathway, it is reasonable to propose that online actions produced by this pathway may be relatively impervious to visual blur (which decreases the clarity of an image). Norman (2002) has used this line of reasoning to interpret the results of Higgins et al. (1998), who found that perceptual decisions (ventrally-based) but not online interceptive actions (dorsally-mediated) were adversely affected by visual blur.

A small number of existing studies in sport have shown that performance in interceptive tasks may be resistant to visual blur, best measured by changes in visual acuity. Applegate and Applegate (1992), for example, examined whether decreased VA would affect set shot shooting performance in basketball. They used a series of lenses with increasingly positive refractive power to simulate the increments in blur experienced with progressive levels of myopia, finding that even when VA was reduced to 6/75 (the poorest level of VA tested), no significant decreases in shooting performance were evident. This was reported to be in contrast to “common sense” or what is “commonly assumed” to be the case that any decrease in VA would result in a monotonic decrease in performance (Applegate & Applegate, 1992, p. 765). In a similar vein, participants in a study by Bulson, Ciuffreda, and Hung (2008; following the publication of Experiment I) performed a golf putting exercise while wearing a series of increasingly positive refractive lenses to decrease VA. They found that only the
highest powered lenses, producing a VA of 6/600, could produce a decrease in putting accuracy.

Experiment I of this thesis examined the influence of refractive blur on motor performance in a task involving high-speed, relative motion requiring challenging coincidence timing. More specifically, it examined the effect of decreased VA on cricket batting – a skill for which successful execution requires very high levels of spatial and temporal precision. [Regan (1997) reported that expert cricket batters at the elite level of competition may exhibit spatial accuracy to within 5 cm and temporal accuracy to within 2-3 ms]. In Experiment I, participants faced balls (projected from a machine) approaching at velocities in the range of 105-115 kph while wearing contact lenses designed to systematically manipulate VA. It was found that VA had to be reduced to approximately 6/60 before any significant decrease in batting performance was evident, with lesser levels of blur found to have no adverse affect on performance. It was proposed that the findings could be explained by the resilience of a dorsally-mediated task to visual blur; however three particular limitations were apparent within that study which may have offered alternate explanations for the observed resilience of interception to blur.

The first potential limitation of Experiment I was the use of a projection-machine rather than a bowler to propel the ball towards the participants; potentially acting to both guide visual search and preclude perception of the advance kinematic information known to be important for expertise in interceptive tasks. The ball always appears out of the same location from a projection-machine, simplifying the visual search requirements of the task when compared to the natural setting, where the ball may be released from varying locations by a bowler who is in motion in their approach towards the batter (Gibson & Adams, 1989). When facing a ball projection-machine, visual search is guided towards the fixed position of ball release, conceivably providing a useful visual anchor point, even with the imposition of refractive blur. In contrast, blur may be expected to adversely affect the additional
requirement that exists to search for the position of ball release when observing a bowler. Moreover, a batter’s ability to accurately perceive advance kinematic information provided by the bowler’s pre-release movement pattern may also be influenced by refractive blur. It is well established that experts are better able to use this information to both anticipate an event outcome (Abernethy & Russell, 1987a; Jones & Miles, 1978), and to effectively couple interceptive movements (Pinder et al., 2009; Shim et al., 2005). Consistent with other interceptive sports, skilled cricket batters are better able to anticipate both the direction and type of deliveries based on pre ball-flight information (Abernethy & Russell, 1984; Müller et al., 2006; Renshaw & Fairweather, 2000). The imposition of visual blur may potentially decrease a batter’s ability to use this information in facilitating performance; either in their ability to accurately contact the ball or, more subtly, in their ability to be in position sufficiently early to execute a more forceful and effective response.

A second limitation of Experiment I is related to the moderate velocity of the ball being intercepted, and the possibility that the increased demands of faster ball speeds may result in an earlier blur-induced decrease in performance. Because of the time taken to generate a bat swing with sufficient force to produce an effective striking action, decisions about the appropriate striking response need to be based on information arising well before bat-ball contact. With increases in ball-velocity, the ball will be relatively more distant from the batter when critical swing decisions are made; conversely for lower ball velocities the ball can be relatively closer before final swing decisions are made. Refractive blur affects the proximity with which objects can be seen clearly; as the level of blur is increased, the closer an object must be for resolution. It stands to reason therefore that the slower the ball-velocity, the closer the ball can be before a response is required, hence allowing a higher level of blur to be tolerated. Conversely, the higher the ball-velocity, the further the ball will be from the batter at the time key ball-flight characteristics must be identified, with less blur able to be tolerated before this essential information cannot be resolved. In the case of Experiment I which
presented medium-paced ball velocities, a high level of blur (+3.00D) was required before there was any decrease in interceptive performance. It seems reasonable to expect that if the ball-velocity is increased, only a reduced level of blur will be tolerated. Indeed as the ball-velocity approaches the upper limits experienced at the highest levels of competition, it is possible that clear vision may be a necessity, with no blur tolerable to maintain habitual interceptive performance.

A third limitation of interest within Experiment I concerns the scoring method used to evaluate batting performance. Whereas in a match situation runs scored provides an objective measure of batting performance, these conditions are difficult to replicate in a laboratory. A difficult challenge for open interceptive tasks conducted in an experimental context is to derive a satisfactory, sufficiently portable measure of interceptive performance. The participants in Experiment I were placed in a simulated game situation and required to bat to score runs whilst avoiding dismissal. A qualified coach provided a score out of 10 for each trial to evaluate the effectiveness of each response; however the highly subjective nature of this score renders replication difficult, and did not permit insight to how performance execution may have changed as a function of refractive blur. For instance, participants may have maintained their quality of bat-ball contact with increases in blur through a more conservative approach to interception (e.g., by reducing bat velocity at contact), yet the score given by the coach may have been insensitive to these changes. Therefore, a more objective means of performance evaluation other than a coach rating is needed.

The purpose of this study was to further examine the relationship between refractive blur and interceptive performance. We sought to replicate and extend the findings of Experiment I, systematically addressing each of the three identified limitations in order to further our understanding of visual control for striking tasks. The first aim of the present study was to examine whether the resilience to blur observed for batters facing a projection-machine would extend to intercepting balls delivered, in-situ, by cricket bowlers. We
hypothesised that if optimal vision was required for the use of pre ball-flight information to facilitate performance, decrements in performance execution would be evident earlier when facing bowlers than when facing a projection-machine. The second aim of the study was to examine the impact of different ball velocities on the relationship between blur and interceptive performance. It was hypothesised that an increase in ball-velocity would result in an observable decrease in interceptive performance at a lower level of blur. Any resilience to blur, especially against a bowler with higher generated levels of ball-velocity, would provide evidence to support the contention that optimal VA is not typically a limiting factor for successful batting performance, and would be consistent with the proposal that dorsally-mediated tasks are unlikely to be affected by low levels of visual blur. In order to more accurately evaluate the task aim, we developed a more objective, multifaceted method of assessing interceptive skill in batting, and used it to assess performance across all task conditions.

### 3.2 METHODS

#### 3.2.1 Participants

Ten skilled male cricket batters (mean age 22.5 ± 4.9 years) took part in the study. All had played in the local regional first grade competition within the previous 12 months, the majority having represented their state/territory at a junior or senior level. Participants reported an average of 9.1 ± 3.6 years of junior and 7.3 ± 4.5 years of senior playing experience. All participants gave written informed consent according to institutional guidelines prior to taking part in the study.

#### 3.2.2 Experimental task and design

Participants were required, using a regulation cricket bat, to intercept balls projected toward them. They were instructed that their task was to bat in a manner that, in a match
situation, would concurrently result in as many runs being scored as possible whilst also avoiding dismissal.\(^1\) Cricket-specific contextual information was presented to the participants to provide a simulation of match conditions. Participants were advised of the locations of the 10 (imagined) fielders, with the instruction that intercepted balls should be directed away from these locations.\(^2\) Fielding positions were printed on a 0.64 x 0.51 m poster and placed on an adjacent wall available for constant reference throughout testing.

All experimentation took place in an indoor cricket testing facility designed to replicate the dimensions and surface of a synthetic cricket pitch. To enhance safety, all participants wore full standard cricket protective equipment, and faced a softer ball specifically designed to act like a cricket ball (Kookaburra Supa Soft with factory lowered seam, Kookaburra Sport Pty. Ltd., Australia). Video footage of all testing was recorded (Sony HDR-FX1E digital video camera, Sony Corporation, Japan) from an elevated position behind the bowler’s release position of the ball. A Stalker ATS Sport Radar (Stalker Radar, USA) measured ball-velocity for each trial. Balls were projected/released in front of a white background to simulate the conditions that a cricket batter would typically experience in a match situation.

To address the first aim to examine for possible differences in performance with and without the presence of pre ball-flight kinematic information, a design was used involving two different presentation conditions - one using a ball projection-machine, and the other using

\(^1\) In the sport of cricket, batters attempt to hit balls with the primary objective being to score runs by hitting the ball to positions on the field other than those occupied by ten fielders. The batter continues to play on until they are dismissed. This typically (but not exclusively) occurs either when the ball after being hit is caught by a fielder without the ball bouncing, or the ball if missed hits the stumps being protected by the batter. For this study, participants were instructed to bat according to a one-day game score of 3/120 off 30 overs. In the one-day form of cricket, a team has a limited number of deliveries (300) from which to score runs, necessitating aggressive and forceful interception.

\(^2\) The cricket-specific fielding positions chosen to represent a field in the second half of a one-day match were wicket-keeper, gully, point, cover, long-off, mid-on, mid-wicket, deep square leg, fine-leg and third man.
live bowlers. In the ball projection-machine condition, a cricket-specific bowling-machine (Bola Professional, Stuart and Williams, UK) with digital control of velocity was used to present trials matching the ball-flight characteristics delivered in the live bowler condition.\(^3\) Trials for both presentation conditions involved comparable release heights (≈2.2 m) and a common projection distance (≈17.7m). To examine the second aim of determining whether interceptive performance is mediated by ball-velocity, three different bowlers were recruited for the live bowler condition; one bowled at a fast-pace ball-velocity (120-130 kph), while the remaining two bowlers were of medium-pace (90-110 kph). All three bowlers had played in their regional first-grade competition within 12 months of testing, and were hence considered to possess comparable skill levels to the batting participants. Logistical constraints with testing resulted in only 7 of the 10 participants (batters) facing the faster bowler. All 10 participants faced three bowlers (at least two medium-paced), although a non-testing related injury to one of the original medium-paced bowlers required his replacement (in the latter stages of data collection) by a substitute bowler of similar pace and skill.

Prior to testing, a vision screening was conducted to facilitate contact lens fitting. Habitual VA was recorded and a full refraction conducted, followed by the fitting of appropriate soft contact lenses making possible four refractive conditions; plano, +1.00, +2.00, and +3.00 (see Experiment 1; Figure 2.2). The plano refractive condition was performed with habitual vision (either with or without contact lenses), whilst participants wore contact lenses to induce corresponding levels of blur for the +1.00, +2.00, and +3.00 refractive conditions. Across all participants the mean habitual VA was 6/5.3 equivalent (range 6/4.5 - 6/6). The three refractive blur conditions (+1.00, +2.00, +3.00) resulted in commensurate increases in mean VA to 6/11 (range 6/6 - 6/19), 6/20 (range 6/10 - 6/33), and 6/49 (range 6/25 - 6/80)

\(^3\) This newer bowling-machine possessed excellent and highly-repeatable control over projection direction and ball velocity, enabling the operator to safely and reliably alter the projection direction and velocity between successive trials.
respectively. Participants with habitual VA worse than 6/6, or those who could not adapt to contact lenses, were omitted from the study.

### 3.2.3 Procedures

Participants took part in both the live bowler and projection-machine presentation conditions under each of the four refractive conditions (plano, +1.00, +2.00, and +3.00). A total of 192 experimental trials were presented to each participant - 96 trials for each of the live bowler and projection-machine presentation conditions. The 96 trials for each presentation condition consisted of four 24-trial blocks – one for each of the four refractive conditions. All 24-trial blocks consisted of three 8-trial sets presented by each of the three bowlers or their projection-machine equivalent. All 24-trial blocks were preceded by six practice trials - two from each bowler or their projection-machine equivalent. A variety of different trials were presented to best simulate the diversity typically encountered in a match situation. To this end both the bowlers and ball-machine operators followed a pre-determined schedule of six different deliveries (short and off-side, good and off-side, full and off-side, good and leg-side, full and leg-side, slower good and off-side) which had a relative frequency selected to be representative of that which a batter might experience in a match. These six deliveries were presented in a randomised fashion to minimise the chance of participants predicting either the position or timing of ball-bounce, with their frequencies and bounce locations within each testing block balanced across both presentation and refractive conditions.

The order of blur conditions was presented in a balanced fashion between participants such that across all participants, each of the blur conditions were equally as likely to occur as the first, second, third, or fourth condition; furthermore there was equal probability that sequential conditions would either be increasing or decreasing in blur. The order of scheduling for the presentation condition (live bowler or projection-machine) was counterbalanced across
participants but held constant within participants (i.e., half the participants always faced the live bowlers first whilst the other half always faced the projection-machine first). A 10 min break was allowed between refractive conditions, with approximately 10 s between consecutive within-block trials. Participants attended two separate testing sessions, each of approximately two hrs duration.

3.2.4 Verification of presentation conditions

The registration of ball-velocity was used to examine the validity of comparisons between the presentation conditions (bowler vs. machine) and between the bowlers of different release velocities.

3.2.4.1 Bowlers vs. projection-machine

For the comparison of bowler and projection-machine conditions, similar ball-velocities were possible for the medium-paced but not fast-paced trials. For the medium-paced trials, there was found to be no difference across the two presentation conditions for the mean (Bowlers vs. Projection-machine: 104.9 vs. 105.2 kph; \( t(9) = .33, p = .75 \)), or standard deviation (Bowlers vs. Projection-machine: 5.4 vs. 4.2 kph; \( t(9) = 1.67, p = .13 \)) of ball-velocity. This was not the case however for the fast-paced trials where the ball-velocity for the bowler was significantly greater than that for the projection-machine (120.8 vs. 107.8 kph; \( t(6) = 50.51, p < .001 \)). This difference was a limitation of the ball used throughout testing, with its release velocity from the projection-machine unable to match that achieved by the fast-paced bowler. For the projection-machine trials designated to match the fast-paced bowler, the maximum speed setting was used on the projection-machine; unfortunately this was insufficient to accurately replicate the ball-speed of the fastest bowler. As a result, for the bowlers vs. projection-machine comparison, only the medium-paced trials were used; all trials for the fast-paced bowler and the attempted projection-machine equivalent were excluded from these analyses comparing presentation conditions.
3.2.4.2 Medium vs. fast-paced ball-velocity

For the live bowlers trials, ball velocity for the fast-pace bowler was significantly greater than that of the medium-paced bowlers (120.8 vs. 104.2 kph; \( t(6) = 13.22, p < .001 \)). As a result the protocol allowed for two comparisons: (1) live bowlers vs. projection-machine for deliveries of medium-pace, and (2) fast vs. medium-paced deliveries for trials presented by the bowlers.

3.2.5 Data analysis

Performance on each trial was rated using three categorical measures of execution relevant to cricket batting; quality of bat-ball contact (QoC), forcefulness of bat-swing (FoBS), and likelihood of dismissal (LoD) (see Table 3-1). These three measures were used in an attempt to reflect the key objectives of a cricket batter, i.e., to successfully strike the ball in such a manner that they would score runs whilst avoiding dismissal. The QoC score, validated by Müller and Abernethy (2008), provides a useful means of assessing interceptive timing yet, when used alone, may fall short of fully assessing the batter’s goal of scoring runs in a simulated environment as it provides no measure of how forceful the interception was. The FoBS score was devised to provide an assessment of how hard the ball is likely to have been hit and to thus provide a measure reflecting the likelihood that any bat-ball contact would result in runs being scored. This score was particularly important to determine whether batters changed their interceptive strategy with the introduction of blur. A higher FoBS score represents an increase in the temporal precision required for successful execution, as the faster bat speed necessary to do so decreases the amount of time the bat will be in the correct location to intercept the oncoming ball. The inclusion of the LoD measure permitted an evaluation of whether changes across refractive blur conditions had altered the chance of the participants being dismissed.
A pilot study revealed that all three measures had acceptable levels of intra-rater reliability. Reliability of the three dependent variables was assessed on a selection of 192 trials. Intra-rater reliability, first assessed by comparing scores measured live and scores derived from a first review of video footage of the same event (two weeks later), demonstrated strong correlations for QoC ($r_s = .86; p < .001$), FoBS ($r_s = .72; p < .001$), and LoD ($r_s = .68; p < .001$). Comparable reliability estimates were also obtained for all three measures for correlations between the scores given at live assessment and at a second video review performed a further one month later; QoC ($r_s = .86; p < .001$), FoBS ($r_s = .67; p < .001$), and LoD ($r_s = .64; p < .001$). Finally, strong correlations were also found between the two video rating scores derived one month apart; QoC ($r_s = .87; p < .001$), FoBS ($r_s = .84; p < .001$), and LoD ($r_s = .82; p < .001$). [See Appendix C for an analysis of the construct validity of these performance measures when applied to a match situation, and an attempt to derive an overall measure of batting performance].

To examine the first aim of the study (assessing the effect of refractive blur across the two presentation conditions), each of the three dependent variables (QoC, FoBS, and LoD) were subjected to separate 2 (Presentation: live bowlers, projection-machine) x 4 (Blur: plano, +1.00, +2.00, +3.00) within-subject ANOVAs with repeated measures on both factors. To examine the study’s second aim (assessment of whether ball-velocity mediated performance with increasing levels of refractive blur), separate 2 (Ball-speed: medium-pace bowler, fast-pace bowler) x 4 (Blur: plano, +1.00, +2.00, +3.00) within-subject ANOVAs were conducted on the three performance measures using data derived from the seven participants who faced both the fast- and medium-paced bowlers. Alpha was set at .05 for all ANOVA testing. Post-hoc comparisons were conducted where significant main effects were revealed as a result of ANOVA testing; successive contrasts were used to examine changes across adjacent levels of blur, and paired t-tests were employed to test for differences across presentation or ball-velocity conditions at each level of blur. Violations of sphericity were corrected according to
the Greenhouse-Geisser method. Partial eta squared ($\eta_p^2$) values were computed for all analyses of variance to provide the proportion of effect + error variance attributable to each factor or combination of factors.

Table 3-1. Operational Definitions for Categorical Scores of Dependent Variables used to Assess Performance on Each Trial

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Score</th>
<th>Operational definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality of Contact</td>
<td>2</td>
<td>Ball contacts the bat face and travels in a direction consistent with the pre-contact plane of bat motion.</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Ball contacts the bat face but deflects in a direction inconsistent with the pre-contact plane of bat motion.</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>Ball does not make contact with the bat.</td>
</tr>
<tr>
<td>Forcefulness of bat-swing</td>
<td>2</td>
<td>Complete follow-through of bat swing after anticipated point of bat-ball contact.</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Incomplete follow-through of bat swing after anticipated point of bat-ball contact.</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>No follow-through of bat swing after anticipated point of bat-ball contact, or no attempt is made to hit the ball.</td>
</tr>
<tr>
<td>Likelihood of dismissal</td>
<td>0</td>
<td>No foreseeable chance of batter being dismissed.</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Ball is hit towards one of ten nominated fielding positions without the ball hitting the ground (chance of being caught), or ball does not hit bat and hits batter on the legs in front of the stumps (chance of being adjudicated leg-before-wicket).</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Ball hits the stumps being protected by the batter.</td>
</tr>
</tbody>
</table>
3.3 RESULTS

3.3.1 Live bowler vs. projection-machine

3.3.1.1 Quality of contact

The analysis of variance for QoC demonstrated a main effect for blur ($F(3,27) = 4.43, p < .05, \eta_p^2 = .33$; Figure 3.1a), due primarily to a significant decrease from the +2.00 to +3.00 blur condition ($p < .05$). No significant effect was found for presentation ($F(1,9) = 3.20, p = .11, \eta_p^2 = .26$), nor was there any interaction between presentation and blur ($F(3,27) = .52, p = .67, \eta_p^2 = .06$).

3.3.1.2 Forcefulness of bat-swing

A significant main effect was found for blur ($F(3,27) = 9.98, p < .001, \eta_p^2 = .53$; Figure 3.1b), due primarily to FoBS decreasing significantly across the +2.00 to +3.00 blur contrast ($p < .01$). There was no main effect for presentation ($F(1,9) = 1.21, p = .30, \eta_p^2 = .12$), but there was a significant interaction between presentation and blur ($F(3,27) = 4.50, p < .05, \eta_p^2 = .33$). For the plano blur condition only, FoBS against the live bowlers was significantly higher than for the projection-machine condition ($p < .05$).

3.3.1.3 Likelihood of dismissal

The examination for LoD failed to demonstrate any significant effects for blur ($F(1.49,13.44) = 1.92, p = .19, \eta_p^2 = .18$), presentation ($F(1,9) = 1.81, p = .21, \eta_p^2 = .17$), or an interaction between these two factors ($F(3,27) = 2.89, p = .054, \eta_p^2 = .24$; Figure 3.1c).
Figure 3.1. Batting performance in terms of (a) QoC, (b) FoBS, and (c) LoD, shown as a function of refractive blur and presentation condition. Significant differences are indicated between presentation conditions (*p < .05), for score differences collapsed across presentation conditions for adjacent blur contrasts (†p < .05), and for presentation-specific score differences across adjacent blur contrasts (Δp < .05, ΔΔp < .01). Data are displayed with standard error bars.
3.3.2 Fast vs. medium-paced ball-velocity

3.3.2.1 Quality of contact

The analysis of variance for QoC revealed significant main effects both for blur \(F(3,18) = 13.73, p < .001, \eta^2_p = .70\) and ball-velocity \(F(1,6) = 24.99, p < .01, \eta^2_p = .81\), along with a significant interaction between blur and ball-velocity \(F(3,18) = 5.71, p < .01, \eta^2_p = .49\); Figure 3.2a). In contrast to the medium-paced condition, QoC for fast-paced trials changed as a function of blur, with a significant decrease evident for the +1.00 to +2.00 blur contrast \(p < .05\).

3.3.2.2 Forcefulness of bat-swing

Main effects for FoBS were found for both blur \(F(3,18) = 13.24, p < .001, \eta^2_p = .69\); Figure 3.2b) and ball-velocity \(F(1,6) = 13.61, p < .05, \eta^2_p = .70\). Contrasts conducted across successive levels of blur revealed a significant change in FoBS only for the +2.00 to +3.00 blur contrast \(p < .01\), while the effect of ball-velocity was found to be due to significantly higher FoBS in the medium-pace condition. There was no significant interaction found between blur and ball-velocity \(F(3,18) = .26, p = .86, \eta^2_p = .04\).

3.3.2.3 Likelihood of dismissal

The analysis of variance for LoD demonstrated no significant main effects for blur \(F(3,18) = .10, p = .96, \eta^2_p = .02\), ball-velocity \(F(1,6) = .05, p = .84, \eta^2_p = .09\), or for the blur x ball-velocity interaction \(F(3,18) = .41, p = .75, \eta^2_p = .06\); Figure 3.2c).
Figure 3.2. Batting performance in terms of (a) QoC, (b) FoBS, and (c) LoD, shown as a function of refractive blur and ball-velocity. Significant differences are indicated between ball-velocity conditions for level of blur (*p < .05, **p < .01), for score differences collapsed across ball-velocity conditions for adjacent blur contrasts (†p < .05), and for ball-velocity specific score differences across adjacent blur contrasts (Δp < .05). Data are displayed with standard error bars.
3.4 DISCUSSION

The overall purpose of this study was to examine how refractive blur influences the execution of an interceptive striking task. Two particular aims were examined by skilled cricket batters attempting to strike balls delivered from either a bowling-machine, or live bowlers, while wearing contact lenses which induced four different levels of refractive blur. The first aim was to examine whether the resilience to refractive blur for batters facing a projection-machine (reported previously in Experiment I) extended to a situation facing live bowlers; the second aim was to determine whether ball velocity is a critical factor mediating the relationship between refractive blur and interceptive performance. In relation to the first aim it was hypothesised that if visual clarity was critical in facilitating performance when facing either a projection-machine or live bowlers, immediate decrements in performance would be evident with the introduction of blur. In relation to the second aim it was proposed that an increase in ball-velocity would necessitate movement initiation relatively earlier in ball-flight when the ball was relatively further from the batter, resulting in observable performance decrements at lower levels of blur.

3.4.1 The addition of advance kinematic information and the effect on performance resilience with refractive blur

Visual blur was found to have a similar effect on performance in each of the projection-machine and live bowler conditions. Consistent with the findings of Experiment I, +3.00 D of blur was required before there was any measurable decrease in performance when striking balls from the projection-machine. Live bowlers, providing the addition of advance (pre ball-flight) kinematic information, produced a similar pattern of performance, with blur needing to reach +3.00D before any measurable changes in batting performance were apparent. Across both presentation conditions, interceptive performance retained a high level of resistance to refractive blur; a VA of 6/49 (equivalence) was required to reduce
performance, approaching the 6/60 level that constitutes legal blindness in many countries (6/60; Department of Family and Community Services, 1996; Farrall, 1991; Grosvenor, 1996).

Commensurate decreases in QoC and FoBS were found with the highest level of blur for both presentation conditions. Despite decreasing their forcefulness of bat-swing and accordingly lessening the temporal constraints of the task, the lower level of QoC indicated that critical visual information was not available in the +3.00 blur condition to support accurate interception. Across both presentation modalities, no adjustments of execution were apparent to compensate for the lesser levels of blur (+1.00 and +2.00D); all three performance measures remained the same as for the plano blur level, despite a demonstrable reduction in visual clarity.

A particular point of interest here was whether the availability of pre ball-flight information in the live bowler condition enhanced performance over and above that evident in the projection-machine condition. By drawing comparison at the level of habitual vision (plano) it was apparent that facing a bowler did not facilitate enhanced QoC (cf. Gibson & Adams, 1989), but that batters demonstrate significantly greater FoBS than for the equivalent projection-machine trials (see Figure 3.1b). This enhanced FoBS was at no expense to QoC or LoD – consequently, with clear vision, the chances of achieving the task goal of scoring runs without dismissal were enhanced when pre-release information was available from the bowlers. As has been shown in previous studies, the availability of advance kinematic information appears to provide a distinct advantage for skilled sportspeople who are attuned/sensitive to this information (see also Shim et al., 2005). The significant advantage on the FoBS measure for the live bowler presentation condition diminished, however, with the introduction of blur. Performance measures for the bowler condition mirror those for the projection-machine condition when experiencing both the +1.00 and +2.00 levels of blur. This raises an interesting question: whether blur has attenuated the batter’s ability to use this advance information to facilitate interceptive performance. Alternate protocols such as the
well-established temporal occlusion paradigm will be useful to examine whether blur adversely affects a batter’s ability to anticipate acts and to effectively couple movements to pre ball-flight information.

### 3.4.2 The effect of ball-velocity on resilience to refractive blur

The increased temporal demands of faster ball-velocity resulted, as hypothesised, in an earlier blur-induced decrease in interceptive performance. When batting with habitual (plano) vision against the fast-paced bowler, batters appeared to reduce the temporal demands of the task by decreasing FoBS and, as a result, maintained similar levels of QoC and LoD to those achieved against the medium-paced bowlers. This batting strategy, shown by FoBS, may have reflected the batter using alternate means to ‘score runs’, for example by using the increased ball-velocity to more effectively ‘guide’ the ball into desired locations (rather than to aggressively hit it). Despite decreasing the forcefulness of bat-swing against the faster bowler, the quality of bat-ball contact still decreased for the fast-paced trials at a lower level of refractive blur (+2.00D) than was evident against the medium-pace bowlers (+3.00). FoBS was consistently greater for the medium-paced ball-velocity condition, yet most importantly the pattern of change as a function of blur (see Figure 3.2b) was remarkably similar. Participants were willing, up to a point (+3.00D), to maintain FoBS at the expense of quality of bat-ball contact, irrespective of ball velocity. This is an important finding as it suggests that batters were not required to modify their batting strategy to maintain performance with more moderate levels of visual blur.

The fast-paced trials in this study were within the upper limit of temporal demands experienced in a sport such as cricket: the mean ball-velocity of 123.9 kph (as measured in our lab and excluding planned ‘slower-ball’ trials) was similar to that which is commonly experienced in elite international matches. Despite the extraordinary demands of this task, there exists within our sample a range of refractive blur where there was no apparent
decrease in batting performance. Batting performance in our sample, particularly as evidenced by QoC, demonstrated no significant decrease with the introduction of considerable visual blur (+1.00D or VA ≈6/11). This finding suggests that clear VA is not typically a constraining factor for interceptive performance, even at the temporal limits required of the interceptive task of cricket batting. Furthermore, it is consistent with the proposal that online interceptive actions (mediated by the dorsal visual pathway) may not be affected by lower levels of visual blur, as this pathway sources specific visual information from the eye that is highly sensitive to movement and contrast, but less so to clarity and colour.

Resilience of interception to visual blur has been demonstrated even when facing a fast in-situ bowler, though this protocol has not examined the effect of blur on potential deviations in ball-flight either in the air (swing) or following ball-bounce (vertical and lateral deviation) – indeed it would be most difficult to do so when comparing a projection-machine and in-situ bowlers in a controlled experiment. It is conceivable that these factors may move the ball in a less predictable manner, and that blur may limit a batter’s ability to effectively detect these deviations. Alternately, if blur has not, to a considerable point, influenced the ability of participants to sufficiently gather the visual information necessary for successful interception, then it may be reasonable to expect that this same information would be used to detect more unexpected movements of the ball. Future studies may look to examine the effect of blur on these more unexpected deviations in ball-trajectory.

### 3.4.3 The role of basic visual function (including VA) in sporting performance

A small subset of vision specialists advocate the viewpoint that enhancing basic visual skills to above-normal levels may result in superior sporting performance. This proposition rests upon the assumption that these general visual skills must normally be a limitation to performance (Abernethy & Wood, 2001), and advocates the use of generalised visual training programs as a means of bringing about improvements in performance. From the results of this
and from previous studies, it is difficult to foresee that VA improved beyond habitual vision would improve performance, especially given the evidence that poorer than normal VA does not result in any observable decrease in performance. This perspective should not be confused with the more commonly held viewpoint that normal visual function is ideal for optimal sporting performance, with any decrease in visual function ideally corrected. From this perspective only those with significant visual deficits require training or correction. The findings from this study do not suggest that full visual correction should not be provided for sporting tasks, but rather indicate that poor VA may not be a limitation to performance. Indeed the neurophysiological underpinnings of the dorsal visual pathway suggest that there is good reason why clear vision should not be a necessity for interceptive performance. However one must keep in mind those sport-relevant (ventrally-mediated) tasks which may require fine resolution which have not been addressed in this investigation: the detection of fine manipulations of the bowler’s fingers holding the ball, reading a scoreboard from a distance, or particular elements of outfielding (for a more detailed consideration of the interaction between the two visual pathways in sport, see van der Kamp et al., 2008). Given the findings of this study though, anecdotes of successful athletes competing with inferior visual skills should not be such a surprise.

3.4.4 Future considerations

The three reported dependent variables provide a useful means of evaluating the participants’ ability to accomplish a specific task aim. This approach of using multiple measures of batting performance has resulted in a less subjective system than a coach rating (Experiment I), and has expanded on the simple QoC measure of interception (Müller & Abernethy, 2006a, 2008); thereby providing a more thorough assessment of the participants’ ability to achieve the task goal. The additional measures of FoBS and LoD have facilitated the examination of underlying causes for changes in performance, and provided a better
understanding of behaviour emergent from the manipulation of visual information. A more sensitive approach for future examinations may be to move beyond simple categorical measures of interceptive performance, and to test for kinematic modifications resulting from alterations in visual clarity. Although this seems to be a logical and somewhat simple step, the gamut of interceptive actions possible in a task like cricket batting make it a considerable challenge to control for the varied types of responses that may occur across the different experimental conditions. Modern technology allows for tools such as accelerometers and gyroscopes to examine the torque with which the bat is swung, high-speed cameras and force plates can record the time-course of movements, and vibration sensors may evaluate the quality of bat-ball contact. The validation of these tools may provide greater insights into how performance execution may change with manipulations such as those used in this study.

Moreover, Land and McLeod (2000) have demonstrated that an expert cricket batter may possess different visual search patterns to non-experts when facing a projection-machine. In identifying critical ball-flight information as early as possible, experts make an earlier predictive eye movement forward to anticipate the position of ball-bounce. If this key eye movement or ‘saccade’ is indeed a reflection of critical visual information being recognised, one may expect the saccade to occur later if there has been a delay in identification. The accurate recording of visual search behaviours hence provides another potentially fruitful means of detecting any change in performance that may occur across manipulations of visual function such as those used in this study.

It is apparent at this point that clear vision may not be a necessity for success in cricket batting; however the implicit assumption in this, and for the previous study, has been that clear vision as a result is not a requirement to become skilled in this task. It is conceivable that informative sources which underpin the development of motor expertise may be different to those relied on after sufficient skill has been developed. If this were to be the case, clear vision may prove be a limitation to the development of interceptive skill. Future studies may
look to elaborate on the role of vision in the acquisition and development of motor skills (e.g., Bennett et al., 1996), rather than simply focusing on the execution of previously acquired ones. The introduction of a low level of visual blur, rather than being a hindrance, may potentially be useful as a training tool for modifying skilled behaviour in interceptive tasks. Extensive research has demonstrated that an external focus of attention may be beneficial for skilled performance (Beilock, Carr, MacMahon, & Starkes, 2002; Wulf, 2007), with internalisation resulting in re-investment of what should be well-learned habitual skills (Beilock & Carr, 2001; Masters & Maxwell, 2004). In a highly technical task like a golf swing or cricket shot, an attentional focus on execution of the task may be detrimental to performance. This can occur particularly as a result of prolonged periods of poor performance (Masters, 2008), resulting in an internal focus of attention to correct what may be perceived to be kinematic errors in movement execution. In a training context, distraction from internalisation using dual-task (Masters, 1992) and analogy (Liao & Masters, 2001) training techniques may be of benefit. Although it is clearly speculation at this stage, refractive blur may provide a safe and effective means of altering focus of attention in a training context. It is apparent that low levels of blur in the vicinity of +1.00D are noticeable and indeed objectionable (Atchison, Fisher, Pedersen, & Ridall, 2005; Ciuffreda et al., 2006), yet the results presented here suggest that interceptive performance is not adversely affected. Anecdotal reports from participants suggest that blurred contact lenses may cause them to focus more strongly on the release point of the ball to search for important visual information as early as possible. If participants perceive the task as being more difficult, such a manipulation may result in modified attentional behaviour. Further work examining focus of attention and visual search appears warranted to assess the potential training efficacy of such an approach.
3.5 CONCLUSIONS

In the case of a cricket batter hitting a ball in a contextually rich environment, it is apparent that visual clarity is not a limiting factor to interceptive performance. The present study has demonstrated that this effect holds true both when pre ball-flight information is available, and when ball speed is increased towards the upper limits of velocities experienced in the sport of cricket. Neurophysiological evidence suggests that the dorsal ‘vision-for-action’ pathway is not reliant on fine visual acuity, and the findings of this study are consistent with the proposal that dorsally-mediated actions should not be affected by low levels of visual blur. Accordingly it is explicable that players, even in some of the most temporally-demanding striking sports, may be able to successfully compete with below-normal habitual vision. Future work may examine the appropriateness of using blur to modify attentional behaviour in interceptive tasks in a way that might facilitate the effective acquisition of hitting skills.
PHASE II

BLUR AND ANTICIPATION
Evidence has been presented to suggest that even highly demanding interceptive tasks may possess some degree of resilience to refractive blur. This holds true even when important advance information is present, though some evidence was found in Experiment II to suggest that an advantage provided by pre-ball-flight information may dissipate with the introduction of blur. More specifically, batters in the plano condition produced significantly greater forcefulness in their bat-swings when facing in-situ bowlers (compared to facing a bowling-machine); a batting strategy which requires greater temporal precision, but is more likely to result in runs being scored. This significant advantage when facing the in-situ bowlers was not present when blur was introduced.

This second experimental phase seeks to examine the direct effect of blur on anticipation in the natural setting. At this stage though, there is no clear evidence for how specific an anticipatory response must be to accurately reflect the conditions which occur in the natural environment. Blurring only an uncoupled (and hence ventrally-based) response may fail to truly represent the effect that blur would have on anticipation in a naturally-coupled response. As a result, Experiment III seeks to first establish the conditions most likely to represent a real-world movement-based response, and Experiment IV then looks to examine the effect of blur on this task.
CHAPTER 4

ACTION SPECIFICITY INCREASES ANTICIPATORY PERFORMANCE AND THE EXPERT ADVANTAGE IN NATURAL INTERCEPTIVE TASKS

‘For a successful technology, reality must take precedence over public relations, for nature cannot be fooled.’

Richard Feynman
4.1 INTRODUCTION

The examination of human motor expertise has historically involved experimental designs that fall short of accurately representing tasks as they occur in the natural environment. Research has commonly relied on verbal responses or simplified movements to provide insights to the perceptual processes underpinning skilled movement. This dissociation of perception and action has provided experimental convenience, yet has been problematic in breaking the coupling between what are likely to be inextricably linked processes. Gibson (1979) highlighted the interdependency of perception and action in natural tasks, proposing that any protocol separating the two may fall short of understanding the true essence of skilled performance. Support for this position has been provided by Bootsma (1989; Bootsma & Wieringen, 1990) who demonstrated that motor actions in coincidence timing are produced as a result of constant interactions between perceptual information and motor control. Oudejans, Michaels, van Dort and Frissen (1996) established the importance of the link between perception and action in decision-making by examining the road crossing behaviour of pedestrians. In determining the size of gaps between cars which allowed them to safely cross, more accurate choices were made by those participants who were walking while making these judgements. In this sense the addition of movement enhances perceptual accuracy; conversely, the removal of action from a protocol may result in important elements of expertise being eliminated.

Clearly sufficient reason exists for tasks examining motor control to accurately replicate the natural conditions, yet this ideal has often been superseded by a desire for tight experimental control and administrative convenience (Abernethy et al., 1993). The partitioning of perception and action has enabled rigorous regulation of experimental tasks but, as a consequence, has reduced the degree to which the tasks accurately reflect naturally occurring conditions. A representative task design (Brunswick, 1956) is a protocol which
closely replicates the conditions occurring in the natural environment. More recently referred to within some realms of cognitive psychology as *ecological validity* (Neisser, 1976), this concept seeks to ensure that the critical sources of information relied on in the natural setting are available in the corresponding experimental representation. This necessitates not only an accurate depiction of the external sources of information, but also of the performer’s own response, to ensure that critical perception-action links remain intact.

The dual-pathway theory of vision advocated by Milner and Goodale (Goodale et al., 1991; Milner & Goodale, 1995) is often cited as neuropsychological evidence for preserving the perception-action relationship inherent in naturally-coupled movement tasks. Within this framework visual input reaching the neural cortex is processed along two parallel pathways according to how that information is intended to be used. The ventral ‘vision-for-perception’ pathway is highly conscious and is used to produce a perceptual interpretation of our surrounds. In contrast the evolutionarily more primitive dorsal ‘vision-for-action’ pathway appears to sub-consciously produce online visually-controlled movements. Recently, van der Kamp, Rivas, van Doorn and Savelsbergh (2008) have argued that most existing studies of motor expertise have probed the response of the ventral visual pathway, not the dorsal pathway most likely to be relied on in the natural setting. They propose that the exclusion of realistic movement responses from many of the experimental paradigms used to examine the putative characteristics of expertise has rendered the existing knowledge limited and somewhat biased.

An important subset of research into motor expertise has involved the examination of performance in fast ball sports, providing insights into the skilled execution of interception in a highly time-stressed environment. This body of literature has consistently demonstrated the enhanced ability of skilled performers to identify key information from the movement patterns of opponents, enabling more time to execute an appropriate response (Abernethy & Russell, 1987a; Jones & Miles, 1978; Shim et al., 2005). This expert advantage in *anticipatory skill* is
based on a capacity to more accurately interpret the kinematic information present in an opponent’s movements prior to the availability of any ball-flight information (Abernethy et al., 2001). A valid criticism of this work has been the dissociation of perception and action, with many paradigms relying on simple verbal or pen-and-paper responses. The expert advantage remains for studies incorporating simplified movements in their testing paradigms (e.g., Savelsbergh et al., 2002; Williams et al., 1995), although these simplified or representative movements typically fail to provide an opportunity for actual interception. Minimal work has been performed to examine if, and to what degree, movement may enhance the expert advantage in anticipatory skill. Farrow and Abernethy (2003) studied the ability of expert and novice tennis players to predict the direction of tennis serves in-situ using a coupled and uncoupled response. Coupling proved advantageous with, but not prior to ball-flight, leading the authors to propose the existence of a dedicated processor for interceptive movements that is reliant on ball-flight information.

The incorporation of movement into experimental paradigms is often performed under the premise of eliciting a response of the dorsal pathway (van der Kamp et al., 2008) yet recent evidence suggests that without acting to intercept, this may not necessarily be the case. Króliczak, Heard, Goodale & Gregory (2006) demonstrated that control of a movement like pointing – which is clearly reliant on visual information – depends on ventral processing in much the same way as does a verbal response. An online motor response with intention to intercept another object was required before the dorsal system was engaged for online visual-motor control. Further evidence using fMRI demonstrated that real and mock (shadowed) interceptive actions are mediated by different areas of neural processing (Króliczak, Cavina-Pratesi, Goodman, & Culham, 2007). The implication for extant research into anticipation is clear; an intention to intercept appears necessary to elicit a dorsal pathway response, and simplified responses that are not interceptive may fall short of testing the desired visual-motor pathway.
In seeking to impose tight experimental control, the predominant use of video simulations in studies of motor expertise may have inadvertently limited the capability of researchers to accurately elicit a true reflection of skill. Notwithstanding the limitations in stereoscopic information inherent in video displays, if the opportunity does not exist to intercept an object, then a true dorsal system response may not be possible irrespective of the degree of coupling in the response. Mann, Williams, Ward & Janelle (2007), in a meta-analysis of perceptual-cognitive expertise, reported a systematic relationship between display fidelity and perceptual skill, with increases in effect size apparent as the mode of stimulus presentation becomes more representative of the “real-world” task. Shim et al. (2005) demonstrated this experimentally, with expert and novice tennis players moving in the predicted direction of strokes intimated by a point-light display, a video display, and live models. They found that an increase in display fidelity did increase performance in expert observers; however it also tended to decrease the performance of novice participants.

Increasing action specificity may be expected to enhance anticipatory performance when observing an in-situ display; however this may not be the case when observing a video simulation. The contrived nature of video simulations may fail to invoke responses of the visual-motor pathway that reflect those used in the natural setting. Indeed there exists limited indirect evidence to support this supposition; while Farrow and Abernethy (2003) demonstrated that an increase in perception-action coupling enhanced anticipatory performance when observing in-situ actors, Ranganathan and Carlton (2007) found a decrease in performance with enhanced coupling when participants observed a virtual simulation. For this reason it is of interest to determine how increases in perception-action coupling alter anticipatory performance across changes in display fidelity.

In the present study, a time-stressed interceptive skill was examined for which the detection of early information is essential - the task of cricket batting - where a player must attempt to intercept an oncoming ball bowled by an opposing player. The temporal occlusion
paradigm was used to test skilled and novice batters’ ability to predict, at specific points in the event sequence, the direction of balls bowled towards them under conditions in which the display information was presented either in-situ or via a video simulation. Accurate in-situ occlusion was produced using event-related signalling of liquid crystal occlusion goggles, improving on the temporal precision used in earlier studies. Across both the in-situ and video simulation display conditions, participants predicted the direction of the oncoming ball for a range of response conditions across which the degree of coupling between perception and action was systematically manipulated. The primary purpose of the study was to determine whether skilled participants, when observing an in-situ display, would demonstrate systematic improvements in their ability to predict the ball direction as the specificity of the action was enhanced. It was expected, in light of the findings of Króliczak et al. (2006), that the opportunity to intercept the ball would improve skilled performance, and the expert advantage, above and beyond that of an identical representative movement where bat-ball interception was not possible. The secondary purpose of the study was to examine for specificity-based changes in anticipation when observing a video simulation of the same display. The proposed inability of the simulated display to elicit responses of the visual-motor pathway relied on in the natural setting provided an expectation that enhancements in action specificity when responding to a video display would produce no corresponding improvement in anticipation.

4.2 METHODS

4.2.1 Participants

A total of 12 skilled and 11 novice male participants voluntarily took part in the study. The skilled group consisted of male cricket batters (mean age 27.2 ± 6.4 years) with an average of 8.6 ± 3.8 years of senior and 7.0 ± 2.4 years of junior playing experience who, at the time of
the study, were competing in their respective first-grade regional competitions. Members of the novice group (mean age 34.5 ± 7.8 years) were males with no senior cricket experience and an average 0.7 ± 1.4 years of junior experience. All participants gave written informed consent prior to taking part in the study.

4.2.2 Experimental Task and Presentation of Test Stimuli

A two-choice prediction task was designed in which participants were required to judge the direction of an approaching ball projected by an opposing actor (bowler). The task represented a cricket batter facing a bowler where the batter would typically try to hit the ball bowled towards them. The task therefore necessitated the batter making a judgment of ball direction relative to their usual stance position near the centre stump.1

The display condition comparison necessitated development of separate in-situ and video simulation conditions to probe the influence of presentation fidelity on the level of perception-action coupling in the response.

4.2.2.1 In-situ display

Three actors were employed to bowl in the study (one right-handed and two left-handed bowlers each with an approximate bowling speed 90 kph). The actors followed a script of intended ball direction for all trials, with all except those trials where the ball was projected directly towards the centre stump being included in the final analysis. Actors correctly delivered 92% of trials as specified to the off or leg side of the centre stump, with post-hoc analysis of all deliveries demonstrating no difference in the number of deliveries presented to either side (off- vs. leg-side = 48.9 vs. 46.7%, t(23) = 1.61, p > .05). A speed gun (Stalker ATS

1 In the sport of cricket a batter attempts to protect three stumps from being hit by a ball, with the batter standing to one side of the centre stump. Balls bowled or delivered by the bowler towards the batter’s side of the centre stump are said to be directed towards the leg side whilst balls towards the opposite side are towards the off side.
sports radar, USA) was used to monitor the consistency of ball speed for each actor across the progression of testing sessions.

All testing took place in an indoor cricket testing facility with markings replicating the dimensions, and an artificial turf surface simulating the conditions, of a synthetic cricket pitch. Force plates (Kistler 9287BA, Kistler Instrumente AG, Switzerland) embedded in the ground enabled the 250 Hz registration of ground reaction forces produced by actors in their penultimate foot-strike prior to releasing the ball.

![Figure 4.1. A participant wearing the PLATO occlusion goggles](image)

Participants stood at their batting position ≈17.7 m from where actors delivered the ball (replicating the distance that a batter would stand from a bowler in a match). Participants wore liquid crystal goggles (Figure 4.1; PLATO Model P-1, Translucent Technologies Inc, Canada) that enabled the experimenters to occlude the vision of participants at specific time points in the bowler’s action sequence. Occlusion goggles were triggered by an actor-specific computer-delayed signal initiated by the registration, by a force plate, of each actor’s approach into their delivery stride (for a full description, see Appendix A). A parallel signal was sent to an LED positioned behind the participant to register the moment of occlusion. Pilot testing
demonstrated highly repeatable times for the delivery action in cricket bowling, enabling occlusion to occur within a 50 ms window prior to a desired moment in time. This degree of temporal accuracy is similar to that achievable in video simulation studies, and compares very favourably to the precision possible in previous in-situ studies (approximately 300 ms; cf. Farrow & Abernethy, 2003; Muller & Abernethy, 2006).

Three occlusion times relative to ball release were chosen to be presented to participants: t1 (0 ms), t2 (50 ms) and t3 (no occlusion). The t1 occlusion condition was designed to examine predictions based purely on kinematic information from the actor’s body prior to their release of the ball. The t2 occlusion condition enabled the addition of up to 50 ms of ball-flight after release by the bowler, while the t3 condition ensured all ball-flight information was available to participants.

4.2.2.2 Video simulation display

Prior to testing, the same three actors who participated in the in-situ display condition were filmed to produce a video-based test stimulus. Footage was recorded from a front-on position using a digital video camera (Sony HDR-FX1E, Sony Corporation, Japan) located at the participant’s position of stance. The camera was located 1.5 m above the ground to represent the position of the participant’s head in the batting stance. For each trial the actor commenced the delivery using their standard approach to the bowling crease with approximately 35 trials being recorded for each actor, capturing a range of trials that were equivalent to the type of deliveries and directional variability present for the in-situ condition.

All video clips were digitised and edited (Pinnacle Studio 8, Pinnacle Systems Inc, USA) to create practice and test stimuli for the video simulation. Three occlusion conditions were chosen relative to ball release to reflect those used in the live display; t1 (0 ms), t2 (80 ms), and t3 (no occlusion). Three sets of practice films each comprising 6 clips, and three test films each comprising 30 clips were produced (presenting, respectively, two and 10 trials from each
Equal proportions of the three occlusion times and two resultant directions (off- or leg-side) were included within each set and mirrored the trial compositions presented for the in-situ display condition.

It is apparent that the t2 occlusion time does not exactly match across the in-situ and video simulation conditions (in-situ vs. video = 50 vs. 80 ms). For the in-situ condition, the 50 ms time window was chosen to be most desirable (as a result of pilot testing) to best test for skill based differences in performance. In seeking to match this occlusion time in the video simulation condition, the second frame following ball-release for a 25 Hz video display will display 40-80 ms of ball-flight. This was chosen as the more appropriate occlusion point (cf. 0-40 ms for the first frame after ball-release) to best match the 50 ms occlusion time for the in-situ condition. It was expected, as a result of this inability to exactly match occlusion time, that the extra vision of ball-flight available at t2 would facilitate enhanced performance in the video simulation condition. There was no expectation that this would be a problem at the t1 occlusion point.

### 4.2.3 Procedure and Design

Four response conditions with different levels of action specificity were used:

(i). Verbal (PA1) – participants were required to verbalise the direction of the ball as either ‘off’ or ‘leg’ side with no movement permitted.

(ii). Foot movement (PA2) – participants were required to move their leading (front) foot towards the direction of the ball with no accompanying upper-body engagement, simulating the lower-body movements a cricket batter would typically produce.

(iii). Shadow batting (PA3) – participants were required to produce a real-time ‘shadowed’ response without the use of a bat, imitating the shot that would be fashioned engaging both the upper- and lower-body.
(iv). Batting (PA4) – participants were required to try to hit the ball with the use of a bat, again engaging the upper- and lower-body in precisely the same manner as they would on-field.

The progression from condition PA1 to PA4 involved a systematic increase in the extent to which the task demands of actual cricket batting were replicated, with each condition (when compared to its predecessor) incorporating a greater degree of action, and hence an increased degree of coupling between perception and action. The presentation of the four coupling conditions was counter-balanced to avoid order effects.

Participants took part in both the in-situ and video simulation display conditions, with the order of presentation counterbalanced across participants. Testing took approximately 90 mins in total per participant.

4.2.3.1 In-situ display design

A 2 (Group: skilled, novice) x 4 (Coupling: PA1, PA2, PA3, PA4) x 3 (Occlusion Point: t1, t2, t3) mixed-factorial design was used for the in-situ display stimuli. Following a 12-trial period of familiarisation with the occlusion goggles, four blocks of test trials were presented, one for each of the coupling conditions. Within each block 6 practice and 30 test trials were presented (2 and 10 from each actor/bowler respectively), with approximately 10 s between trials. Equal distributions of occlusion points and delivery directions were presented across all trials in a randomly sequenced manner. Participants and actors were given a 3 min break between blocks.

In the interests of safety, a net was suspended from a supporting beam positioned 0.8 m in front of participants for the PA1-PA3 coupling conditions; the net put in place to eliminate the possibility of participants being struck by the ball (Figure 4.2). Thin protective netting was used to minimise any obscuration of vision in these conditions. The net was retracted in the PA4 condition to provide participants with an opportunity to engage in bat-ball interception.
All participants wore full standard cricket batting protective equipment, and faced a purpose-made ball designed to act like a cricket ball, but with softer properties (Kookaburra Supa Soft with factory lowered seam, Kookaburra Sport Pty. Ltd., Australia). Participants were instructed that all responses were required to be made in time for effective interception (i.e., by the time the ball hit the net, or when the ball reached this equivalent position with the net retracted in condition PA4).

Figure 4.2. Demonstration of a participant standing behind the protective net from (a) front-on view, and (b) behind participant.
4.2.3.2 Video simulation display design

We used a 2 (Group: skilled, novice) x 3 (Coupling: PA1, PA2, PA3) x 3 (Occlusion point: t1, t2, t3) mixed-factorial design for the video display stimuli. The fourth coupling condition involving actual interception of ball with bat was not possible for this display and hence excluded from the video simulation condition. Sets of practice and trial clips were presented in a balanced manner for the three coupling conditions. A 3 min break was permitted between blocks with a 5 s interval between trials.

All video footage was back-projected (NEC LT260 projector, Japan) onto a 3 x 3 m screen (Figure 4.3), with participants standing 3.4 m from the screen such that the bowler at delivery subtended an identical visual angle to that subtended in the in-situ display condition. Participants were again instructed that all responses were to be made in real-time during the video display (i.e., by the time that the ball would have reached the participant).

Figure 4.3. Projection screen used to present video simulation display
4.2.4 Analysis of Data

Performance in each condition was measured by response accuracy (RA), determined as the percentage of deliveries where the dichotomous differentiation of the direction of the response (off or leg) matched that of the ball (off or leg). Footage from a digital video camera (Sony HDR-FX1E, Sony Corporation, Japan) placed at an elevated position directly behind the bowler’s approach was viewed by a trained observer to determine both the direction of the ball and, for coupling conditions PA2 - 4, the direction of the response of the participant. Ball direction was judged according to the direction of the ball relative to the centre stump (i.e., off- or leg-side), with those trials where the ball was judged to have been directed at the centre stump (rather than to either side) being excluded from all analyses. Participant responses were judged simply according to whether the movement of the leading foot (PA2), the plane of motion of the hands (PA3), or the plane of motion of the bat-swing (PA4) was directed towards the off- or leg-side of the centre stump. All verbal responses (either ‘off’ or ‘leg’; PA1) were recorded by a research assistant at the time of testing. Trials where no occlusion took place (occlusion point t3) were included in the protocol even though the data were not critical for any of our analyses; they were put in place to ensure that participants maintained an expectation that interception may occur on any given trial. We were concerned that if all trials were occluded, participants may be more likely to disengage the perceptual-motor system and produce simply perceptual-cognitive responses. Hence the data for t3 are not presented.

Data for RA underwent an arcsine transformation before being subject to statistical analysis. In light of the incongruencies of information from the absence (t1) and presence (t2) of confirmatory ball-flight and considering their different response characteristics (Farrow & Abernethy, 2003), it was considered more appropriate to analyse the t1 and t2 data separately (see Jackson, 2003). The presence of confirmatory ball-flight information may result in statistically significant effects that are of no relevance to the principal interest in anticipation
(judgements based exclusively on pre ball-flight information). For this reason, an analysis using separate temporal conditions was conducted.

Data for the in-situ display condition were analysed by factorial 2 (Group) x 4 (Coupling) ANOVAs with repeated measures on the second factor at both t1 and t2, with video display data subject to comparable 2 (Group) x 3 (Coupling) ANOVAs with repeated measures on the second factor also at t1 and t2. Further, 2 (Group) x 2 (Display) x 3 (Coupling) ANOVAs with repeated measures on the last two factors were used at t1 and t2 to compare common coupling conditions (PA1-3) across the in-situ and video simulation display conditions. One of the skilled participants took part in the in-situ, but not the video simulation conditions - their data were included in the analyses for which it was available. Successive contrasts were used to test the hypothesis that skilled participants would increase their RA with increases in perception-action coupling. Planned t-tests examined whether skilled participants performed better than their novice counterparts for each coupling condition, and whether performance was above the 50% chance level that could be expected of guessing. Alpha was set at .05 for all testing, with appropriate checks performed to ensure no violations against the assumption of sphericity. Partial eta squared ($\eta_p^2$) values were computed for all analyses of variance to provide the proportion of the effect + error variance that was attributable to each factor or combination of factors.
4.3 RESULTS

4.3.1 In-situ Display – 4 Coupling Conditions

The analysis of variance for the t1 occlusion point in the in-situ display condition revealed a significant main effect for group \( (F(1,21) = 9.51, p < .01, \eta_p^2 = .31) \) with skilled participants \( (M = 60.0\%, SE = 1.7) \) performing better than novices \( (M = 51.7\%, SE = 2.3) \). No main effect of coupling was evident \( (F(3,63) = 1.76, p = .16, \eta_p^2 = .077) \), however there was a significant interaction between coupling and group \( (F(3,63) = 4.35, p < .01, \eta_p^2 = .17; \text{Figure 4.4a}) \). Skilled participants improved RA as a function of coupling, with significant improvements across the PA1 to PA2 and PA3 to PA4 successive contrasts (both \( ps < .05 \)). Novice participants demonstrated no such changes across any of the successive comparisons for perception-action coupling, with their RA remaining at chance levels for all conditions.

The analysis of variance for the t2 occlusion point revealed a significant main effect for group \( (F(1,21) = 12.56, p < .01, \eta_p^2 = .37) \) with skilled participants \( (M = 86.3\%, SE = 2.7) \) outperforming novices \( (M = 74.6\%, SE = 2.7) \). No main effect of coupling was evident \( (F(3,63) = 1.30, p = .28, \eta_p^2 = .058) \), however again there was a significant group x coupling interaction \( (F(3,63) = 4.00, p < .05, \eta_p^2 = .16; \text{Figure 4.4b}) \). Successive contrasts revealed a significant increase in skilled RA across the PA2 to PA3 comparison \( (p < .05) \), with no corresponding changes for novice participants across any of the coupling conditions.
Figure 4.4. Response accuracy for the in-situ display condition as a function of perception-action coupling and skill level for occlusion conditions t1 (top panel, a) and t2 (lower panel, b). Broken line indicates 50% level achievable through guessing. At occlusion point t1 skilled participants perform above chance guessing levels in the PA2, PA3, (both ps < .05) and PA4 conditions (p < .001), with novice RA not different to 50% for all four coupling conditions. At t2 all data points for both skilled and novice participants are significantly greater than the 50% chance level (all ps < .001). Significant differences are indicated in skilled-novice comparison for each coupling condition (* p < .05, ** p < .01, *** p < .001), and across successive coupling conditions for skilled participants († p < .05; no significant differences evident across successive conditions for novice participants). Data are displayed with standard error bars.
4.3.2 Video Simulation Display – 3 Coupling Conditions

The analysis of variance for trials occluded at the t1 occlusion point in the video display revealed no significant main effects for group \((F(1,20) = .616, p = .44, \eta^2_p = .030)\) or coupling \((F(2,40) = 1.10, p = .34, \eta^2_p = .052)\), plus no interaction between these two factors \((F(2,40) = .474, p = .63, \eta^2_p = .023; \text{Figure 4.5a})\). Similarly, for those trials occluded at the t2 occlusion point there were no significant main effects observed for the factors of group \((F(1,20) = .127, p = .73, \eta^2_p = .006)\) and coupling \((F(2,40) = 1.01, p = .37, \eta^2_p = .048)\), and no interaction between these two \((F(2,40) = 2.319, p = .11, \eta^2_p = .10; \text{Figure 4.5b})\).

4.3.3 In-situ vs. Video Simulation Display – 3 Coupling Conditions

The analysis of variance for the t1 occlusion point comparing performance across the in-situ and video simulation display conditions failed to find any significant main effects for group \((F(1,20) = .030, p = .87, \eta^2_p = .001)\), coupling \((F(2,40) = .042, p = .96, \eta^2_p = .002)\), and display \((F(1,20) = .54, p = .47, \eta^2_p = .026)\), or for any higher order interactions.

The analysis of variance for the t2 occlusion point revealed a significant main effect for display \((F(1,20) = 8.45, p < .01, \eta^2_p = .30)\), with performance when observing the video simulation display \((M = 86.2\%, SE = 1.4)\) significantly better than that for the in-situ bowlers \((M = 79.4\%, SE = 1.7)\). No main effects were evident for group \((F(1,20) = 3.33, p = .083, \eta^2_p = .14)\) or coupling \((F(2,40) = 1.73, p = .19, \eta^2_p = .079)\). The group x display x coupling interaction \((F(2,40) = 7.70, p < .01, \eta^2_p = .28)\) was the only significant higher order effect. Skilled (Figure 4.4b) but not novice (Figure 4.5b) participants improved RA when observing the in-situ but not video simulation displays as coupling was enhanced.
Figure 4.5. Response accuracy for the video simulation condition as a function of perception-action coupling and skill level for occlusion conditions t1 (top panel, a) and t2 (lower panel, b). Broken line indicates 50% level achievable through guessing. At occlusion point t1 skilled and novice participants both perform above chance guessing levels for PA3 only (skilled p < .01, novice p < .05) whilst at t2 all data points are significantly greater than 50% (all ps < .001). No skilled-novice differences were evident for any of the coupling conditions, nor any differences in successive contrasts for skilled or novice participants. Data are displayed with standard error bars.
4.4 DISCUSSION

This study examined whether the anticipatory performance of skilled and novice cricket batters would change as a result of increased action specificity under in-situ and video simulation display conditions. Based on previous findings we expected to find increases in anticipation commensurate with increases in perception-action coupling; however we expected to find this effect for the in-situ but not the video simulation display. In particular we expected to find a significant improvement when skilled participants were provided with an opportunity to intercept an approaching target. Temporal occlusion was used to probe perceptual skill, with an existing technique modified to permit more precise control of the timing of in-situ occlusion.

Consistent with the hypotheses, significant increases in skilled but not novice anticipation were found for the in-situ condition, with the anticipatory performance of the skilled players progressively increasing as the required action more closely replicated the movement produced in the natural environment. With the availability of only pre ball-flight information, skilled batters demonstrated significant improvements in RA for simple movement responses (PA2) over verbal responses (PA1); and for actual interceptive movements (PA4) over a simulated equivalent (PA3). In the absence of ball-flight information, the significant improvement when introducing a simple movement reflects the role that even a low degree of perception-action coupling can play in enhancing anticipatory skill. Based on the findings of Króliczak et al. (2006) we proposed - and duly found - a further significant increase in anticipatory performance when participants attempted to intercept the ball with a bat. This finding is consistent with the proposal that a realistic chance of bat-ball interception is required to elicit most favourable anticipatory performance. Having established the important relationship between anticipation and perception-action coupling in the in-situ setting, future studies may seek to identify whether the significant improvement found in the PA4 condition
can be explained simply by the presence of a bat per se, or rather that the opportunity for bat-ball interception is required for most favourable anticipation.

The demonstration of movement-based increases in anticipatory skill for the in-situ condition in the absence of ball-flight information (occlusion condition t1) is in contrast to the findings of Farrow and Abernethy (2003), who found this relationship to exist only in the presence of ball-flight information. It is speculated that a realistic opportunity for, and an expectation of interception, may be an important point of divergence between the two studies. In the Farrow and Abernethy study the low likelihood of actual interception may have forced participants to engage a more perceptual mode of processing, with 100% of trials in that study occluded at some point, and 80% occluded prior to the availability of any ball-flight information (cf. 66% and 33% respectively in the current study). The more precise control of occlusion timing in the present study may have also afforded participants exposure to more information than was the case in the previous study. As a result, our findings do not support their proposal of a dedicated processor for movement-centred anticipation based on ball-flight information, which was proposed to be incapable of coupling anticipatory movements to pre-release information. Rather, our results are consistent with the model put forward by van der Kamp et al. (2008; p. 109, Figure 3) who speculated that the dorsal system could initiate movement responses based on advance information, rather than it be necessary for this system to wait for asserting ball-flight information. Based on our findings we propose that the expectation of, or at least the opportunity for interception, is an essential factor in engaging the visual-motor pathways relied on in the natural setting. Although the results presented here may be interpreted to be supporting evidence for this proposition, they fall short (at this stage) of being conclusive proof. Considering that the two visual streams maintain strong interactions rather than acting in isolation (Milner & Goodale, 2008; van der Kamp et al., 2008), it cannot be ruled out that the more representative task design aided the functioning of
the ventral system rather than the enhanced performance being a direct outcome of dorsal processing.

In contrast to the potential ambiguities in predicting outcomes based on pre-release information, the addition of only a small amount of ball-flight (t2 in the in-situ display condition) ensures that performance is well above chance guessing levels for both skilled and novice participants. For the t2 occlusion point, the significant increase in performance found in the transition from the lower-body (foot movement; PA2) to full-body (shadow batting; PA3) coupling condition is in line with observations from previous studies of hitting skills. A number of studies (Abernethy, 1981; Hubbard & Seng, 1954; Ranganathan & Carlton, 2007) have suggested that advance (pre ball-flight) kinematic information is critical for appropriate body positioning in time-stressed interceptive tasks, with ball-flight necessary for the fine adjustments required of successful interception (Montagne, 2005). For a task like cricket batting, this would suggest that the kinematic information available prior to ball-release may be functionally useful for lower body positional movements, while the upper body and hence bat movements are adjusted according to ball-flight parameters. The present findings for the in-situ display indicate that the availability of pre-release information results in a significant improvement in predictive performance for responses made with lower-body but not upper-body engagement, whereas the availability of ball-flight information conversely results in an upper-body (PA3) but not lower-body (PA2) based improvement. The significant improvement found at t1 for skilled participants responding in the fully interceptive condition (PA4, when compared to PA3) may be interpreted to be inconsistent with this proposition, as the upper-body engagement has resulted in significantly greater anticipation, even when it was based only on pre-release information. It may be, though, that the opportunity to intercept the ball in the PA4 condition has engaged the dorsal visual system, and that the dorsal control has resulted in more accurate lower-body movements. That is to say that the significant improvement for the PA1-PA2 contrast at t1 may have been a result of ventrally-driven lower-
body movement, whilst the improvement for the PA3-PA4 contrast could have been a result of more dorsally-mediated control of lower-body movements.

While the pattern of increasing RA with enhanced action specificity was clear for the in-situ display, this was not the case for the video simulation display. The specific point of interest here was not so much in comparing overall performance across the two display conditions, but rather with determining whether the video display was able to elicit increased anticipation with enhanced action specificity. The significant group x display x coupling interaction found at t2 demonstrates that, in contrast to the in-situ display, the video display failed to enhance skilled anticipation commensurate with action specificity. The mean RA for the video simulation was better than for the in-situ display at t2, however this was most likely a reflection of the difficulty in matching the t2 occlusion times across the two conditions, and the probability of comparatively more ball-flight information being available in the video display condition.

It is possible that the artificial nature of a video display, while effective in most cases for evaluating perceptual judgements, may be incapable of fully eliciting responses from the visual-motor pathway required for successful interception in-situ. Additionally, in contrast to the majority of video-based studies of expert anticipation (e.g., Abernethy & Russell, 1987a; Jackson et al., 2006; Jones & Miles, 1978), the video display condition in this study failed to demonstrate any differences across skill levels. The absence of such a finding in this study may be a consequence of either the narrow dimension over which direction can vary in this task, and/or the lack of any conscious coaching or analysis of such a skill for expert cricket batters. Rather than serving to question previous research demonstrating expertise-based perceptual differences using video displays, this study actually suggests that these previous findings may have underestimated the true effect size, further underlining the importance of these anticipatory skills in expertise.
4.5 CONCLUSIONS

The key premise that motivated this study, and has been reinforced by its findings, is that examination of expertise should take place, wherever feasible, in situations that replicate the natural environment as closely as possible. Skilled anticipation in a time-stressed motor task was enhanced as the coupling between perception and action was progressively increased when observing an in-situ display. This linkage between performance and coupling specificity for in-situ display conditions was evident both when anticipatory judgments were made solely on the basis of pre-release kinematic information, or when supplemented with viewing of a brief (50 ms) period of post-release ball-flight information. In contrast, we were unable to demonstrate a relationship between prediction accuracy and coupling specificity when observing a video simulation display, questioning the validity of this type of stimulus to accurately test motor expertise in skilled performers. The results are therefore consistent with van der Kamp et al.’s (2008) conceptualisation of ventral and dorsal interaction in the execution of motor tasks, which asserts that in fast-ball sports the dorsal system may be capable of acting on information available prior to ball release to facilitate successful interception. The expectation of an interceptive outcome is important in optimising expertise-based effects in online motor tasks, with simplified movements potentially failing to accurately reflect the true, or at least full, nature of perceptual-motor expertise.
CHAPTER 5

VISUAL INFORMATION UNDERPINNING SKILLED ANTICIPATION: THE EFFECT OF BLUR ON A COUPLED AND UNCOUPLED IN-SITU ANTICIPATORY RESPONSE

‘Ideas are like rabbits. You get a couple, learn how to handle them, and pretty soon you have a dozen.’

John Steinbeck
5.1 INTRODUCTION

The anticipation of event outcomes based on the observation of an action sequence forms an important element of expertise in many interceptive tasks, yet traditional means of assessing this skill may rely on different neural mechanisms to those used in the real-world setting. Skilled athletes are better able to predict the movement outcomes of opposition players based on the availability of advance visual information (Jones & Miles, 1978) - the movement pattern which occurs prior to the availability of unambiguous confirmatory information (e.g., ball-flight in the case of a tennis serve). Skilled athletes (when compared to novice observers) make predictions of an event outcome earlier in the progression of the action sequence (Abernethy & Russell, 1987a) based on the meaningful perception of segments more proximal to the body core (Abernethy, 1990a; Goulet et al., 1989), and based on a reliance on the underlying kinematic pattern (Abernethy et al., 2001) to specify the relative movement of adjacent body segments (Müller et al., 2006). The accurate perception of advance information facilitates enhanced interceptive performance in skilled athletes through the provision of movements which can occur earlier (Shim et al., 2005) and/or at the most appropriate moment (Ranganathan & Carlton, 2007), with this facilitation of movement allowing for outcomes more suitable to the task goal (Experiment II). However, a considerable proportion of the evidence for skilled anticipation has been developed requiring skilled participants to make a highly perceptual prediction of an event outcome, rather than examining responses which are based on the naturally-occurring movement. As a result, it has been proposed that the majority of the literature examining anticipation has been based on assessments of the ventral, rather than the dorsal visual pathway, which is more likely to be relied on for actual interception (van der Kamp et al., 2008).

As the response condition in the examination of skilled anticipation more closely replicates the actual response required in the performance of the task in-situ, there has been a
general expectation that anticipatory performance would be enhanced (e.g., Abernethy et al., 1993). Farrow & Abernethy (2003) manipulated the degree of perception-action coupling for participants anticipating the direction of a tennis serve and showed that coupled responses were superior to uncoupled ones, though only when some ball-flight information was available. No such effect was found to exist for anticipation based on pre ball-flight information. Farrow & Abernethy (2003) proposed that the coupled and uncoupled responses were underpinned by different perceptual processors, and noted that their findings were consistent with a dissociation of responses from the dorsal and ventral pathways. The lack of any advantage for coupling in the absence of ball-flight was interpreted to suggest that any coupling-based processing was reliant on the presence of ball-flight information. In a model ascribing the relative contributions of the two streams in visual anticipation, van der Kamp et al. (2008) proposed that anticipation based on pre ball-flight information is predominantly sourced by the ventral visual pathway, but it also relies on contributions from the dorsal visual stream (they went on to propose that the dorsal stream provides the predominant contribution to the interceptive action following ball release). Experiment III of this thesis found evidence, when examining cricket batters anticipating ball direction in-situ, for an advantage of perception-action coupling based on pre ball-flight information. For participants predicting ball direction based only on pre ball-flight information, a simplified movement response enhanced the anticipation of skilled batters over a verbal prediction. Furthermore, a more complex movement response requiring an attempt at interception (reasoned to be most likely to engage the dorsal visual system) produced a further improvement in anticipation above and beyond that achieved by a simplified movement. These findings were interpreted to support the van der Kamp et al. (2008) model, with what was reasoned to be a dorsally-based (coupled) response facilitating enhanced performance compared to an (uncoupled) ventral response when based on pre ball-flight information.
The neurological pathways which are thought to underpin coupled and uncoupled anticipatory responses may be based on rather disparate sources of visual information. Visual information from the retina relays to the brain along two parallel pathways: the *magnocellular* pathway conveys information which is processed rapidly and is highly sensitive to movement and contrast, and the *parvocellular* pathway is responsible for signals of much finer visual acuity and colour-based information (Livingstone & Hubel, 1988; Milner & Goodale, 1995). The dorsal visual pathway produces the online visual guidance of interceptive movements based on visual input sourced only from the magnocellular stream. The ventral pathway on the other hand produces a conscious perceptual interpretation of the world and is reasoned to have evolved relatively later in the evolutionary pathway, based on shared input from both the magnocellular and parvocellular streams (Goodale et al., 1991; Milner & Goodale, 1995). As a result, the dorsal visual stream produces actions based on information which is highly sensitive to movement and contrast, but the incoming information is relatively blurred and colourless when compared to the normal (ventral) interpretation of our surrounds. Although the ventral stream has the capacity for movement and contrast sensitivity, its processing is relatively slower as the clear and more colourful information tends to dominate processing. The disparate visual information supplying the two visual pathways offers a potential means to differentially affect the input of the two streams. For example, the ventral but not dorsal visual stream is reliant on clear visual information; hence the introduction of visual blur may be expected to have a much greater effect on the ventral than on the dorsal stream.

Visual blur simulated by either spectacles or contact lenses has been shown to adversely affect performance in a number of different perceptual tasks, though the impact of blur on motor skills appears to be less severe. In an examination of driving performance, Higgins, Wood & Tait (1998) found that the introduction of blur resulted in immediate decrements for perceptual judgements such as road-sign recognition, road-hazard avoidance, and total driving time; yet it had no effect on the participants’ ability to drive through targets.
Norman (2002) in a discussion of the dorsal and ventral dissociation interpreted this to be a result of visual blur limiting the performance of ventrally-dependent perceptual tasks, but not dorsally-dependent motor tasks – consistent with clear visual information supplying the ventral but not dorsal visual system. Jackson and Abernethy (in press) recently (following the publication of Experiment I) investigated the effect of blur on visual anticipation. They manipulated video footage of a series of tennis serves using three levels of Gaussian blur (0%, 20%, 40%).\(^1\) It was reported that 20% blur reduced the verbal anticipation of serve direction to levels achievable by chance guessing (when based on pre-ball-flight information). This provides an example of visual blur affecting what would be interpreted to be a ventrally-based task. Most peculiarly though, the 40% blur condition resulted in a significant increase in anticipation. It was reasoned that this increase may have reflected a change in strategy on the part of the participants, with better judgements in the 40% blur condition proposed to be a result of a switch in the interpretive strategy from a featural (fine acuity) to a figural (coarse acuity) prediction.

In contrast to the perceptual tasks which appear to rely on fine visual acuity, motor tasks have tended to demonstrate some degree of resilience to visual blur. This has been shown by the maintenance of performance (despite high levels of blur) in tasks such as the basketball free-throw (Applegate & Applegate, 1992) and golf-putting (Bulson et al., 2008). Although these particular tasks may be argued to possess a low dependence on online visual information, this finding has been replicated in an interceptive striking task (cricket batting) which is much more likely to require fine online visual-motor manipulations (Experiments I & II of this thesis). Collectively these results are consistent with Norman’s (2002) conceptualisation of visual clarity being a limitation to ventrally-based, but not dorsally-based

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\(^1\) Gaussian blur applies a mathematical function to reduce image noise and detail in a video display. This study provided no indication of what the levels of Gaussian blur would equate to in terms of visual acuity or dioptic blur.
tasks. As a result it appears reasonable to propose that if visual clarity (in terms of normal, habitual visual acuity) is a requirement for perceptual performance, then blur may adversely affect a ventrally- but not a dorsally-based task. In the case of an examination of anticipation, it may be reasonable to expect an interaction between blur and perception-action coupling such that there is an immediate decrease in the performance of an uncoupled prediction of movement outcomes, but not a coupled prediction of outcome.

Experiment II performed an examination of interceptive performance in cricket batting and demonstrated that the effect of blur on interceptive skill was dependent on target velocity, with increased ball-velocity resulting in a lesser amount of blur being required to produce a significant decrease in performance. Although this association was attributed to the differences in ball-velocity, there is reason to expect that this relationship may extend to the observation of pre ball-flight information. For instance, tests of dynamic visual acuity seek to address the ability of observers to resolve meaningful detail in a moving target (Ludvig & Miller, 1958). For clear resolution, results suggest that larger target sizes are required as the velocity of the target is increased (Hoffman et al., 1981). This effect becomes particularly pronounced for observation times less than 600 ms (Long & May, 1992). If one considers two objects of similar size but different movement velocities, then it is reasonable to extrapolate that better acuity will be required for the adequate resolution of the faster moving target. As a result it seems fair to expect that progressive increments in visual blur should affect the resolution of faster moving targets earlier than it would for slower moving targets. When considering skilled anticipation, if faster ball velocities are demonstrated to be the result of faster movement action sequences (that is to say that faster ball-velocity is most likely a result of a faster arm movement by the bowler/pitcher), then one may reasonably expect anticipation based on faster pre ball-flight movements to be affected by a lower level of visual blur than that level which would affect the perception of slower movements.
This study adopted the protocol of Experiment III to examine anticipation in-situ based on pre ball-flight information. Participants predicted the direction of cricket balls bowled toward them by responding in each of two response conditions which differed according to the degree of coupling between perception and action: an *uncoupled* (verbal) response and a *coupled* (interceptive) response. Experiment III found that skilled cricket batters could use coupled but not uncoupled responses to predict ball direction at levels significantly greater than that achievable by chance guessing.\(^2\) Data were collected concurrent with Experiment II, ensuring that the same actors and participants were examined allowing direct comparisons to be made across the two studies.

The present study set out to address two specific aims. The first was to examine the interaction between visual blur and the degree of perception-action coupling in the participant response used to test anticipatory performance. It was hypothesised - consistent with the findings of Experiment III - that performance for coupled responses would be greater than for uncoupled responses when decisions were based on pre ball-flight information in habitual viewing conditions (no visual blur; *Hypothesis 1.1*). Based on the proposition that coupled and uncoupled responses are sourced by different types of visual information, an interaction was expected as visual blur may have a different effect according to the degree of perception-action coupling used in the anticipatory response (*Hypothesis 1.2*). Based on visual clarity not being a limiting factor to performance in a dorsally-based task, and consistent with the predictions of Norman (2002), it was hypothesised that the coupled response would demonstrate some degree of resilience to blur (*Hypothesis 1.3*). In contrast it was expected that performance in the uncoupled condition would be similar to levels achievable by chance.

\(^2\) Skilled anticipation when reliant on an uncoupled perceptual response is generally reported to be above chance guessing levels (Mann et al., 2007), however this was not the case for this particular task (see Chapter 4 for a discussion).
guessing (consistent with Experiment III), and would remain so for all levels of visual blur (Hypothesis 1.4).

The second aim of the study was to examine the mediating effect of increased movement-velocity on the relationship between visual blur and perception-action coupling. Accordingly it was expected that there would be an interaction between movement-velocity and visual blur such that trials necessitating the perception of higher movement-velocity would be adversely affected by a lower level of blur (Hypothesis 2.1). More specifically it was expected that this relationship would hold for the coupled trials (Hypothesis 2.2) but not for the uncoupled trials (Hypothesis 2.3), where performance would be at levels explainable by chance guessing for all conditions of visual blur.

5.2 METHODS

5.2.1 Participants

A total of 10 skilled male cricket batters (mean age 22.5 ± 4.9 years) voluntarily took part in the study. All participants had played in the local regional first grade competition within the previous 12 months, with the majority (eight) representing their state at a junior and/or senior level. Participants reported an average of 9.1 ± 3.6 years of junior and 7.3 ± 4.5 years of senior cricket playing experience. All gave written informed consent according to the relevant institutional guidelines prior to taking part in the study.

5.2.2 Experimental Task

A two-choice prediction task was designed with the aim for participants to predict the impending direction of an approaching ball projected by an opposing actor (bowler). The direction of the ball was judged to be either towards the off or leg side of a centre stump in front of which the participant stood. The task represented an important element of expertise
in cricket batting, where the direction of the ball must be judged quickly and accurately to facilitate most favourable bat-ball interception.

Three actors were recruited to assist in the study, bowling balls toward participants in-situ. All actors had played as bowlers in the local regional first grade competition within the previous 12 months and were considered to be of a comparable skill level to the participants. One of these actors was classified as a bowler of fast-paced bowling velocity (ball-speeds: 120-130 kph) with the remaining two actors classified as bowlers of medium-paced bowling velocity (ball speeds: 90-110 kph). All ten participants faced three bowlers, though only seven of the participants faced the fast-paced bowler due to logistical constraints with testing. Whenever a bowler was unavailable (due to injury) they were replaced by a substitute bowler of medium-paced bowling speed. As a result all participants faced three bowlers: seven participants facing two medium- and one fast-paced bowler, the remaining three participants each facing three medium-paced bowlers.

All bowlers followed scripts of intended ball direction for each trial to ensure an equal distribution of trials to the off and leg side (actual resultant direction = 49.1 v. 47.1% respectively; \(t(9) = 0.98; p = .35\)). Bowlers correctly delivered 86% of trials as specified to the off or leg side of the centre stump. A speed radar (Stalker ATS sports radar, USA) was used to monitor ball velocity for each trial to ensure consistency across conditions. The classification of bowlers by ball-velocity was confirmed by a significant difference in ball-velocity between the two groups (fast-pace vs. medium pace = 120.8 vs. 104.2 kph; \(t(6) = 13.22, p < .001\)). More importantly, this difference in bowling-velocity was underpinned by a commensurate disparity in movement-velocity, with the movement pattern used by a cricket batter to anticipate event outcomes (bowler back foot-contact to ball-release; Müller et al., 2006; see Figure A2 in Appendix A) found to occur quicker for the fast-paced bowler than for the medium-paced bowlers (fast-pace vs. medium pace = 309 vs. 367 ms). As a result, anticipation of the faster-
paced bowler in this study required anticipation based on a faster action sequence than when observing the medium-paced bowlers.

Liquid crystal occlusion goggles worn by participants (PLATO Model P-1, Translucent Technologies Inc., Canada) facilitated the occlusion of vision at desired points in the approach sequence of the bowlers. To examine anticipation skill, participants observed the approach of the bowler with vision occluded either (i) at (or immediately prior to) the ball being released from the bowler’s hand (ball-release condition), or (ii) no occlusion (no occlusion condition). This ensured that judgments of ball direction were made in the ball-release condition based purely on pre-release kinematic information, or in the no occlusion condition with the addition of all ball-flight information. The occlusion goggles were triggered by a bowler-specific signal-delay which was initiated by the registration of a reliably occurring point in the bowling event sequence (a full explanation of this methodology is provided in Appendix A). Pilot testing demonstrated that skilled bowlers have a consistent time-delay from the penultimate foot-strike prior to ball release through to the point of ball release, providing a potential trigger-point for the accurate occlusion of vision in-situ. Surface-embedded force plates sampling at 250 Hz (Kistler 9287BA, Kistler Instrumente AG, Switzerland) registered the penultimate foot-strike prior to ball-release, with a bowler-specific computer-delayed signal used on chosen trials to occlude vision immediately prior to ball-release. This method of occlusion has been demonstrated to facilitate occlusion windows within 50 ms of the desired time-point, which compares very favourably to the 300 ms time windows accepted in previous studies of occlusion in-situ (Farrow & Abernethy, 2003; Müller & Abernethy, 2006a). A second signal was sent, parallel with that for occlusion, to an LED to facilitate post-hoc examination of test footage to confirm the trials where occlusion took place.

Testing was conducted in an indoor facility with the surface replicating an artificial cricket pitch and with markings replicating the dimensions of a pitch used for official play. Participants stood at their batting position ≈17.7 m from where actors delivered the ball
(replicating the distance from a bowler that a batter would stand in a match). To prevent the ball from hitting the batter, a small net was suspended 0.8 m in front of participants (Figure 5.1). The top of the net sat 1.4 m above the ground, ensuring that vision of the bowler in their approach was unobstructed from the stance of the batter. The positioning and suspension of the net ensured that bat-ball interception was still possible, with participants able to hit the ball through the net. Participants wore all standard protective equipment, and faced a softer ball (Kookaburra Supa Soft with factory lowered seam, Kookaburra Sport Pty. Ltd., Australia) specifically designed to maintain the appearance and properties of a cricket ball. Video footage of all testing was recorded (Sony HDR-FX1E digital video camera, Sony Corporation, Japan) from an elevated position behind the position where the bowler released the ball.

A vision screening was performed prior to testing to facilitate the fitting of appropriate contact lenses to participants. Habitual visual acuity (VA) was assessed in addition to a full refraction which made possible the fitting of soft contact lenses to simulate four refractive conditions relative to habitual vision: plano; +1.00; +2.00; and +3.00 (see Figure 2.2). In the plano condition, participants took part with habitual vision; wearing either no correction, or soft contact lenses if they would usually bat with visual correction in a game. All participants wore contact lenses for the +1.00, +2.00, and +3.00 conditions. Mean habitual VA for all participants was 6/5.3 equivalent (range 6/4.5 - 6/6), with VA for the three remaining blur conditions (+1.00, +2.00, and +3.00) found to be 6/11 (range 6/6 - 6/19), 6/20 (range 6/10 - 6/33), and 6/49 (range 6/25 - 6/80) respectively. Participants with habitual VA worse than 6/6, or those who could not adapt to contact lenses, were omitted from the study.
Figure 5.1. Demonstration of a participant standing behind the protective net from (a) front-on view, and (b) behind participant.
5.2.3 Procedure and Design

The prediction of event outcome was examined in each of two response conditions which varied according to the degree of coupling between perception and action: (1) a coupled condition in which participants were required to hit the approaching ball with a cricket bat (as would occur in a match situation), and (2) an uncoupled condition where participants verbalised the anticipated direction of the ball as either towards the off or leg side with no concurrent movement. The coupled and uncoupled conditions were respectively selected (based on the outcomes of Experiment III) as being the responses most representative of the dorsal and ventral pathways (see van der Kamp et al., 2008). Participants were instructed that responses in both conditions were to be made prior to the ball hitting the net.

A 2 (Coupling: coupled, uncoupled) x 4 (Blur: plano, +1.00, +2.00, +3.00) x 2 (Movement-velocity: fast, medium) within-subject design was used to examine for changes in coupling-based anticipation across increasing levels of refractive blur. The order of presentation for blur condition was balanced across participants, with the order of coupling conditions held constant within-subject, but counter-balanced across all participants. Each participant faced a total of 144 experimental trials: 72 trials to test the coupled response (an 18-trial set for each of the four blur conditions) and 72 trials to test the uncoupled response (a further 18-trial set for each of the four blur conditions). Each 18-trial set comprised a 6-trial block from each of the three bowlers. Six practice trials (two trials from each bowler) preceded each 18-trial set. Following a randomised schedule, two-thirds of all trials were to be occluded at ball-release, with four of the six practice trials and twelve of the 18 experimental trials for each set randomly occluded at ball release, and no occlusion for the remainder of the trials. All testing took approximately two hours to complete, was performed over two different days, and took place concurrent with the data collection for Experiment II.
5.2.4 Data Analysis

Task performance was assessed by a measure of Response Accuracy (RA), calculated as the percentage of trials where the predicted direction matched the actual direction of the ball. All verbal responses (either ‘off’ or ‘leg’) were recorded by a research assistant at the time of testing, with the response in the coupled condition and the actual ball direction for all trials judged by a trained observer (blind to the blur condition) viewing video footage post-hoc. Participant responses for the coupled trials were judged as being either ‘off’ or ‘leg’ according to whether the plane of motion of the bat-swing was directed towards the off- or leg-side of the centre stump. Ball direction was also judged to be either ‘off’ or ‘leg’ according to the direction of the ball relative to the centre stump, with those trials where the ball was judged to have been directed at the centre stump excluded from all analyses.

The trials where no occlusion took place were included to ensure that batters would participate in trials where bat-ball interception was likely to occur, as a result engaging the visual-motor pathway responsible for online interception. If occlusion were to occur at ball-release for all trials, the minimal chance of interception in these trials may result in participants engaging visual-perceptual rather than visual-motor processing (see Experiment III for a further discussion). As the trials without occlusion were of no interest to the primary aim to examine anticipation, they were excluded from all analyses. Accurate occlusion proved to be difficult for one of the five bowlers recruited in the study as their penultimate foot-strike prior to ball release frequently missed the force plate, resulting in the majority of trials not occluding. In particular, this resulted in an uneven distribution of trials for this bowler across conditions within-participants. As a result all trials from this bowler were excluded from analyses.

All data for RA underwent an arcsine transformation prior to being subject to statistical analysis. To investigate the first aim examining for coupling based changes across levels of blur, a 2 (Coupling) x 4 (Blur) x 2 (Movement-velocity) ANOVA with repeated measures on all
factors was performed. To investigate the second aim examining for coupling based
differences at the two different movement velocities (and because there were different
participant numbers across the two movement-velocity conditions), separate 2 (Coupling) x 4
(Blur) ANOVAs were conducted for the fast-paced (seven participants) and medium-paced (ten
participants) movement-velocity trials. Successive contrasts were used to examine for within-
group changes in RA across increasing levels of blur, with \( t \)-tests performed to determine
whether mean responses were significantly different from the 50% level achievable by chance
guessing. Alpha was set at .05 for all testing, with the degrees of freedom adjusted for any
violations of sphericity according to the Greenhouse-Geisser method. Partial eta squared (\( \eta_p^2 \))
was calculated to determine the proportion of total variability accounted for by an effect or
combination of effects.

5.3 RESULTS

5.3.1 Response Accuracy across all Trials

The 2 (Coupling) x 4 (Blur) x 2 (Movement-velocity) ANOVA for the seven participants
who experienced both fast and medium-paced trials failed to demonstrate significant main
effects for coupling (\( F(1,6) = .56, p = .48, \eta_p^2 = .09 \)), blur (\( F(3,18) = 2.36, p = .11, \eta_p^2 = .28 \)), or
movement-velocity (\( F(1,6) = 1.37, p = .29, \eta_p^2 = .19 \)); it did however reveal a significant
interaction between coupling and blur (\( F(3,18) = 3.70, p < .05, \eta_p^2 = .38 \); Figure 5.2) in the
absence of any other higher-order interactions. Coupled anticipation was found to
demonstrate a degree of resilience to blur, with RA at levels significantly greater than 50% for
the plano (\( p < .01 \)), +1.00 (\( p < .01 \)), and +2.00 (\( p < .05 \)) blur conditions. RA was not different to
chance guessing levels for the +3.00 blur condition. On the other hand, uncoupled anticipation
improved with a low level of blur, with RA becoming significantly greater than 50% in the +1.00
blur condition.
Figure 5.2. Coupled and uncoupled response accuracy as a function of refractive blur, averaged across both fast and medium-paced movement-velocity trials. Response accuracy is indicated for those mean data points significantly greater than the 50% level achievable by chance guessing (* $p < .05$, ** $p < .01$). Data are displayed with standard error bars.

5.3.2 Response Accuracy by Movement-velocity

When examining the two movement-velocity conditions separately, the analysis of variance firstly for the seven participants who faced fast-paced movement velocity trials demonstrated a main effect for blur ($F(3,18) = 3.59, p < .05, \eta^2_p = .37$; Figure 5.3a) due to an increase in performance from the plano to +1.00 blur condition ($p < .05$), and a subsequent decrease from the +1.00 to +2.00 condition ($p < .05$). No significant effects were found for coupling ($F(1,6) = .49, p = .51, \eta^2_p = .08$), or for the interaction between blur and coupling ($F(3,18) = 1.29, p = .31, \eta^2_p = .18$). RA was found to be significantly greater than the level achievable by chance guessing for the plano and +1.00 coupled conditions, and for the +1.00 uncoupled condition (all $ps < .05$).
Figure 5.3. Coupled and uncoupled response accuracy as a function of refractive blur for fast-paced (top panel, a) and medium-paced (lower panel, b) movement-velocity trials. Response accuracy for those mean data points significantly greater than the 50% chance level are indicated (* $p < .05$, ** $p < .01$), along with significant changes in performance across successive blur conditions for the coupled condition ($\Delta p < .05$), and collapsed across both coupling conditions ($\dagger p < .05$). Data are displayed with standard error bars.
The analysis of variance for all 10 participants against medium-paced trials failed to demonstrate effects for coupling \((F(1,9) = .41, p = .54, \eta_p^2 = .04)\), blur \((F(3,27) = 1.18, p = .34, \eta_p^2 = .16)\) or for the interaction between coupling and blur \((F(3,27) = 1.77, p = .18, \eta_p^2 = .16)\); Figure 5.3b). RA was found to be significantly greater than the 50% chance guessing levels for the plano \((p < .05)\), +1.00 \((p < .05)\), and +2.00 \((p < .01)\) coupled conditions, and for the +2.00 uncoupled condition \((p < .05)\).

### 5.4 DISCUSSION

This study was performed with two specific aims in mind. The first aim was to examine the relationship between visual blur and the degree of coupling in the anticipatory response. Hypothesis 1.1 predicted that coupled anticipation would be better than the uncoupled equivalent when viewing pre ball-flight information with clear vision. Hypothesis 1.2 predicted a significant interaction between visual blur and perception-action coupling, with Hypothesis 1.3 more specifically expecting the coupled response to demonstrate some resilience to visual blur, whilst Hypothesis 1.4 predicted that uncoupled anticipation would remain at chance guessing levels for all levels of blur. The second aim of the present study was to examine whether the relationship between visual blur and coupling was mediated by the speed of the movement being observed. Hypothesis 2.1 foresaw a significant interaction between movement-velocity and visual blur with an expectation that higher movement-velocity trials would be more susceptible to blur. It was predicted that the greater blur-susceptibility for higher movement-velocity trials would hold true for coupled trials (Hypothesis 2.2), but that no such relationship would exist for uncoupled trials where performance in all blur conditions would not be different to levels achievable through chance guessing (Hypothesis 2.3).
5.4.1 Visual Blur and Perception-action Coupling

Coupled but not uncoupled anticipation (based on pre ball-flight information) was shown to be at a level significantly greater than chance for the plano visual condition, consistent with the prediction of Hypothesis 1.1 that coupled anticipation would be superior to that for the uncoupled response. This finding replicates that found in Experiment III, supporting the case for a coupling-facilitated improvement in performance as the task more closely replicates the real world conditions (Farrow & Abernethy, 2003), rather than resulting in a decrease in performance due to increased task complexity or in producing an earlier response (Ranganathan & Carlton, 2007). Most interestingly, the support for coupling-enhanced anticipation in the absence of confirmatory ball-flight information supports the role of movement in facilitating anticipation, and is consistent with (but of course not proof of) the van der Kamp et al. (2008) model that the dorsal visual stream makes critical contributions to anticipation, even when decisions are made based purely on pre ball-flight information. It provides further support for the tentative conclusion in Experiment III that the enhanced performance in the condition providing greatest perception-action coupling (PA4) was a result of dorsal (rather than ventral) processing.

Testing revealed - consistent with Hypothesis 1.2 - a significant interaction between visual blur and coupling. As was predicted by Hypothesis 1.3, the coupled response condition demonstrated a degree of resilience to blur, with +3.00D of blur required to reduce RA to the 50% level achievable though guessing (Figure 5.2). This finding suggests that visual clarity is not a limitation to performance for coupled anticipation, and is consistent with the expectation that a low level of blur would not adversely affect functioning of the dorsal visual stream which relies on a relatively poor quality of visual acuity (Brown et al., 2005; Livingstone & Hubel, 1988; Norman, 2002). Furthermore this level of blur is comparable to that shown previously to decrease interceptive performance in cricket batting (Experiments I & II). In contrast to the response for coupled anticipation, uncoupled anticipation was not different to
chance guessing levels with clear vision; rather curiously however (and in contrast to Hypothesis 1.4) performance tended to increase with the introduction of some blur (Figure 5.2). Verbal predictions of ball direction were significantly greater than chance guessing levels with the +1.00D simulation of blur and remained at comparable levels with the addition of further blur. This is a most intriguing finding which will be revisited shortly. Collectively these contrasting responses to visual blur support the proposal that the different forms of anticipatory response (based on differences in perception-action coupling) are underpinned by different neural pathways which source different types of visual input.

5.4.2 The Effect of Movement-velocity on the Interaction between Visual Blur and Perception-action Coupling

The experimental findings did not support Hypothesis 2.1, which predicted that there would be a significant interaction between movement-velocity and visual blur. On this basis it would appear that visual blur is not more likely to adversely affect faster movement velocities, yet this is most likely a reflection of the low statistical power resultant from the number of participants examined in the present study (only seven participants were able to face both the medium- and fast-paced bowlers). To further investigate this issue, separate ANOVA examinations were performed for the fast- and medium-paced bowlers, providing some support that greater participant numbers may have lead to evidence corroborating with Hypothesis 2.1. When first considering the coupled responses across the two different movement velocities (Figure 5.3) it is apparent that RA decreases significantly with +2.00D of blur for the fast-paced movement-velocity trials, and with +3.00D of blur for the medium-paced trials. This is consistent with both Hypothesis 2.1 and 2.2 that faster movement velocities would be adversely affected by lower levels of visual blur, and is consistent with the results from work on dynamic visual acuity which has established that visual resolution is more difficult at faster movement-velocities (Hoffman et al., 1981; Long & May, 1992). Remarkably
the levels of blur which adversely affect performance replicate those found in Experiment II which was performed using the same participants and bowlers. In that study +2.00D of blur decreased interceptive performance against the fast-paced bowler, and +3.00D of blur was required to decrease performance when facing the medium-paced bowlers. Collectively these findings may be interpreted to provide further support for increased movement-velocity requiring better acuity for resolution. Considering that the fast-paced bowler was delivering balls at speeds close to the maximum experienced at the highest levels of cricket, it appears that +1.00D of blur is tolerable in this particular task for both effective anticipation and for interception, and hence visual clarity does not appear to be a necessity for optimal performance.

There was an expectation, based on the findings of Experiment III, that the uncoupled responses would be at chance guessing levels for all levels of blur (Hypothesis 2.3), yet most interestingly this was not found to be the case. Some evidence was found to suggest that specific to the movement-velocity of the bowler, a particular level of blur enhanced the verbal prediction of ball-direction. Uncoupled anticipation was found to be significantly greater than 50% in the +1.00 blur condition when facing the fast-paced trials, and in the +2.00 condition when facing the medium-paced trials. Most interestingly these levels of blur directly correspond to the highest levels of blur tolerated prior to decreases in coupled anticipation (Figure 5.3). Further increases in blur result in commensurate decreases in both the coupled and uncoupled conditions. Although this could be a result of coincidence, the responses demonstrated in Figure 5.3 are consistent with the uncoupled response defaulting to the coupled one at a level of blur specific to the movement-velocity of the bowler. A possible mechanism for this may lie on the interactions between the two visual streams. Milner and Goodale (2008, p.776) explain that there is:

no such thing as a pure ‘visuomotor task’ nor a pure ‘perceptual task’. Even when we perform an apparently simple task like reaching or grasping, we cannot help but
simultaneously perceive the goal object and often also our hand reaching out towards it.

Considering that both visual streams may be acting even when performing the uncoupled task, it is possible that the improved judgements with the addition of blur in the uncoupled condition may reflect a relative increase in the contributions of the dorsal stream, as in these situations the ventral stream may only be able to act in a sub-optimal fashion.

5.4.3 Evidence for Improved Ventral Processing with Visual Blur?

The evidence in this study suggesting that certain levels of visual blur may enhance uncoupled anticipation are – although tentative – consistent with the findings of Jackson and Abernethy (in press), who reported that a particular level of Gaussian blur (40%) enhanced the verbal anticipation of tennis serves. They attributed this effect to observers altering their focus from featural to figural information. Considering that the only two known studies to examine the effect of blur on verbal (and hence ventrally-based) anticipation have found similar speculative results, this effect may be worthy of further consideration in the context of the wider body of literature addressing visual perception.

A small number of studies have reported enhanced task performance with the introduction of visual blur, and they may provide important insights to this apparent phenomenon. Harmon (1973) used computer simulations to blur images of human faces and found that the removal of high spatial frequency information (necessitating fine VA) had very little effect on the ability to recognise a face. Even with levels of blurring which were so extreme that facial features were entirely indistinguishable, the remaining low frequency information permitting some identification of head shape (plus neck and shoulder geometry) was sufficient for a good degree of facial recognition. In extending this work Harmon (1973) produced block facial portraits where the image was divided into squares of uniform size, with the brightness for each square averaged across all the points in that square. He found that
blurring significantly enhanced the recognition of the faces depicted in these block images, as it removed the higher spatial frequency information which acted as noise interfering with facial recognition. An image (much like sound) can be considered as a combination of simple component frequencies - in Harmon’s (1973) studies the blur was considered to act like a low-pass filter, removing high but not low frequency visual information. Interestingly, this distinction has been used to explain the curious smile evident in the Leonardo Da Vinci masterpiece *The Mona Lisa* (Kontesevich & Tyler, 2004). Commentators have often remarked that the subject in this painting has a distinct smile which is evident when the observer focuses anywhere but at the mouth. When looking at her mouth, the smile seems to disappear. This phenomenon has been explained on the basis of spatial frequency: low spatial frequency images of the painting (which are incidentally how peripheral vision views the image) reveal a broad smile which is hidden by higher spatial frequency ‘noise’ (the image which is seen with central vision). That is to say that the relatively blurred images produced by peripheral vision reveal the lower spatial frequency (in this case the broad smile of the woman) hidden by the high spatial frequency information detected by central vision. The capacity for visual blur to remove these higher spatial frequencies may hold an important implication for the interpretation of the results found in the present and indeed in other studies.

Visual blur has been identified as a potential facilitator of two particular advantages in the perception of fast-moving visual information. The first is based on the work of Luria and Newacheck (1992) who found that the introduction of visual blur improved the ability of participants to discern the temporal order of two flashing lights. This study examined the amount of time that needed to elapse between the presentation of two spatially close stimuli for the lights to be perceived as flashing one before the other rather than as being simultaneous (a task considered to be important in naval navigation). Luria and Newacheck (1992) performed this examination using five different levels of visual blur (plano, +1.00, +2.00, +3.00, +4.00) and found that for the discrimination of temporal order, the time that needed to
elapse between the presentations decreased as the blur increased from plano to +2.00, and remained constant with further increases in blur. This represented an improvement in visual function with the addition of visual blur, as participants with blur were able to distinguish shorter lag times between the two lights. This effect was proposed to be a result of the blur altering the spatial characteristics of the visual image to favour visual mechanisms sensitive to movement (i.e., changes in the visual image). In this case the blur is seen to reduce the quality of the high spatial frequency information visible to the participant, shifting the reliance of the visual system from high to low spatial frequency information. This is interpreted to be the cause of the perceptual advantage, as low spatial frequency information is known to possess a greater capacity for the discrimination of temporal frequency and is processed with shorter response latencies. This information is likely in the habitual situation to have been processed in the visual cortex, but may have been made redundant as preference is generally allocated to clearer, higher spatial frequency input. This is consistent with the ventral system (according to the current understanding and terminology) altering its reliance from parvocellular input to magnocellular input which is more similar to the visual information the dorsal pathway would typically rely on. One final point of interest from the Luria and Newacheck (1992) study is their comment that participants reported an increased sense of apparent motion when wearing blurred lenses. It was reported that participants “no longer needed to rely on a difficult temporal judgement but could now respond on the basis of a salient perception of direction of movement” (p.362). If this were to be true, this may provide further insight to why blur may have enhanced the perception of meaningful movement in the present study.

The second potential advantage for blur in enhancing the perception of temporal visual information is based on the work of Di Lollo and Woods (1981), who presented work on visual persistence which has been used to partially explain the outcomes of Luria and Newacheck (1992), and may further help to rationalise the findings of the present study. Di Lollo and Woods (1981) reported that progressive increases in visual blur (resulting in a
progressive reduction in the high spatial frequency components of the display) produced corresponding reductions in the duration of visual persistence. Visual persistence refers to the perceptual phenomenon that a brief visual stimulus will remain perceptible as a photograph-like representation of that image for a short period of time. This concept is said to be associated with cognitive processing time, with longer visual persistence a result of longer visual processing (Di Lollo, 1977, 1980). Visual blur reduces the contribution of high spatial frequency information which is associated with longer visual persistence (and hence longer processing time), and as a result decreases the visual persistence of an image. If the vision produced by the ventral pathway is considered to be a series of high-frequency images in succession, then a decrease in visual persistence can be conceptualised as producing a series of more distinct images which do not overlap. This would be akin to increasing the shutter speed to improve the resolution of high-speed footage recorded by a video camera. It is possible that this reduction in visual persistence has aided participants in the present study to make more judicious perceptual judgments of ball direction through the provision of a more distinct perception of relative motion. Di Lollo and Woods (1981; p.769) suggest that the blurring may force the visual system to rely on the lower spatial frequency information which previously was made redundant by higher frequency input. This statement may be seen to corroborate with the findings demonstrated in Figure 5.3, where at particular points of blur the uncoupled response accuracy begins to mirror the coupled response. It is as if the blurring has caused the uncoupled response (proposed to be ventral in nature) to rely on the same visual information upon which the coupled response (supposed to be dorsal by nature) is produced.

At this point it is worth revisiting the results of Jackson and Abernethy (in press), who found that verbal anticipation of ball direction for a tennis serve was initially decreased, and then increased, with the progression of increasing image blur. They reasoned that this later increase in performance with blur was the result of participants shifting their focus from
featural to figural display information. Perhaps an alternate explanation for their (and the current) study in light of the existing literature may be that the removal of higher spatial frequency information has been advantageous in forcing the ventral visual pathway to make decisions based on the lower spatial frequency information (which the dorsal system would typically rely on). It appears that this lower spatial frequency information – which is typically considered redundant by the ventral visual system – may afford temporal advantages to aid conscious movement detection. Indeed it is possible that this is the most useful form of information for movement detection and discrimination – otherwise one may have expected the improved visual quality of the ventral pathway to have been adopted by the dorsal pathway through evolutionary processes. This is of course speculation, with further work required firstly to replicate and secondly to extend on these findings. Future studies may look to examine whether particular bands of spatial frequency are most favourable for movement perception, and if these bands are found to exist, they may prove to be specific to the velocity of the movement being observed. Such a finding could hold important implications for tasks of conscious movement perception such as those involved in driving, flying, air traffic control, the military, and skills facilitating sporting performance.

5.4.4 The Neurological Basis for Superior Anticipatory Performance with Increased Perception-action Coupling

Enhanced anticipation based on increased perception-action coupling has been proposed to be a result of better ecological validity, which more effectively examines the neural pathways and connections relied on in the real-life environment (Farrow & Abernethy, 2003; van der Kamp et al., 2008). In this sense the ability to obtain functional information from movement (e.g., Oudejans, Michaels, Bakker et al., 1996; Oudejans, Michaels, van Dort et al., 1996), and to couple these movements to the invariants specific to environmental properties, has been seen to facilitate improved decision making (e.g., Michaels, 2000).
Indeed anticipation has been associated with common coding theory (Abernethy et al., 2008) and shown to share a neurological basis with the mirror neuron network (Wright et al., 2010; Wright & Jackson, 2007), providing further evidence that anticipation maintains a strong interactive relationship with movement production. This is based on a sound theoretical foundation, yet the results of this study provide a potential ‘red herring’ which at this stage cannot be excluded as an alternate (or at least adjunct) explanation for the effect of enhanced perception-action coupling. It is possible that it is the quality of the visual information rather than the actual coupling per se which provides the functional reason for improved performance with perception-action coupling. The results of the present study (particularly as presented in Figure 5.3) suggest that, at some point, the addition of blur causes the performance of an uncoupled response to mirror that of the coupled response. This could be explained based on the type of visual information relied on by the two types of response. Improvements in perception-action coupling appear to involve a shift in the relative dependence from the ventral to dorsal visual streams, and hence a change in the dependence on the quality of visual information used. If one accepts that the dorsal pathway is relying on relatively impoverished visual information (when compared to the ventral pathway), then with experience it has learned to converge upon the meaningful visual information on the basis of this relatively poorer visual information. That is to say that if for example a skilled tennis player has learned (using the dorsal visual system) to couple their movements to the advance pre-contact information available from the opposition player’s actions, they have done so on the basis of an image of relatively poor visual quality. In contrast, the ventral stream relies on a clearer visual image. It is possible that the higher spatial frequency information in this ventrally-produced image may act as noise, effectively distracting the observer in their attempt to detect the important visual information which the dorsal stream has learned to rely on. This
relatively poorer image may be, as a result of experience, the most functionally meaningful visual information for the brain in anticipating context-specific events.\(^3\) Hence, as the degree of perception-action coupling in the anticipatory response is increased, it is conceivable that the increased dorsal stream engagement means that the brain relies on a visual image of poorer quality, but that this could be an advantage as it provides an image that is closer to that used by the dorsal stream.

### 5.5 CONCLUSIONS

This study supports the supposition that responses which differ according to the degree of coupling between perception and action are underpinned by distinct neural processes, which in turn may be sourced by disparate visual information. Anticipation of advance pre-release information is superior for a coupled compared to an uncoupled response – most likely a result of the enhanced ecological validity in the task, which may also include access to the most appropriate visual information for the task of interest. Coupled anticipation is shown to demonstrate a moderate level of resistance to visual blur, suggesting that habitual vision is not a requirement for the performance of this task, a finding consistent with the relatively impoverished visual information sourced by the dorsal visual pathway. Some evidence is found to suggest that visual blur may aid in the production of conscious perceptual interpretations which require the interpretation of movement.

\(^3\) Of course the complication here is in the term ‘meaningful’ – our current understanding of the concept of ‘meaning’ in the dorsal visual stream is poor, as is whether this information is available to conscious awareness. The dorsal stream maintains relatively poorer connections with memory and hence it may not be possible for the ventral stream to access meaningful information used by the dorsal stream.
CHAPTER 6

DISCUSSION AND CONCLUSIONS: THE EFFECT OF VISUAL BLUR ON A SPATIALLY AND TEMPORALLY DEMANDING INTERCEPTIVE ACTION

‘It has been a good journey – well-worth making once.’

Winston Churchill
This final chapter will bring the thesis to a close by drawing conclusions based on the collective findings from the four experimental chapters. The results will be synthesised to examine the likelihood that visual clarity is a limitation to interceptive performance, and the integrated outcomes will be interpreted from the perspective of the dual-pathway theory of vision. The methodology used throughout this thesis will be critically analysed to appraise its validity and limitations, followed by an evaluation of the practical implications and future directions for the outcomes of the reported experimental work. Finally conclusions will be drawn in response to the aims outlined at the commencement of this thesis.

6.1 THE EXPERIMENTAL SERIES

6.1.1 Phase I – Blur and Interception

The aim of the first phase in the experimental series was to examine the effect of visual blur on the execution of an interceptive task, in this case using cricket batting to represent a spatially- and temporally-demanding striking task. Experiment I (Chapter 2) was performed to establish the effect of refractive blur on cricket batting, whilst Experiment II (Chapter 3) expanded on these findings by more closely simulating the highly demanding performance conditions experienced at the upper levels of this sporting task.

6.1.1.1 Experiment I – Is optimal vision required for the successful execution of an interceptive task?

The first experiment in this thesis was designed to establish the effect of visual blur on interceptive performance when interception was based purely on ball-flight information. Skilled cricket batters intercepted balls propelled by a projection-machine at medium-paced ball-velocities (105-115 kph) for each of four refractive blur conditions (plano, +1.00, +2.00, and +3.00). Contextual information was provided to guide the batting style of participants, with performance evaluated by two different scores: firstly a simple categorical tool to
evaluate quality of contact (Müller & Abernethy, 2008), and secondly a subjective coach-rating of performance to evaluate achievement of the specified goals for this interceptive task.

Interceptive performance was found to be moderately resilient to refractive blur, with the highest level of blur (+3.00D) required to produce a measurable decrease using either the QOC or coach-rating measures. This finding provided empirical evidence for a range of visual clarity to exist where performance was not adversely affected, and more importantly was noted to be the first study to demonstrate a level of blur where vision does become a limitation to motor performance. The finding corroborated with that of Applegate and Applegate (1992), who found that blur did not affect free-throw shooting performance in basketball even when VA was decreased to 6/75. Furthermore these results have been substantiated in a subsequent study by Bulson et al. (2008), who reported that a reduction in VA to 6/600 was required before there was any significant change in golf-putting performance. However the basketball free-throw and golf-putt represent closed skills where the visual demands are much more simple than for an open skills where there is movement of the target to be intercepted. Moreover novice participants were tested in these other studies, with floor effects potentially limiting how generalisable the results would be to a situation which would test skilled perceptual-motor coupling. Experiment I overcame each of these limitations, demonstrating resilience to blur: (i) for skilled athletes, and (ii) in an open, spatially- and temporally-demanding striking task where there was relative motion between both the target and the hitting implement.

This first experimental chapter demonstrated that clear vision is not a prerequisite for accurate interception, with acuity levels approaching those which constitute legal blindness required to decrease performance. From an optometric perspective, where even the lowest levels of blur (+0.25) are reliably seen to decrease perceptual acuity, this finding would be considered somewhat surprising. Although this study demonstrated that ‘normal’ vision is not a limitation to performance, it did not examine the advance kinematic information which is
normally available in hitting tasks and is known to facilitate skilled interception (Jones & Miles, 1978; Renshaw et al., 2007; Shim et al., 2005), nor did the temporal demands of the task reflect those inherent at the highest levels of competition. Furthermore, it is possible that the measures used to evaluate performance (QOC and coach-ratings) were insufficiently sensitive or comprehensive enough to effectively detect potential modifications in movement control - such as less forceful bat-swings - which may have been employed to maintain effective interception with increasing blur.

6.1.1.2 Experiment II – The resilience of natural interceptive actions to refractive blur

The second experiment sought to determine whether the findings of Experiment I would extend to conditions more accurately reflecting the environmental constraints under which skilled participants would be expected to perform. Skilled batters intercepted balls from both a projection-machine and in-situ bowlers, doing so under the same four conditions of visual blur used in Experiment I (plano, +1.00, +2.00, and +3.00). Two ball-velocities were presented, classified as medium- and fast-paced. Participants were instructed to intercept the ball in a fashion likely to maximise the runs scored in a game situation but to concurrently minimise their likelihood of dismissal. Experiment II therefore extended on the first experiment in three ways. First, Experiment II examined whether the resilience to blur found when facing a projection-machine (in Experiment I) also holds when facing a bowler in-situ. It was proposed that an earlier blur-induced decrease in performance would be found if clear vision was a necessity for the ability to use advance kinematic information to facilitate interceptive performance. Second, ball-velocity was moderated to examine whether the resilience of interception to blur would still hold when the ball-speed was increased to simulate the more extreme temporal demands experienced by skilled cricket batters at the highest levels of competition. Third, in an attempt to improve and extend on the scoring method used in Experiment I, three systematic categorical scores (quality of contact,
forcefulness of bat-swing, and likelihood of dismissal) were used to more comprehensively measure the batter’s response and better reflect the ability of participants to achieve the goals of the task.

In the replication and extension of Experiment I, three particular findings were of interest. Firstly, the results when facing medium-paced trials from the projection-machine replicated those of Experiment I: the highest level of visual blur was required before a significant decrease in batting performance was observed (specified by significant decreases in both QOC and FoBS). There was no change in the FoBS for lower levels of blur, indicating that modulation of batting aggressiveness was not necessary to maintain performance at these lower levels of blur. The second important outcome revealed that the resilience to blur found against the projection-machine extended to comparable trials when facing in-situ bowlers. The score for batting aggressiveness (FoBS) was significantly greater against the bowlers than it was against the bowling-machine, though only for the plano visual condition. This may be because the advance information provided in-situ by pre ball-flight kinematics may help facilitate earlier movements (Shim et al., 2005) which, in turn, afford better positioning for more aggressive interception (Renshaw et al., 2007). The third finding of interest concerned performance across the two different ball-velocity conditions. A lower level of blur (+2.00) was found to adversely impact on interceptive performance in the fast-pace condition; this was evident in terms of a significant decrease in QOC but no change in FoBS or LOD. This study therefore demonstrated that clear vision was not necessarily required for optimal performance, even in a case where the temporal constraints of the task approach the upper limits achievable by the visual-motor system.

6.1.2 Phase II - Blur and Anticipation

The aim of the second experimental phase was to examine the effect of visual blur on anticipation, a skill known to be an important element of expertise for many striking tasks.
Anticipatory skill is conventionally tested using temporal occlusion, with participants observing a video display and predicting the likely outcome using a verbal or pen-and-paper response (Abernethy et al., 1993). Although this paradigm has consistently demonstrated an advantage for expert sportspeople, it fails to accurately reflect the perceptual and motor conditions characteristic of the performance environment (Farrow & Abernethy, 2003). Furthermore, the visual information used for participant responses in these relatively artificial testing conditions may be different to the visual information sourced for responses which are a result of online visual-motor control (Brown et al., 2005; Króliczak et al., 2006; Milner & Goodale, 1995). An uncoupled perceptual response is likely to be produced via the ventral visual pathway which is reliant on clear input of fine visual acuity; as a result a low level of visual blur may be expected to adversely affect such a response. On the other hand movement-based responses are likely to be produced based on relatively impoverished visual information via the dorsal pathway, and hence are less likely to be affected by visual blur. Accordingly this experimental phase sought to examine the effect of blur on anticipation, with participants predicting event outcomes using both a coupled response (which simulated the performance environment), and an uncoupled response (which replicated laboratory conditions).

An in-situ design which would require interception to test anticipation presents considerable logistical, methodological, and ethical issues; hence Experiment III (Chapter 4) was performed to establish the minimal requirements necessary to elicit optimal levels of skilled anticipation. Subsequently the results informed the design of Experiment IV (Chapter 5) which examined the effect of blur on both a coupled prediction (which best reflects the performance environment) and an uncoupled prediction (representing the conventional method of testing anticipation) of event outcome.
6.1.2.1 **Experiment III – Action specificity increases anticipatory performance and the expert advantage in natural interceptive tasks**

Experiment III set out to establish the conditions necessary for the examination of blur on coupled and uncoupled anticipation. Within the context of this experimental series, Experiment III was performed with three specific aims in mind. The first aim was to ascertain whether, when based on pre ball-flight information, a coupled response would enhance anticipatory performance beyond that for a perception-only response. Following this, the second aim was to establish the degree of action specificity necessary to optimise skilled anticipation. In other words, it sought to establish how closely the coupling between action and perception must be in order to maximise skilled anticipation. The third aim was to manipulate the presentation display shown to participants to compare the coupling-based anticipatory response across natural (in-situ bowlers) and simulated (video) display stimuli.

Skilled and novice cricket batters anticipated ball direction in four response conditions which systematically varied how specifically the action represented the typical cricket batting response. These response conditions were, in increasing order of specificity: a verbal response, a response using only the lower body, a response using whole body movement but without a bat, and the intact, natural movement response in which coordinated movements of the whole body and bat were used. Participants observed both in-situ bowlers and an equivalent video simulation, with PLATO occlusion goggles and video editing used respectively to present three temporal occlusion conditions: occlusion prior to ball-release, occlusion 50ms post-ball release, and no visual occlusion.

The increases in perception-action coupling resulted in significant improvements in anticipation for skilled (but not novice) participants facing the in-situ bowlers. For those trials occluded prior to ball-release, the coupling of action with perception produced superior anticipation when compared to that possible with uncoupled responses. This study is the first to demonstrate that coupling may enhance anticipation based on pre ball-flight information,
with this finding proposed to be a result of the more realistic and valid experimental conditions when compared to previous studies (e.g., Farrow & Abernethy, 2003; Ranganathan & Carlton, 2007).

The addition of a bat (which afforded an opportunity for interception) facilitated significantly greater anticipation above an identical response with the bat removed. This result is consistent with that of Króliczak et al. (2006), who demonstrated that an actual interceptive movement is necessary to test the dorsal visual system, and suggests that an attempt at interception is necessary to elicit most favourable anticipation in skilled athletes. The coupling-based improvements in anticipation evident against in-situ bowlers were not found when observing an equivalent video simulation. When responding to this video simulation, a perceptually-based prediction of event outcome elicited similar levels of anticipation to a movement-based response. This suggests that the artificial nature of these simulations may be insufficient to garner responses of the pathway which generates movement responses.

The results of Experiment III emphasise the importance of experimental conditions simulating those found in the performance environment as closely as possible – fidelity seems to be important for both display and response characteristics. A fully-coupled striking response against in-situ opposition is the most favourable scenario for testing skilled anticipation, most likely providing the best chance to assess the response of the visual-motor system relied on in the “real-world” environment.

### 6.1.2.2 Experiment IV – Visual information underpinning skilled anticipation: the effect of blur on a coupled and uncoupled in-situ anticipatory response

The aim of Experiment IV was to examine the effect of visual blur on anticipatory skill, as measured in two different response conditions: a coupled response reflecting the constraints inherent in the performance environment, and an uncoupled response reflecting laboratory testing conditions. From the perspective of the dual-pathway theory of vision
(Milner & Goodale, 1995), a coupled response is more likely to be testing the dorsal visual pathway which relies on visual input of relatively poor acuity, whilst tan uncoupled response tests the ventral system which relies on very clear visual information.

Skilled cricket batters predicted in each of the two different response conditions the direction of balls projected in-situ by bowlers; doing so in each of four visual blur conditions (plano, +1.00, +2.00, and +3.00). For the coupled response, participants attempted to hit the ball using a bat as they typically would when batting in cricket. For the uncoupled response, participants verbally predicted ball direction. PLATO liquid crystal occlusion goggles were used to occlude the vision of participants for a selection of trials prior to ball-release.

Coupled anticipation was revealed to be resilient to refractive blur; a finding consistent with the relatively blurred visual information relied on by the dorsal visual system. Anticipation based on pre ball-flight information was resilient to up to +3.00D of blur for medium-paced ball-velocity trials, and to +2.00D for fast-paced trials. These results mirrored those found when intercepting balls from the same bowlers in Experiment II. It was proposed that the reduced resilience to blur against the faster bowler was a result of the finer acuity required to resolve the relatively quicker movement pattern of this bowler.

The examination of uncoupled anticipation revealed some most intriguing results. It was hypothesised, a priori, that this task - being ventrally-based - would be highly sensitive to blur. The floor effect experienced in the plano condition reflected the inability of participants to verbally predict ball-direction; a result rendering difficult an examination of decreased performance with visual blur. Remarkably though, visual blur appeared to facilitate uncoupled anticipation. Above chance predictions of ball direction were found in the +2.00 blur condition for the medium-paced trials, and in the +1.00 blur condition for the fast-paced trials. Potential mechanisms for these most unusual findings were proposed based on previous work examining the effect of blur on visual perception. In particular, it was speculated that blur may reduce the perception of high spatial frequency information, forcing the visual system to rely
on information of lower spatial frequency which is more sensitive to the perception of specific movement velocities.

6.2 SYNTHESIS OF FINDINGS

6.2.1 Visual Acuity as a Limitation to Performance

The experimental series provides evidence of a goal-directed interceptive action which exhibits resilience to visual blur. The trials of medium-paced ball-velocity represented the lesser demanding of the tasks presented across the experimental series, yet they still required exquisite timing to successfully intercept balls travelling in the vicinity of 90-110 kph. The resilience of interception for up to +3.00D of blur found facing a projection-machine in Experiment I was firstly replicated in Experiment II, and secondly found to extend to a condition where participants faced in-situ bowlers. Performance in the striking task decreased with levels of blur exceeding +2.00D due to concurrent decreases in QOC and FoBS. No modifications in performance execution were evident for 0-2.00D of blur. The resilience of interception to blur was replicated by an identical effect of blur on coupled anticipation, with resilience again found to exist for up to +3.00D of blur (Experiment IV). Evidently, clear vision is not a necessary requirement for skilled striking of balls projected at medium-paced ball-speeds.

The fast-paced trials represent a marked increase in the requirements for coincidence timing, with temporal demands more accurately representing those experienced at the highest levels of this sport. When compared to the medium-paced trials, an earlier decrease in performance was evident against the fast-paced in-situ bowler (Experiment II). Resilience to +1.00D of blur was evident, with +2.00D required to produce a decrease in QOC. Once again the effect of blur on coupled anticipation replicated that for the interception of fast-paced trials, with +2.00D required to produce a decrease in anticipatory performance (Experiment
Here again, clear vision is concluded not to be necessary for skilled interception. Even approaching what is reported to be the spatio-temporal limits of the human visual-motor system (Regan, 1997), clear vision is found not to be a limitation to striking performance. These results are consistent with the outlined predictions based on the dual-pathway theory of vision (Milner & Goodale, 1995). The dorsal pathway is sourced almost exclusively by the magnocellular visual stream, which is not sensitive to fine visual acuity (Brown et al., 2005; Livingstone & Hubel, 1988; Milner & Goodale, 1995). A compelling case has been put forward to suggest that both the interceptive striking and coupled anticipatory tasks tested throughout this thesis are likely to be activities mediated by the dorsal visual stream. This would suggest that low levels of blur should not affect performance in these actions, a proposition which has been supported by the aforementioned experimental findings. As has been outlined, Norman (2002) used an identical proposition to interpret the outcomes of Higgins et al.’s (1998) study examining the effect of blur on driving a motor vehicle, a study which found that visual blur affected perceptual but not motor tasks associated with driving.

### 6.2.2 Perception-action Coupling

Skilled anticipation was found to improve commensurate with increasing action specificity; this relationship revealed for participants observing an in-situ stimulus but not an equivalent video simulation (Experiment III). This is the first experimental evidence to support the role of movement in enhancing skilled anticipation based purely on pre-ball-flight information. Rather than supporting the existence of a dedicated processor which is capable of only using ball-flight information to facilitate movement responses (Farrow & Abernethy, 2003), it suggests that movement can act upon the relatively more ambiguous advance information which is available prior to ball-release. This is consistent with the model proposed by van der Kamp et al. (2008), which hypothesised that movement-based (dorsal) processing is
capable of acting on pre ball-flight information (see Appendix B for a published response to the van der Kamp et al. paper).

An expert advantage has been consistently demonstrated across the many studies of anticipation, yet the occlusion protocol has been criticised as the anticipation of even the most highly skilled athletes tends to be well below perfect levels of performance. Van der Kamp et al. (2008) outlined that when highly-skilled athletes anticipate event outcomes in a perceptual (ventrally-based) task, they tend to demonstrate errors of considerable magnitude. Here Experiment III has simulated the performance environment as closely as possible, yet when vision is occluded at ball-release, considerable prediction errors are still evident (i.e., performance is still well below 100%). It is clear that the visual-motor system (in this case proposed to be the dorsal system) cannot ‘predict’ exactly where the ball will be before it is released. Indeed other in-situ studies using visual occlusion have shown that almost all ball-flight is necessary for successful bat-ball contact (Müller & Abernethy, 2006a; Müller et al., 2009). There are a number of different perspectives from which to address this issue. Firstly, the action sequence of the batter is best conceptualised as being separated into two movement phases rather than a singular movement, viz. initial body positioning featuring movement of the lower body, and a secondary movement involving the hand-held bat which is swung to intercept the ball. While advance information may be useful for both phases, it is most likely to be useful for the initial positioning phase (see also Ranganathan & Carlton, 2007). This enables the athlete to be in an appropriate position as early as possible. Later, more specific ball-fight information is then necessary for the successful execution of the second interceptive phase. Indeed in the studies performed in this experimental series (Experiments III & IV), when occlusion of vision took place, participants were observed to often be in an appropriate whole-body position (demonstrated by their above chance levels of direction prediction), yet they rarely actually made contact with the ball. This provides some anecdotal support (consistent with Müller & Abernethy, 2006a; Müller et al., 2009; an issue
worthy of further experimental consideration) for the proposition that the advance information is very useful for appropriate positioning, but less so for actual bat-ball contact. Indeed Experiment III demonstrated that this advance information may allow more aggressive interceptive responses to be made, necessitating good and early body positioning movements. The second issue of interest here is the gradual increase in anticipatory performance as the occlusion takes place later in the action sequence. The ability of the skilled athlete to predict event outcomes as early as possible may be seen as a gradual increase in situational probability. Athletes who are sensitive to this meaningful information may be preparing for their anticipated outcome (including loading appropriate muscles ready for early movement) and when confirmatory ball-flight information is available they are more ready to act accordingly. That is to say that rather than relying on advance information to act; it is being used to anticipate their own movements which may be confirmed by ball-flight information. Future studies may take advantage of force plates or EMG to examine how skilled athletes use advance information to help facilitate early positioning movements.

The enhanced anticipation that was revealed when participants were provided with an opportunity for bat-ball interception is consistent with the prediction based on the present understanding of the dual-pathway theory of vision. A number of previous studies of anticipation have used this theory as justification for the incorporation of movement in the participant response (van der Kamp et al., 2008). Króliczak et al. (2006) demonstrated that simply producing a movement may be insufficient to test the dorsal visual system; rather an opportunity for an online interceptive action may be necessary to accurately elicit the involvement of - and to test - this pathway. The significant improvement in anticipation facilitated by the opportunity to intercept (when compared to an identical representative movement without interception - Experiment III) is consistent with the assertion of Króliczak et al. (2006). This is the first demonstration that an opportunity for target interception facilitates a significant improvement in anticipation above and beyond that which results from an
identical movement with no opportunity for interception. The inability of video display conditions to elicit coupling-based improvements in anticipation may be further evidence for the criticality of an opportunity to intercept. No matter how specific the action may be when observing a simulated display, the inability to participate in target interception may force engagement of the ventral vision-for-perception rather than the dorsal, vision-for-action pathway.

It is important to consider whether the temporal occlusion paradigm is a valid methodology to test a response of the dorsal visual pathway. It may be problematic to interpret that a fully-coupled anticipatory movement is indicative of a dorsal response. Online visual information is relied on for the production of dorsally-mediated movements, and hence the occlusion of vision may be expected to interfere with such a response. Króliczak et al. (2006) used temporal occlusion in their discrimination of movements controlled by the dorsal-system, though the key caveat was that occlusion occurred following the initiation of movement. It has been proposed some time ago that the initial body positioning movement that forms a critical part of an interceptive action (such as a baseball swing or cricket stroke) is modified according to online visual information (Hubbard & Seng, 1954) and, more recently, that this movement can be regulated by advance information (Ranganathan & Carlton, 2007). Thomlinson (2009) demonstrated that skilled cricket batters commence their initial stepping movement 80-100 ms after ball-release, and concluded that the initiation of this movement must be based on pre ball-flight information. It seems reasonable then to infer that decisions on movement (albeit subconscious ones) are being generated prior to ball-release.

Experiment III found firstly that anticipation improves concurrent with the specificity of the movement, and secondly that this information embedded in movement may not be consciously accessible via an uncoupled response. These findings infer that different neural pathways are being engaged for movement and, based on the current understanding of the neural visual-motor pathways, it appears reasonable to infer that this may be mediated by the
dorsal visual pathway. As a result the results presented in Experiment III would be consistent
with (but not definitive proof of) the movement decisions of the dorsal pathway not being
readily accessible by the conscious responses of the ventral pathway (for further discussion see
Milner & Goodale, 1995; van der Kamp et al., 2008).

This thesis has conceptually, and at this stage necessarily, separated the functioning of
the ventral and dorsal visual streams (see also Brown et al., 2005; Króliczak et al., 2006). For
example, in Chapters 4 and 5, coupled and uncoupled responses have been assumed to be
outcomes of the dorsal and ventral streams respectively. In reality, and has been discussed
previously (see Section 5.4.2, p. 154), there is an inextricable link between the functioning of
these two systems. For the coupled responses produced when testing anticipation, ventral
stream input accompanies that of the dorsal pathway, and conversely dorsal input may assist
the ventral stream for uncoupled responses. In a complex task such as cricket batting,
successful performance requires the complex interplay of perceptual decisions, interpretations
and planning (all mediated by the ventral stream) with the online visually-regulated motor
skills performed by the dorsal stream (e.g., van der Kamp et al., 2008). Even throughout the
actual execution of online movements, the cognitive functioning of the ventral stream is likely
to play an important mediatory role, for example in changing the force of the bat-swing to
ensure that the ball, after being hit, lands either short of, or beyond, the remembered position
of a fielder. Likewise, the recognition of seam position in the air may produce a change in shot
execution, or the conscious perception of the length of ball-bounce may result in an
intentional decision not to play a shot at all. These complex interactions between the
conscious and sub-conscious have a critical role to play in successful interception, yet few
studies have attempted to unravel how these intricate and disparate sources of information
are capable of producing coordinated and successful motor responses (for exceptions, see
Gray, 2009; Sutton, 2007).
6.3 METHODOLOGICAL CONSIDERATIONS AND LIMITATIONS

A conscious effort was made throughout this thesis to replicate - as closely as possible - the environment in which skilled athletes develop and display their expertise. The benefits of such an approach have been extensively outlined elsewhere (Abernethy et al., 1993; Farrow & Abernethy, 2003; Mann et al., 2007; Shim et al., 2005) and have been further highlighted in this thesis, particularly in Experiment III where increased fidelity in the action response and stimulus characteristics lead to direct improvements in anticipatory performance. The aspiration of enhanced ecological validity in experimental methodology is a “double-edged sword” and a decision to conduct experimentation within the natural setting is not one to be taken lightly. Considerable sacrifices are made in terms of experimental control and rigour; indeed it is important to accept these limitations and to control the experimentation as tightly as possible. In light of the evidence advocating testing protocols which represent the task as closely as possible, scientific paradigms should strive to embrace technological advances in an effort to strike a balance between fidelity and rigour.

6.3.1 The Experimental Task

Within an experimental context it is generally considered preferable to use a closed skill such as a basketball free-throw or a golf-putt as the environment is stable and predictable, and there is considerable experimental control over the task being performed (Poulton, 1957; Schmidt & Lee, 2005). These skills are typically self-paced and have few possible outcomes, therefore rendering the evaluation of performance a relatively simple and objective process. Although closed tasks may be preferable to maximise experimental rigour, they are unlikely to test the temporal and spatial limitations of the visual-motor system. An open skill on the other hand is more likely to represent a situation where the environment is less predictable and is externally paced, requiring greater temporal precision of the performer. Cricket batting has been used as the task of interest throughout this thesis, an open skill where there may be
numerous solutions for any given trial. The examination of such a skill presents a variety of experimental challenges and is not without difficulty. For example, with the imposition of visual manipulations, participants may be able to adapt and produce changes in execution, enabling them to produce alternately acceptable responses. As the experimental series in this thesis has evolved, so too have the attempts to evaluate performance and the changes in task execution. The evaluation of performance in a game is relatively straightforward as there is a direct score reflecting the number of runs scored; doing so in a more controlled experimental context imposes considerable challenges. Experiment I used an established categorical tool to evaluate interception (Müller & Abernethy, 2008) in addition to a coach rating of performance on each trial. The aim of the coach rating was to extend on the QOC score by providing a more holistic evaluation of performance which could allow for other factors such as the forcefulness of bat-swing and the likelihood of dismissal, whilst also allowing for the quality of the delivery. Although the effect of blur on this coach rating was consistent with that for the percentage of all bat-ball contacts, it was highly subjective and lacked clear guidelines to inform systematic scoring. Furthermore, the recruitment of a qualified coach was a burden in terms of time and expense. Experiment II took a more systematic approach to evaluate performance. The three categorical tools employed in that experiment appear to be a fruitful extension on the use of the QOC tool alone in order to better understand the mechanisms underpinning changes in interceptive performance. To facilitate future studies in an experimental context, an overall score of performance may prove to be useful to systematically account for these important performance attributes. Such a score may be calculated using a combination of attributes reflecting the task goal (such as QoC and LoD), and could be validated in actual matches by comparing the calculated performance score to the number of runs scored (see Appendix C for one such example).

The safety of participants was an important consideration in the design of the experimental series, particularly considering the visual manipulations performed in
conjunction with the attempt to strike an approaching ball. Appropriate measures were taken to minimise the risks of injury, including the use of a softer-ball, and the provision for participants to wear extensive padding and a helmet. Experiment III has highlighted the important role for interception in examining anticipation, suggesting that, where possible, participants should be encouraged to perform an interceptive movement to optimally test anticipatory skill. Although there may be good reason for researchers to maximise the ecological validity of these experimental tasks, the potential danger to participants remains when combining interception with visual occlusion. Even with measures put in place, participant safety remained a concern, with a number of trials in Experiment IV using both visual blur and the occlusion of all ball-flight information. In order to better account for the possibility of participants being hit by the ball, a small protective net was used in Experiment IV for both the coupled and uncoupled conditions to protect participants. This net was placed below the primary gaze of participants and therefore did not obscure the batter’s view of the approaching bowler; furthermore it was suspended sufficiently close to participants so that they were able to strike the ball through the net. One concern in using this approach was that the use of a net could minimise the opportunity for interception and as a result could modify the degree of ecological validity. Interestingly however a comparison of anticipation for the comparable coupled conditions both with (Experiment IV) and without (Experiment III) the net in place reveals similar performance for decisions based on pre ball-flight information (71.8 ± 4.4 vs. 68.9 ± 6.7% respectively). This similarity may be interpreted as evidence that the presence of a protective net does not impede the opportunity for interception; therefore it represents a valid experimental adaptation to permit interception whilst concurrently enhancing participant safety. Alternately, there may be a trade off as the decrease in fidelity inherent with the net in place may be offset by an increase in participant confidence as they recognise that they cannot be hit by the ball. Either way, these results support the use of
netting as a viable means of providing participant safety whilst eliciting optimal anticipatory performance.

The recruitment of in-situ bowlers throughout this experimental series has provided enhanced ecological validity but also raises significant methodological limitations. When compared to a bowling-machine, in-situ bowlers provide important advance information which skilled players learn to use for both the anticipation of event outcomes, and for coupling their early movements. When compared to a video display, the use of in-situ bowlers provides three-dimensional information and an opportunity for bat-ball interception. Although this additional information and the ensuing results advocate the use of in-situ displays wherever possible, a number of considerable experimental limitations are apparent. Firstly, the use of live stimuli makes it difficult to ensure that identical visual information is presented to all participants. Trials may differ across testing sessions and hence appropriate allowances are made such as increased trial numbers and strict inclusion criteria for trials to minimise the impact of trial variability across participants. Secondly, a task such as cricket bowling imposes a considerable workload on bowlers, with strict limits to the number of trials that should be performed by each bowler. Accordingly a number of different bowlers need to be recruited to obtain sufficient trial numbers; whilst the same bowlers can be presented across different participants, the reliance on an increased number of bowlers does increase the likelihood of one or more being unavailable due to injury or drop-out. Throughout this thesis, in the event of bowler unavailability, a replacement was sought of similar pace and skill wherever possible. This does, of course, limit the consistency of display stimuli across participants. A third limitation lies in the implicit assumption that the availability of advance kinematic information generalises across different bowlers. For example, in Experiment II the comparison of performance against medium- and fast-paced ball-velocities has been made based on the assumption that the only difference across the two conditions is ball-velocity. Of course the bowler-specific delivery actions could be different across ball-velocity conditions, limiting the
validity of any conclusion that differences are based purely on ball-flight velocity. Ideally a
greater number of (in particular) fast-paced bowlers would be recruited to provide a more
thorough cross-section of bowlers, rather than just observing one specific action sequence.
Recruiting suitable bowlers though is difficult; particularly those competing at the highest level
able to bowl in excess of 130 kph. These limitations are acknowledged but accepted in the
pursuit of suitable ecological validity for the experimental tasks examined in this thesis.

6.3.2 Visual Manipulations

Three of the four studies in this experimental series have used contact lenses to
examine the effect of visual blur on motor and/or perceptual performance; this is in contrast
to previous studies which have relied on spectacle lenses (Applegate & Applegate, 1992;
Bulson et al., 2008; Heasley et al., 2004; Higgins et al., 1998) or blurred video footage (Jackson
& Abernethy, in press) to simulate different levels of refractive blur. The use of contact lenses
in the experiments presented in this thesis was an important advance, particularly when
compared to the use of spectacle lenses for in-situ studies: there was no restriction to the
visual field of participants, no prismatic effects were induced away from the lens centre
(Bennett & Rabbetts, 1998), there was enhanced participant safety without the placement of
spectacle lenses in front of the eyes, and the use of contact lenses ensured that the occlusion
goggles could be used concurrently with blur. The evolution of contact lens materials has
ensured that current generation lenses are extremely soft, thin, and comfortable to wear. As a
result even those who have never previously worn contact lenses are typically able to
habituate to the lenses very quickly (generally within a minute of wear). There is little reason
for the sheer presence of a contact lens of no power to alter performance. [Although a
comparison of no contact lens and a lens of habitual correction was included where possible in
Experiment I, it was excluded from subsequent studies to minimise trial numbers]. As a result,
contact lenses provide a useful and efficient means of inducing visual changes for future studies; this conceivably may facilitate manipulations of blur, contrast, or colour.

Experiments III & IV used an event-related method of in-situ occlusion which improved on the relatively poor temporal resolution possible from the occlusion of vision in previous in-situ studies of anticipation. This new technique (specifically outlined in Appendix A) relies on a force plate to register the occurrence of a repeatable event in the bowling action sequence (BFC). The consistent delay between this event and the subsequent event of interest is used to program occlusion to take place (in this case) at time points relative to ball-release. This new method results in enhanced precision for the moment of occlusion (close to one magnitude) when compared to those previous in-situ studies which have relied on a manual button-press to trigger occlusion (e.g., Farrow & Abernethy, 2003; Müller & Abernethy, 2006a; Müller et al., 2009; Starkes et al., 1995). As a result, a more powerful and sensitive experimental protocol is made possible: it decreases the number of trials which need to be included to account for those trials where occlusion inadvertently takes place outside of the desirable window of occlusion times, and there is more certainty that occlusion took place at a very specific moment in time rather than across a variety of times within a relatively large window of necessarily acceptable occlusion points. This new protocol represents an important advance for future in-situ studies of anticipation, and has the potential to be applied across a variety of experimental tasks within the sporting domain.

6.4 PRACTICAL IMPLICATIONS

6.4.1 Skill Acquisition

The potential use of low levels of visual blur to implicitly train visual attention has been an intriguing prospect which has arisen as a result of the experimental findings presented in this thesis. It is well established that an external focus of attention may be beneficial for the
performance of skilled athletes (Beilock et al., 2002; Wulf, 2007). An internal focus of attention on the other hand is frequently associated with the breakdown of well-learned habitual skills (Beilock & Carr, 2001; Masters & Maxwell, 2004). This internalisation can occur particularly following a prolonged period of poor performance, as the athlete may concentrate on performance execution in an attempt to correct what are perceived to be errors in the kinematic execution of the skill (Masters, 2008). As the experiments performed throughout this thesis evolved, it became apparent that rather than the blur acting as a hindrance to batting, a number of participants demonstrated an anecdotal preference for batting with low blur (primarily the +1.00 condition). Participant comments (which were formally recorded but not reported in Experiments II & IV - see Appendix D) revealed a number of references to participants feeling that they were watching the ball more closely in the blur conditions, an effect that some participants felt led to better batting performance. This raises the possibility that visual blur may alter the focus of attention of participants when batting. Blur in the vicinity of +1.00D has been demonstrated here to provide no impediment to the safe execution of any aspect of performance, yet participants appear to perceive the task as being more difficult. Although it is clearly speculative at this stage, such a level of blur may prove useful to facilitate a safe means of modifying attentional behaviour in a training context.

Rather than focussing on their own movement kinematics and/or other internal factors, the apparent perception of increased difficulty that the batter experiences with blur may encourage a more external focus of attention, forcing batters to watch the ball more closely, and to ‘pick-up’ the early ball-flight information as quickly as possible. Further work is warranted to explore whether such an effect is reproducible, and in particular whether a period of batting with blur would firstly alter attentional behaviour, and secondly whether any change would be maintained when the blur is removed. This potential training effect will be revisited shortly.
Consistent with previous studies of skilled performance, the results of this thesis have highlighted the limited role for automated projection instruments such as bowling-machines in the acquisition of skill (Pinder et al., 2009; Renshaw et al., 2007). Skilled anticipation (as represented by the prediction of ball-direction in Experiments III and IV) is based on the detection of advance kinematic information evident from the opposing player’s kinematic movements (Abernethy et al., 2001; Jones & Miles, 1978). Skilled athletes learn to couple movements to this pre-release information in the process of developing their interceptive skill (Pinder et al., 2009; Weissensteiner, Abernethy, Farrow, & Müller, 2008). Evidently if a projection-machine is used as the basis for learning interception, it precludes the ability of the batter to couple movements to this advance kinematic information to facilitate performance. This highlights the importance of learning to play against other players rather than projection-machines and applies to numerous sports such as tennis, baseball, volleyball, and cricket. However rather than completely ruling out the usefulness of projection-machines in the practice environment, these instruments may still have an important role to play in the accumulation of sufficient training volume when other players are not available. For skilled players bowling-machines can also be a useful tool for building confidence and for working on pre-determined shots or skills. The important message for coaches may be that the bowling-machine can play a specific role in practice and for building confidence, but that it has limited value in facilitating the learning of interceptive skill.

Tests of anticipation have been pinpointed as a potentially useful tool for talent identification and to monitor skill development (Weissensteiner et al., 2008; Williams et al., 1999), yet the results of Experiment III suggest that caution should be exercised unless these tests are highly specific to the task it represents. Testing paradigms which simplify the represented task (either in the display or response characteristics) will typically demonstrate an advantage for skilled observers, but it is evident that this will provide an under-representation of that true expert advantage (Farrow & Abernethy, 2003; Mann et al., 2007;
Shim et al., 2005). In a practical sense this diminished effect of skill is often accepted in order to facilitate administrative, logistical, and methodological convenience. Yet it is important to point out that no study to date has demonstrated evidence for a correlation to suggest that those who score well in the most representative test will also be those who rank highest in the more diminished task representation. That is to say that there is no evidence to suggest that a good score in a test with a moderated representation will predict good performance in the more coupled task. It may be that some athletes possess very good procedural/declarative knowledge and perform well in a perceptually-based task, but this may not transfer to a situation where a real-time motor response is required. Furthermore the anticipation of ball direction in Experiments III & IV provides an example of a task which skilled athletes are able to perform when a coupled response is generated, yet their chance levels of guessing in the verbal response condition appears to suggest that they have no conscious knowledge of how to do so. If this verbal test (or even a movement-based response when observing video footage) was used to test for skill, it would have provided a false representation of the true skill which these athletes appear to possess.

6.4.2 Optometric Perspective

Based on the experimental results of this thesis, it would be easy to assume that the correction of refractive errors is unnecessary when playing sport. Although it has been demonstrated that clear vision may not be a necessary precursor for optimal sporting performance, this does not imply that vision should not be corrected for these tasks. There does not (at this stage) appear to be any clear advantage in leaving athletes uncorrected; considering the importance of other skill-relevant tasks including reading a scoreboard and detecting signals from other players who can be considerable distances away, there certainly are still good reasons to optimally correct vision. Van der Kamp et al. (2008) have ascribed a clear role for the interaction between the dorsal and ventral streams in sporting skills, so clear
vision may well be important for those ventrally-based tasks such as a baseball batter
detecting the rotation of the stitching on the ball, or a cricket batter noticing the finger and/or
wrist position of the bowler, to better inform dorsally-based movements.

A critical contribution of this experimental series has been a demonstration of how
good visual acuity needs to be in order to support successful interceptive performance. From
an optometric perspective it has been suggested that the findings are surprising; belying the
natural assumption that clear vision is a necessity for optimal performance (Gardner &
Sherman, 1995). The results help to explain why athletes tend to demonstrate a similar
prevalence of visual deficiencies to the general population, and suggest that it is not so
surprising that anecdotal stories exist of elite athletes who have successfully competed at high
levels of competition with sub-normal vision. Vision specialists should exercise caution when
correcting the vision of athletes who may have been competing with poor vision over a long
period of time. There may be an expectation that the correction of this refractive error would
improve performance markedly (Sherman, 1980); this may be a promise though that does not
bear fruition. In reality it may garner increased confidence, but be of minimal or
inconsequential direct benefit to task performance. The relative benefits of such a correction
must be assessed in light of these findings, and communicated to the athlete accordingly.

Although the experimental series reported here has not directly examined a visual
attribute typically targeted by generalised vision training programs (e.g., Revien, 1987; Revien
& Gabor, 1981), it would be remiss to not briefly address this issue in a review on vision in
sporting activities. Generalised vision training has generated significant interest throughout
the literature on sporting expertise (Abernethy & Wood, 2001; Williams et al., 1999; Wood &
Abernethy, 1997), and has resulted in what may be seen as a misrepresentation of the
optometric profession. Such programs, said to benefit all athletes rather than just those with
visual deficiencies, are advocated by a small subsection of vision specialists rather than by the
wider optometric profession. It is important to make a clear and strong differentiation
between the targeted vision training conducted on those with deficiencies, and generalised training programs which are performed *irrespective* of the presence or absence of a visual deficiency. Behavioural Optometrists will typically train visual skills if, and only if, there is evidence of a deficiency requiring correction (cf. Ward & Williams, 2003; Weissensteiner, 2008). A small number of studies have demonstrated the inefficiency of these generalised training programs (Abernethy & Wood, 2001; Wood & Abernethy, 1997), although one may question whether visual skills were likely to be a limitation to the performance of the novice populations used in these studies. It has been shown here that a visual attribute as fundamental as visual acuity is not necessarily a limitation to sporting performance. The challenge for those who advocate generalised vision training is to demonstrate, rather than assume, that these attributes being trained are a limitation to performance. Furthermore, any improvement in these skills must be shown to transfer into measurable improvements in sporting performance.

## 6.5 FUTURE DIRECTIONS

### 6.5.1 Sports Vision

Visual acuity has been used as the visual attribute of interest throughout this experimental series. Whilst a clear case has been made for the role of clear vision as a primary assessor of visual performance, this finding does not necessarily generalise to other visual characteristics such as stereopsis, contrast sensitivity, and monocular blur. These attributes, all likely at some point to influence striking performance, may prove to be more or less of a limitation to performance than binocular blur. This thesis has presented a framework for the empirical verification of how critical to performance a visual attribute may be. It would be overly zealous to suggest that this framework should be repeated across the whole range of visual attributes; indeed there are many, and some are difficult to manipulate in isolation. The
framework can, though, be applied to those attributes which may be of particular interest. For example, the lighting levels necessary to facilitate sufficient visual contrast to support optimal performance has recently been of interest in a number of sports. Continuing with cricket as the sport of interest, current playing laws require umpires to make a subjective assessment of lighting as being sufficient to continue play (International Cricket Council, 2009). This degree of subjectivity results in inconsistencies across different matches, and has exposed umpires to substantial criticism when making decisions others perceive to be incorrect. A systematic analysis for the level of visual contrast necessary to support optimal performance would have the potential to generate evidence-based rules for assessing the suitability of lighting levels for play; as a result light-meters could be used rather than relying on umpires to assess the suitability for play. Most importantly, the dual-pathway theory of vision provides additional evidence that a perceptual interpretation of sufficient contrast may be an inaccurate reflection of the true contrast levels necessary to support optimal interceptive performance. The dorsal visual pathway is understood to be highly sensitive to contrast (Milner & Goodale, 1995), and it is conceivable that the dorsal pathway may be more sensitive to decreased lighting levels than what would be assumed to be the case when relying on conscious (ventrally-based) perceptions of contrast. The framework presented throughout this thesis provides a methodology for the empirical verification of the critical role for contrast in online interceptive actions such as hitting and catching (cf. Campbell et al., 1987), and how this may differ to the effect of lighting/contrast on conscious (ventral) decisions required, in particular, for umpiring tasks.

It has become widely accepted across the literature on sporting expertise that skilled sportspeople are not characterised by superior visual attributes, though ceiling effects have been identified in this thesis as a potential limitation for a number of these expert-novices comparisons. Anatomical limitations mean that numerous characteristics such as visual acuity, contrast sensitivity, stereopsis and colour vision are unlikely to extend to ‘supra-normal’ levels.
This also highlights that there is minimal improvement or ‘trainability’ for many of these attributes. This does not, though, apply to all visual characteristics. The exhaustive literature review performed in Chapter I (summarised in Table 1-1) highlighted several factors such as eye movements and ocular-motor alignment which may warrant further examination. An important differentiation here is that these particular skills tend to be trainable and may be enhanced with (rather than being a necessary precursor for) the development of skill. For example the potential for skilled athletes to possess superior eye movements has arisen numerous times throughout this thesis, particularly in light of expert differences in dynamic visual acuity (Burg & Hulbert, 1959; Hoffman et al., 1981), the acceleration profile of eye movements (Morgan, in press), and visual search patterns (Savelsbergh et al., 2002; Williams et al., 1994). Although visual search patterns are more likely to reflect perceptual-cognitive rather than ocular characteristics; there is insufficient evidence to conclude whether skilled athletes possess superior neuromuscular control of the extraocular muscles. Such a skill would be reflected by superior acceleration profiles for eye movements, resulting in faster and more accurate fixations (Morgan, in press). Considering the critical role for the online coupling of perception and action (Bootsma & van Wieringen, 1990), more accurate target fixations have the potential to facilitate superior visual-motor control. Current eye-movement registration systems used for research into sporting expertise lack the temporal precision necessary to detect the potentially fine differences that may exist across skill levels. The concurrent measurement of traditional means of visual search along with technologies such as electro-oculography (EOG) recordings may prove to be fruitful; this would combine the spatial precision of eye-camera systems with the known temporal accuracy of the EOG. If expert-novice differences are found in an evaluation of the neuromuscular control of extra-ocular muscles, subsequent examinations must determine whether this comprises an essential cause, or is simply a by-product, of expertise.
6.5.2 Action Specificity and Skilled Anticipation

Experiment III has added weight to the argument that greater action specificity will elicit enhanced anticipation, yet the results of Experiment IV were used to speculate that this could be explained by the different visual information relied on, rather than simply by changes in ecological validity. This is highly speculative though may be worthy of further consideration. The present understanding of both the visual input and the interactions between the dorsal and ventral visual streams makes this type of work rather complicated. Further work which examines ventral processing and how its response to visual degradation compares to established dorsal responses may help to shed light onto this otherwise difficult issue to resolve.

The role of action in the development of anticipatory expertise is poorly understood, and is another related issue worthy of further consideration. Aglioti et al. (2008) have recently presented evidence to suggest that engagement of the motor system may play a role in the proficient anticipation of action sequences. Much is yet to be learned of how this skill is acquired – for example little is known about the neurological basis, the time-course of acquisition, and the degree of transfer or generalisability of anticipation across different movement patterns. Recent work has suggested that anticipatory skill may develop at a point later in the developmental spectrum when it is required to overcome temporal constraints (Weissensteiner et al., 2008), implying that anticipation may be born out of necessity rather than as a by-product of motor development. Anticipatory skill can be learned as part of a training program (Abernethy, Wood, & Parks, 1999; Farrow, Chivers, Hardingham, & Sachse, 1998; Singer et al., 1994; Williams, Ward, & Chapman, 2003; Williams et al., 2002; Williams, Ward, Smeeton, & Allen, 2004), though acquisition may be advantageous if performed in a more implicit manner (Farrow & Abernethy, 2002). To date there has been little or no consideration of anticipation at an individual level – whether the development of anticipatory skill is a necessity for expert performance, or how those who do not develop this skill are able
to compensate in order to support expert performance. There appears to still be a great deal to learn about the development of anticipatory skill. Future paradigms will need to carefully consider the relative trade-offs between the superior ecological validity of in-situ designs and the methodological convenience of more artificial simulations.

6.5.3 Visual Blur

The novel concept of using a low level of visual blur to modify the attentional behaviour of athletes has been put forward on what may be a sound theoretical basis; nonetheless empirical verification is certainly necessary to support such a proposition. If low levels of visual blur do successfully modulate attentional behaviour, then experimental interventions such as the dual-task paradigm (Abernethy, 1988a; Parker, 1981) or those imposing an internal/external focus of attention (Beilock et al., 2002) may be useful in providing insights to such an effect. Furthermore rather than simply relying on assessments of overall performance, more sensitive measures of performance execution may prove to be useful in establishing how low levels of blur modify behaviour. For example the visual manipulation (in this case blur) may result in the favourable modification of visual-search behaviours thought to support skilled performance. If visual blur does guide attention towards early ball-flight information, the use of eye-tracking instruments may be used to reveal whether there is any modulation of the early predictive saccade thought to be an important component of interceptive expertise (Land & McLeod, 2000). The registration of kinematic changes that occur as a result of visual manipulations along with an investigation of new technologies such as accelerometers, gyroscopes, force-plates and vibration sensors may also prove useful in detecting changes in performance execution with the introduction of low levels of blur. If any of these factors associated with expertise are found to be favourably modulated with the use of blur, a training study may be warranted to determine whether these changes can be maintained when the blur is removed. If this is found to be the case, visual blur may
prove to be another useful and unique tool for coaches to use in specific and appropriate conditions to modify athletic performance.

The tentative conclusion from Experiment IV that blur may facilitate the uncoupled perception of movement (as evidenced by increased anticipation) is another outcome from this experimental series that certainly appears worthy of further consideration. It was proposed that visual blur may compel the visual system to rely on lower spatial frequency information which is known to be more sensitive to movement. Such an effect would only occur for ventrally-based tasks which would typically rely on visual information of high spatial frequency, and hence one would not expect such an effect of blur when performing an online (dorsally-based) movement task which is already highly movement sensitive. Considering that the results of Experiment IV were based on a small number of subjects and a small sample of different movement patterns (from, in this case, bowlers), replication of these and Jackson and Abernethy’s (in press) results certainly appears necessary. Furthermore if this is demonstrated to be a replicable effect then extensive work is warranted to firstly provide a better understanding of these findings, and secondly to explore whether visual blur may be applied to enhance the performance of tasks requiring judicious decisions based on the perception of movement. For example it would be useful to establish whether this finding generalises to the perception of other type of movements, and the necessary movement-velocity for such an effect to occur. Moreover it would be useful to know whether blur enhances movement perception based on the pure kinematic information present in a point light display (Johansson, 1973), or whether important featural information is necessary to produce such an effect. On a much more contentious note, there was tentative speculation in Experiment IV that visual blur may force the ventral system to act more ‘dorsal-like’. One way to explore such a hypothesis may be to replicate the protocol of Króliczak et al.(2006), who differentiated the responses of the dorsal and ventral visual systems using the perception of the hollow-face illusion. If blur were to make the response more dorsal-like, then the uncoupled ventral
responses which were fooled by the illusion in the protocol of Króliczak et al. would be expected to switch at some point to act like the dorsal system and no longer be fooled by the visual illusion. If the effect of blur on movement perception is better understood, there may be significant implications both within and beyond the sporting domain. Blur may be used in the learning process to attune the observer to the key visual information in a display; with studies examining whether such an acquired skill can be maintained with the removal of blur. The finding may also have wider implications for systems designed for motion recognition, for example in the development of automated methods of biometric gait recognition (e.g., Boyd & Little, 2005).

6.6 CONCLUSIONS

This research has shown that a complex interceptive task - even with highly demanding spatio-temporal constraints - can be resilient to induced visual blur. Clear vision is concluded to not necessarily be a necessity for skilled coincidence timing. This finding appears to be in contrast to conventional optometric wisdom, or what would be ‘assumed’ to be the case. On this basis it is not surprising that athletes have been reported to successfully compete at the highest levels of their sport despite demonstrating below-normal vision. Whilst stopping short of recommending that optimal correction is not necessary for sport, it is recommended that caution be exercised in suggesting that the correction of a previously uncorrected deficiency will result in marked improvements in performance.

The resilience of online motor tasks to blur is consistent with predictions based on the dual-pathway theory of vision, which differentiates the dorsal and ventral visual pathways based on the intended use of the incoming visual information. Visual clarity is not thought to be a critical characteristic of visual input to the dorsal system, and this has been reflected by low levels of visual blur having no effect on the performance of what have been interpreted to be dorsally-based tasks. This theory has been used to both question existing assumptions of
skilled motor performance, and to inform appropriate experimental designs which may facilitate a better understanding of the essence of sporting expertise. In particular it is concluded that an opportunity for interception is necessary to truly test the degree of expertise inherent in skilled anticipation, and that any simplification of either the display or response characteristics when testing such a skill will result in a diminished manifestation of expertise. This adds further weight to the argument that skilled athletes may have very little conscious awareness of the skills and movements which they have acquired over many years of extensive practice. Rather than visual blur resulting in decreased performance, some evidence has been presented to suggest that blur may actually enhance the conscious visual-perceptual discrimination of movement patterns. It has been suggested that this effect may be the result of blur inducing a shift from a reliance on high to relatively lower spatial frequency visual information which is more sensitive to movement detection, however further work is required to better establish the existence of this peculiar finding.

Relatively recent neuroanatomical developments have provided an important theoretical framework for this thesis, with an underlying theme that ecologically valid methodologies are important to best examine how these findings may be applied to further our understanding of expert performance. New technologies allow what have previously been laboratory-dependent studies to progress into the natural setting. Although cognisant of the methodological and logistical limitations of these newer techniques, this thesis has added to the now overwhelming evidence for the critical importance of experimental designs which seek to replicate the performance environment as closely as possible. As our understanding of the human visual-motor system rapidly evolves, stronger hypotheses can be developed to further our understanding of the remarkable feats of skill exhibited on the sporting field. Those who embrace these neuro-anatomical and technological developments will be best placed to progress our understanding of the critical role of vision in complex interceptive actions.
'You don’t need to be bright to be a scientist, you just need to be persistent as hell.'

*Dudley Herschbach*
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APPENDIX A

AN EVENT-RELATED VISUAL OCCLUSION METHOD FOR EXAMINING ANTICIPATORY SKILL IN NATURAL INTERCEPTIVE TASKS

This appendix outlines a new methodology (used in Experiments III & IV) for the in-situ occlusion of vision.
INTRODUCTION

Skilled performance in high-speed interceptive tasks relies upon finely tuned perceptual-motor responses developed over many years of extensive practice. For interceptive sporting skills such as a return of serve in tennis or a goalkeeper saving a soccer penalty, every moment counts, and skilled athletes effectively ‘make time’ by superior anticipation. This involves being more attuned to kinematic information provided by the opposition player’s movements available prior to ball flight (Abernethy & Russell, 1987; Jones & Miles, 1978). The skilled baseball batter, for example, can ‘read’ the body movements of the pitcher to anticipate the type of pitch before the ball is released. This early information pick-up may, in turn, facilitate earlier selection and initiation of the most appropriate hitting movement, consequently improving hitting performance (Shim, Carlton, Chow, & Chae, 2005).

Using Visual Occlusion to Measure Anticipatory Skill

Testing for skilled anticipation has predominantly used a temporal occlusion paradigm, in which the contribution to performance of visual information available before specific points in an event sequence is examined through occlusion of all subsequent visual information. The most common time point for occlusion in studies of sports anticipation has been the final moment immediately prior to the availability of confirmatory ball-flight information; for example the point of racquet-ball contact when receiving the tennis serve, or foot-ball contact when keeping goal against a soccer penalty kick.

The temporal occlusion paradigm has relied heavily upon the use of video display simulations to maintain experimental rigour and simplicity of administration (Abernethy, Thomas, & Thomas, 1993). Participants typically view footage edited to occlude display information at critical points in the action sequence and, following occlusion, are required to predict the resultant ball direction (or other key characteristics) either verbally or using a pen-
and-paper response. Video displays, although methodologically convenient, are limited when seeking to accurately simulate the full visual information inherent in a natural display. Some characteristics, such as the three-dimensional information aiding depth perception, is inevitably either lost or diminished in most video simulations. The temporal occlusion paradigm can be applied in-situ using liquid crystal goggles that are capable of transitions between transparency and opacity within 5 ms (Milgram, 1987). This provides an important advance in ensuring that the visual information presented more accurately replicates that experienced in the performance environment. Studies examining expert anticipation in-situ using liquid crystal goggles have usually reproduced the expert advantage noted in laboratory studies using video simulations (e.g., Abernethy, Gill, Parks, & Packer, 2001; Farrow, Abernethy, & Jackson, 2005; Müller & Abernethy, 2006; Müller, et al., 2009; Starkes, Edwards, Dissanayake, & Dunn, 1995).

Rather than relying on verbal or pen-and-paper responses, a further improvement in the design for numerous studies of anticipation has been to preserve the natural coupling between perception and action by more accurately representing the actual movements produced in the performance environment. Early attempts to allow for this did so using simplified movements performed when observing video based simulations (e.g., Savelsbergh, Williams, Van der Kamp, & Ward, 2002; Williams & Davids, 1998). Examinations of anticipation using protocols that require naturally coupled movement responses are desirable though as verbal and/or simplified motor responses may be simply unable to elicit responses via the same visual-motor pathways relied upon in-situ. For example, a response stimulus providing an opportunity for target interception is more likely to accurately test the vision-for-action pathway relied on in the performance setting (Króliczak, Heard, Goodale, & Gregory, 2006; Mann, Abernethy, & Farrow, 2010; Van der Kamp, Rivas, van Doorn, & Savelsbergh, 2008). More recently, in-situ study designs have allowed more natural movements to occur, providing the opportunity for interception between an object and target (Farrow & Abernethy,
Appendix A An event-related method of occlusion

Farrow and Abernethy (2003) used an in-situ design in an attempt to demonstrate that observation of the full magnitude of the expert advantage requires a movement which maintains the natural coupling between perception and action rather than a verbal response. Obviously, wherever possible, experimental designs should replicate the perception and action requirements of the performance environment as closely as permissible to permit a full picture of expertise to be gained.

Challenges in Using Occluding Goggles to Examine Anticipation In-Situ

In-situ studies, while more closely simulating the natural performance conditions, are currently limited by an inability to accurately occlude vision at specified times in natural actions like hitting, throwing and bowling. Video-based simulations are able to occlude vision within one frame (typically 33-40 ms) of any specific point of interest. In-situ occlusion studies in contrast - where event-related occlusions are achieved by an experimenter pressing a button to manually estimate the trigger point for occlusion - typically accept time windows up to 300 ms (Farrow & Abernethy, 2002; Müller & Abernethy, 2006; Müller, et al., 2009). High-speed video footage has been used to perform post-hoc analysis of occlusion times in an effort to overcome such a limitation, ensuring that only those trials meeting inclusion criteria are considered for analysis. A consequence of this is that larger trial numbers are typically conducted to compensate for those to be discarded, and this creates a particular problem in terms of the workload requirements of the actor(s) performing the action to which the participant is responding. To enhance stimulus reproducibility across participants it is desirable for the same actor (or at least only a small set of actors) to be viewed by each of the participants; this would result though in high workloads for actors even without the issue of trial loss/duplication resulting from errors in administration of the occlusion condition. Clearly a method to more accurately occlude vision in-situ is desirable, and this necessitates the development of a more precise event-related trigger for the occlusion points of interest.
Oudejans and Coolen (2003) occluded the vision of basketball free-throw shooters using an online assessment of kinematic changes, improving on the button-press approach. Although this technique presents an adaptable and potentially accurate means of occlusion, it relies heavily upon extensive knowledge of computer programming for algorithm development to detect movement patterns, and the use of expensive and specialised equipment. A simple and accurate means of occlusion is desirable to provide an alternate approach to advance on currently available methods for the application of occlusion methods in-situ.

This report outlines the development of a new method for accurate, event-related occlusion of vision in-situ. A four-step process was followed. First, we identified a typical interceptive task from a high-speed sport (the task of batting in cricket) for which the in-situ measurement of anticipatory skill using a temporal occlusion methodology has been deemed desirable. Second, we examined the event sequence within this task to identify a measurable, repeatable event (Event 1) that preceded the event of interest for occlusion (Event 2). The temporal lag between these two events was measured and the consistency of this lag verified both within and between individuals. Third, an automated system was developed for the controlled occlusion for time points relative to Event 2, based on triggering from Event 1. Finally, timing occlusion accuracy with respect to Event 2 was validated with the results compared to those for the manual triggering methods reported previously in the literature.

**METHODS**

The four step process took place as follows;

**Anticipation in Cricket Batting as a Test Case**

An abundance of time-stressed interceptive tasks exist for which early pick-up of visual information facilitates performance; we chose the task of cricket batting in which a batter attempts to hit a ball projected towards them by an opposition bowler at velocities that can
exceed 150 kph. Batters must overcome severe time constraints in order to be successful, with as little as 450 ms of ball-flight available for the execution of a successful response. Proficiency in anticipation of ball-flight characteristics can aid in overcoming these demands; the earlier these features are identified, the greater the time available to carry out a response (Abernethy, 1981). Early information pick-up can make possible successful bat-ball contact that may not have otherwise occurred, or more subtly, may enable earlier body positioning which, in turn, may permit a more aggressive (and hence a more effective) bat-ball contact. In laboratory-based temporal occlusion studies using video displays, skilled cricket batters have been shown to be better than novices in anticipating delivery characteristics prior to the ball being released by a bowler (Abernethy & Russell, 1984; Müller, Abernethy, & Farrow, 2006; Penrose & Roach, 1995). In-situ studies using occluding goggles (e.g., Müller & Abernethy, 2006; Müller, et al., 2009) confirm this advantage for expert batsmen. The in-situ examination of anticipation in cricket batting is an important methodological advance, recognising the essential perception-action coupling embedded in skilled movements (Farrow & Abernethy, 2003), and affording a consideration of the additional importance early ball-flight information may have for expertise in batting (Land & McLeod, 2000; Müller & Abernethy, 2006; Müller, et al., 2009).

Cricket bowling provides a suitably reliant movement sequence with deterministic kinematics to help specify particular characteristics in advance of ball-flight. The bowler can produce different deliveries with very distinct characteristics (e.g., ball direction, ball swing) which require their own distinct kinematic nuances, providing skilled batters sensitive to these with an opportunity for picking up identifiable advance information. In the bowling action sequence (Figure A.1), a bowler runs towards the batter and jumps into a final ‘delivery stride’ prior to ball-release. In this stride, the furthest (back) foot from the batter lands first, followed by the leading (front) foot, each landing with considerable peak vertical ground reaction forces (front foot: 2.37 x body weight; back foot: 5.75 x body weight; Hurrion, Dyson, & Hale, 2000).
The landing of each foot proceeds the moment of ball-release. This reliable sequence of events, plus the extent of the foot-ground interaction, presents potential for the automated triggering of occluding goggles.

**Identification of a Measurable, Pre-Occlusion Event**

Occlusion points in studies of anticipation skill are generally designed and expressed relative to a single critical event: for cricket bowling this is characteristically the moment of ball-release. Occlusion points immediately prior to ball-release are of interest to examine how early predictions about ball type and direction can be made based purely on the bowler’s pre-release movement pattern, while those after release examine whether skilled players are better able to make use of early ball-flight information. To facilitate automated occlusion at set times either before or after the moment of ball-release (Event 2), a preceding event in the bowling sequence (Event 1) must be identified and it must fulfil three primary requirements. First, Event 1 must occur sufficiently prior to Event 2 to provide adequate time to trigger occlusions before Event 2, taking into account both delays in detecting Event 1 and any inherent delays in the automated system. Second, Event 1 must be reliably recordable to register the trigger point. Third, the time-lag between Events 1 and 2 must be highly repeatable to ensure that the first event accurately predicts the second.
Figure A.1. Time course of delivery stride for three exemplar cricket bowling action sequences.
Back foot contact (BFC; see Figure A.2) presents promise as a reliable trigger point able to address the aforementioned requirements for time points relative to ball-release. First, BFC (as a potential Event 1) always occurs prior to ball-release (Event 2). On initial inspection it appears to be sufficiently far in advance of Event 2 to allow essential computation and occlusion triggering to occur, but sufficiently close in time to offer the prospect of minimising errors based on extrapolation of the time-lag. Second, registration of the considerable reaction forces generated by contact with the ground offers a potential means for registering the onset of Event 1. In an effort to address the third criteria, an analysis was undertaken to assess whether the inter-event time-lag is sufficiently repeatable to permit the time of ball-release (Event 2) to be accurately predicted from the time of BFC (Event 1).

Figure A.2. Illustration of the moment of i). back foot contact, and ii). ball-release in a cricket bowling action sequence.

The inter-event time lag between BFC and ball-release was determined by visual inspection of recorded video footage. High-speed video records (Phantom v4.2, Vision Research, USA), filmed at 100-250 Hz from a side-on perspective were sourced for 32 bowlers
of different age and skill levels. BFC (Event 1) was defined as the first frame where the penultimate foot-strike prior to release made contact with the ground, and ball-release (Event 2) as the first frame where there was visual separation between the bowler’s hand and the ball. The inter-event time-lag calculated across a series of trials (see Table A-1) examined both the absolute degree of variability within this lag, and whether this was influenced by either bowler skill level or performance conditions (game vs. laboratory). A highly repeatable time-lag was observed for five elite bowlers recorded in a laboratory, with an average standard deviation of 9 ms (range 8 – 11 ms; intra-class correlation of mean R = .97). Comparable findings were observed for state representative (SD 11 ms; range 6 - 16 ms; R = .88), and under 19 elite (SD 11 ms; range 5 - 17 ms; R = .92) bowlers recorded in a laboratory and for elite bowlers recorded in a match (SD 12 ms; range 11-12 ms; R = .97). Furthermore, this consistency found in experts was also observed for less-skilled bowlers; footage of six local club-level bowlers revealing inter-event time-lags of similar magnitude and consistency (SD 9 ms; range 7 - 13 ms; R = .96).

These results demonstrate that although there are individual differences in the mean time-lag for BFC-ball release, there is a high degree of consistency within-bowlers regardless of skill level or testing environment. Furthermore, Event 1 across this sample occurs at least 200 ms, on average, prior to Event 2, ensuring a reliable trigger point for occlusion that occurs sufficiently in advance of ball-release to potentially permit reliable automated occlusions to be made relative to the time of ball-release (Event 2).
Table A-1. Characteristics of Inter-Event Time-lag Across Skill Levels and Testing Environments

<table>
<thead>
<tr>
<th>Skill level</th>
<th>Testing environment</th>
<th>Frame rate (frames per sec)</th>
<th>No of bowlers</th>
<th>No of trials (per bowler)</th>
<th>Mean (min-max)</th>
<th>SD (min-max)</th>
<th>Intra-class correlation of mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elite</td>
<td>Laboratory ^a</td>
<td>250</td>
<td>5</td>
<td>30</td>
<td>327 (287 – 405)</td>
<td>9 (7 – 10)</td>
<td>.97</td>
</tr>
<tr>
<td>State</td>
<td></td>
<td>9</td>
<td>30</td>
<td></td>
<td>296 (258 – 337)</td>
<td>11 (6 – 16)</td>
<td>.88</td>
</tr>
<tr>
<td>Elite U/19</td>
<td></td>
<td>10</td>
<td>30</td>
<td></td>
<td>286 (209 – 334)</td>
<td>11 (5 – 17)</td>
<td>.92</td>
</tr>
<tr>
<td>Elite</td>
<td>Game</td>
<td>100</td>
<td>2</td>
<td>15</td>
<td>361 (314 – 407)</td>
<td>12 (11 – 12)</td>
<td>.97</td>
</tr>
<tr>
<td>Club</td>
<td>Laboratory</td>
<td>200</td>
<td>6</td>
<td>10</td>
<td>354 (298 – 405)</td>
<td>9 (7 – 13)</td>
<td>.96</td>
</tr>
</tbody>
</table>

* BFC for these trials recorded as back foot flat on ground, typically occurring 20 ms after initial contact with ground.

Development of an Automatically Triggered Occlusion Approach

The identification of a temporally consistent inter-event latency made possible the development of an automated system for occlusion. This permitted the visual occlusion of response stimuli at time points relative to Event 2, based on triggering from Event 1. In the section that follows we describe the three essential components of the automated system: the registration of BFC; introduction of a bowler-specific time-lag; and the method of automated triggering.

(i). Registration of BFC. A force plate was used to register the onset of ground reaction forces generated by BFC. The size (900 x 600 mm) and location (situated where the back foot of most cricket bowlers would land) ensured that bowlers with conventional bowling
approaches would not be required to make a conscious effort to land on the plate. Signals from ground-embedded force-plates (Kistler 9287BA, Kistler Instrumente AG, Switzerland) were relayed to a specifically designed comparator box to detect the onset of force. The z-direction voltage generated by the force plate was compared to a set-point controlled by a potentiometer; the manual dial on the potentiometer was adjusted to the lowest possible setting above threshold so that the onset of the smallest permissible force on the plate would generate a voltage to exceed the set-point. When this occurred, a TTL (transistor-transistor logic) signal was generated. This signal was relayed via a 25-pin parallel cable connection and provided an external trigger to a laptop running ToTaL Control (v2.0.1, Translucent Technologies Inc, Canada) – the software specifically designed to control the occlusion of PLATO goggles (PLATO Model P-1, Translucent Technologies Inc, Canada). The signal generated by the ToTaL control program was transmitted via a modular 4-connector phone jack to both the PLATO occlusion goggles, and to a triple LED located behind the participant (see Figure A.3). The ToTaL control program facilitates occlusion by switching the PLATO goggles from transparent to opaque. It does so either immediately upon receiving a signal or following a pre-specified, manually-entered time delay. Illumination of the LEDs occurred contemporaneously with the occlusion of vision, facilitating post-hoc analysis of video footage to verify occlusion time relative to ball-release.

1 The occlusion goggles were tethered in this paradigm, but did not restrict participant movements. Modifications permitting wireless occlusion currently present considerable time-delays, with future models anticipated to improve on this limitation.
(ii). Introduction of a bowler-specific time for signal-delay. A bowler-specific time for signal-delay was calculated using the mean inter-event (BFC-ball release) time-lag to facilitate occlusion at, or for time points relative to, ball-release. High-speed video footage of bowlers (Phantom v4.2, Vision Research, USA) was recorded from a side-on perspective such that each of (i) the moment of BFC, (ii) the moment of ball-release, and (iii) the LED were all visible within the field of view. A signal-delay of 0 ms was entered into the ToTaL control software program to ensure that the LED would be illuminated upon registration of BFC. The LED was used to establish BFC to discount any potential disparity between the visual and force plate registration of BFC, and to allow for any inherent delay in the automated system due to signal processing and transmission.
Programming the software to trigger occlusion at the mean inter-event time-lag would result in ball-flight being visible for at least 50% of trials. To occlude vision immediately prior to ball-release, the signal-delay was shortened by two standard deviations of the mean inter-event time-lag. Statistically this ensures that almost 98% of trials occlude prior to ball-release, with minimal chance for the presentation of any ball-flight information. As a result, the bowler-specific signal-delay for occlusions to take place immediately prior to ball-release was calculated according to the following formula:

\[
\text{Signal-delay} = \text{Mean}_{\text{time-lag}} - 2.\text{SD}_{\text{time-lag}}
\]

(iii). Automated triggering of occlusion goggles. The bowler-specific signal-delay was entered into the ToTaL control software program prior to each trial, specific to both the bowler and the desired moment of occlusion. As a result, an appropriately delayed signal was relayed to the occlusion goggles and LED following BFC.

Validation of the Automated Method

Three skilled male cricket bowlers (mean age 29.1 ± 6.1 years; mean weight 76 ± 7 kg) were recruited to take part in a validation of the automated system of occlusion. All were considered to be medium-paced bowlers (85–110 kph) and had played in the first or second grade of their regional club cricket competition within the previous 12 months.

The first step in the validation was to establish the inter-event signal-delay for each of the three bowlers. High-speed video footage (500 Hz; Phantom v4.2, Vision Research, USA) was recorded from a side-on perspective with a signal-delay of 0 ms entered into the ToTaL control software program to illuminate the LED upon registration of BFC. The video footage was recorded for ten trials from each of the three bowlers and viewed to record Event 1 (BFC: moment of LED illumination) and Event 2 (ball-release: first frame where separation between
the ball and hand was visible). Based on the inter-event time-lag (Bowler 1: 287 ± 11 ms; Bowler 2: 313 ± 9 ms; Bowler 3: 406 ± 5 ms), the appropriate signal-delay was calculated for each bowler with the intention to occlude vision at, or immediately prior to, ball-release.

The second step in the validation was to establish the moment that occlusion took place relative to ball-release. To this end each bowler delivered a further 20 trials with their specific signal-delay entered into the ToTaL control software program. High-speed video footage (500 Hz) was used to calculate for each trial the instance of occlusion (moment of LED illumination) relative to the point of ball-release.

**RESULTS**

Table A-2 demonstrates the results for the point of occlusion relative to Event 2 for each of the three bowlers. The moment of occlusion occurred either prior to (or at) ball-release for 58 out of 60 trials, with the earliest occlusion occurring 50 ms prior to ball-release. Occlusion transpired 2 ms after ball-release for the two trials which did not occlude prior to Event 2. On average the moment of occlusion occurred between 11 and 23 ms prior to ball-release (depending on the bowler).

*Table A-2. Validation Data for Moment of Occlusion Relative to Ball-release*

<table>
<thead>
<tr>
<th>Bowler</th>
<th>Time-delay (ms) from ball-release to occlusion&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Number of trials which occluded after ball-release</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Min</td>
</tr>
<tr>
<td>1</td>
<td>-23</td>
<td>-50</td>
</tr>
<tr>
<td>2</td>
<td>-11</td>
<td>-34</td>
</tr>
<tr>
<td>3</td>
<td>-14</td>
<td>-28</td>
</tr>
</tbody>
</table>

<sup>a</sup> Negative value indicates visual occlusion occurred prior to ball-release.
DISCUSSION

The automated system presented here allows for the accurate and relatively simple occlusion of vision in-situ at specific points in the action sequence. The accurate measurement of inter-event time-lag ensures that for the vast majority of trials, occlusion occurs within a small and well-defined time period preceding ball-release. Accurate measurement of the bowler-specific mean (and SD) inter-event time-lag ensures that occlusion theoretically, on average, occurs at a time point two standard deviations prior to ball-release. Accordingly, almost 98% of trials occlude within four standard deviations of ball-release; a window approximating 40 ms in the wide sample of bowlers presented here. This is comparable to the one-frame limit achievable from conventional video simulations (33-40 ms), and very favourable when compared to the 300 ms windows reported in previous in-situ studies (Farrow & Abernethy, 2003; Müller & Abernethy, 2006).

The temporal accuracy of this method (outlined on a theoretical basis) has been validated using high-speed footage to examine the moment of occlusion relative to ball-release. These results demonstrated that occlusion took place prior to (or at) ball-release for 97% of trials, a figure close to the 98% expected when applying the outlined method. There was strong congruence between the theoretically anticipated time of occlusion prior to Event 2 (based on mean occlusion taking place two standard deviations prior) and the empirically measured time-delay (Bowler 1: 22 vs. 23 ms; Bowler 2: 18 vs. 11 ms; Bowler 3: 10 vs. 14 ms respectively). Occlusions took place across all three bowlers within a 52 ms window which is comparable to the 33-40 ms achievable by video simulations, and certainly favourable when compared to the 300 ms currently accepted by in-situ studies relying on a manual button press for occlusion.

The enhanced temporal precision for occlusion control outlined in this paper facilitates a more powerful experimental design when examining anticipation in-situ. With occlusion
transpiring within a small window of time, this greater control ensures that few trials need to be excluded from analysis as a result of falling outside of the desired time range. This results in either less trials being necessary for the same number of trials to be included for analysis, or that greater statistical power is possible for the same number of trials performed. Furthermore if an in-situ protocol such as those used previously accepts large time windows for occlusion, participant decisions are likely to be made based on a wide variety of occlusion times which are assumed to be uniform. For example an occlusion that occurred 250 ms prior to ball-release will be grouped in the same category with one that occluded immediately prior to ball-release, but it will deny important visual information that transpired between occlusion and ball-release. The greater precision made possible with this new technique ensures the availability of as much information as possible on all trials.

Rather than being limited only to the sport of cricket, this protocol may be used for other actions like a volleyball serve or rugby side-step where the opposing player moves towards the observer. The reliance of such a protocol on force-plates need not be limiting, as this approach may be as effective using cheaper and similarly simple triggering mechanisms such as pressure pads or light gates for appropriate action sequences.

When seeking to examine action sequences for which the opposing player is more stationary (e.g., tennis serve, baseball pitch), it may be possible to map the time-course of the ground reaction force to discover events highly correlated with the critical point in the sequence. Rather than relying upon the onset of loading, this may depend on a desired threshold force being required for an accurate trigger. For example, the back-foot weight transference of a tennis serve or the unloading from the back-foot of a baseball pitcher may prove to occur at a highly reliable time prior to ball contact or release, providing a potential signalling point for accurate occlusion comparable to that provided by BFC in cricket bowling.
CONCLUSION

A more accurate and reliable means of event-related visual occlusion allows for enhanced precision in the examination of perceptual expertise. Rather than relying on the observation of video simulations, in-situ designs are advantageous in preserving the skilled performer’s highly developed links between perception and action. The automated approach we have described enhances considerably the precision with which event-related display occlusions can be made, affording a more sensitive methodology and making possible more powerful experimental designs. Furthermore, the protocol is relatively fast and simple to execute. Such an advance allows us to more readily build on our existing understanding of the development of skill in interceptive actions.
REFERENCES


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Appendix A  An event-related method of occlusion


APPENDIX B

DUAL PATHWAYS OR DUELING PATHWAYS FOR VISUAL ANTICIPATION? A RESPONSE TO VAN DER KAMP, RIVAS, VAN DOORN & SAVELSBERGH (2008)

The following paper is a published response to van der Kamp, Rivas, van Doorn and Savelsbergh (2008). The target article examined anticipatory skill from the perspective of the dual pathway theory of vision.

It is estimated that David Mann contributed approximately 35% of the manuscript, with the remaining 65% by Professor Bruce Abernethy.
As van der Kamp and co-authors (2008) correctly point out in their lead article, while there has been substantial reference in recent studies of anticipation in sport to the important distinction drawn by Milner and Goodale (e.g., Goodale & Milner, 1992; Milner & Goodale, 1995) between vision-for-perception (provided by a ventral cortical pathway) and vision-for-action (provided by a dorsal cortical pathway), there has been very little work done as yet either to thoroughly conceptualise how a dual pathways model of vision might help understand the extant studies on visual anticipation in sport or to verify experimentally the respective dorsal and ventral contributions to anticipation. The article by van der Kamp et al. (2008) presents an initial and important contribution to the former and provides an excellent foundation for the latter. We find ourselves in general agreement with the authors on the major points of their paper and quibbling only with some issues primarily related to the (retrospective) interpretation of existing studies of expert anticipation from a dual pathways’ perspective.

First and foremost it is difficult to argue with van der Kamp et al.’s fundamental contention that the distinction between vision-for-perception and vision-for-action made by Milner and Goodale is an important one and one of direct relevance to the understanding of expert anticipation as it occurs in various sport situations, especially fast ball sports. For a worthwhile account of expert anticipation to be developed it is imperative that evidence is gathered from experimental studies that utilise the cortical pathways for vision in the same way as occurs in the natural task setting.

In our view, van der Kamp et al. present a compelling argument that the vast majority of the existing evidence on visual anticipation comes from approaches which tap only the ventral vision-for-perception system and that a far greater sensitivity to the coupling of perceptual tasks with ecologically valid movement responses is necessary to re-dress this imbalance and to work toward the important goal of a fuller understanding of dorsal (vision-for-action) contributions to expert anticipation. Contemporary neuroscience research has
clearly suggested that responses involving perceptual judgements of orientation (Goodale, Milner, Jakobson, & Carey, 1991) or size (Brown, Halpert, & Goodale, 2005), or even pointing towards a particular object or direction (Króliczak, Heard, Goodale, & Gregory, 2006) invoke use of the ventral pathway. As a consequence, it appears that very strong, immediate and complete perception-action couplings are required in order to ensure that the dorsal, vision-for-action pathway is indeed utilised.

Gaining a comprehensive understanding of expert anticipation in sport tasks, such as those involved in anticipating an opponent’s strokes while playing tennis, will necessitate having information not only from studies involving verbal and pencil-and-paper responses of the type already in existence (e.g., Jones & Miles, 1978; Goulet, Bard, & Fleury, 1989) and reflecting ventral vision-for-perception processing, but increasingly more information from studies in which the response is to actually intercept and hit return shots and, in so doing, invoke dorsal vision-for-action processing. The existing predominance of anticipation studies using simple and uncoupled movement responses has, in our view, been largely a consequence of methodological constraints rather than necessarily a strong, conscious commitment by researchers to cognitive models of compartmentalised information processing. With the improved technology for providing in situ manipulation of vision and in situ recording of movement response kinematics, studies with faithfully preserved perception-action coupling are becoming increasingly more feasible and more common. Indeed some of our own recent attempts to understand expert anticipation (e.g., Farrow & Abernethy, 2003; Mann, Ho, De Souza, Watson, & Taylor, 2006; Müller & Abernethy, in press) have involved natural interceptive responses of this type and the type we believe van der Kamp et al. to be advocating.

In the history of many branches of science, dichotomous distinctions, such as those between the vision-for-perception and vision-for-action pathways, have generally proven invaluable in advancing conceptualisation but have also frequently proven ultimately
inadequate to fully explain the complexities of many natural phenomena. With this in mind we contend, in line with the thinking of van der Kamp et al., that not only will it be important to experimentally verify the putative characteristics of vision-for-perception and vision-for-action using anticipation tasks but understanding the interaction between the two pathways will also be absolutely critical (see also Goodale & Westwood, 2004). The dual visual pathways may be highly complementary under most circumstances but equally have the potential under other circumstances to also come into competition and act as a source of mutual interference.

There is clear evidence for cognitive mediation of dorsally based tasks by the ventral system (Creem & Proffitt, 2001; Toth & Assad, 2002), with interaction necessary for the visual-motor system to produce meaningful actions. In addition to this, it appears unlikely that the dorsal pathway is able to utilise anticipatory information on its own (Brown et al., 2005), reflecting the dorsal system’s ‘on-line’ activity and its lack of reliance on past (stored) information. Considering the contrasting means by which the ventral and dorsal pathways appear to process their input, much work is required to understand if, and how, cognitive information on anticipation is utilised by an expert in deriving a meaningful response. This is particularly the case given the proposition by van der Kamp et al. of varying degrees of input from the two visual pathways throughout the learning and execution of movement.

While it is becoming increasingly apparent that tasks become more implicitly-based with the development of expertise (e.g., Beilock & Carr, 2001), the reliance on the dorsal and ventral pathways for this progression is less clear. Króliczak et al. (2006) recently demonstrated that while flicking an object is a dorsally-based task, pointing at it or making a perceptual evaluation of its distance is ventrally-based. Assuming the dorsal and ventral pathways differ fundamentally in the extent to which their modus operandi is implicit or explicit, it is difficult to easily resolve how flicking could be implicit if pointing were explicit. Likewise in a sporting context, if both a novice and an expert are to receive a tennis serve, it appears more likely that both players would utilise the dorsal pathway for such an interceptive
action – with the expert’s dorsal system being more attuned to the task and hence better able to manipulate the constraints than the novice – rather than the dorsal pathway utilisation being strictly only within the purview of the expert. It is difficult to accept unreservedly the proposition that the dorsal system is responsible for control in the expert only, with the same task needing more ventral pathway involvement in the novice. Perhaps with practice both the ventral and dorsal systems are able to improve and become highly automatised. The mapping of behavioural characteristics to the different visual pathways, and the examination of changes in these mappings with skill learning, is clearly something that requires (but is fortunately also amenable to) empirical verification. To this end, van der Kamp et al. have made an important contribution by laying out clearly the type of experimental work that needs to be done to effectively utilise the dual pathway notions of Milner and Goodale to broaden understanding of visual anticipation.

There are two, relatively minor, points in relation to van der Kamp et al.’s (re)interpretation of existing studies of expert anticipation from a dual pathways’ perspective about which we have some differences in opinion. The first relates to the contention that relatively large errors in predicting landing position under full vision conditions in many existing laboratory-based measures indicates that ‘...judging the future landing location has tapped into the metrically less precise ventral system..’. While tasks that require participants to predict landing position from visual simulations of the hitting actions of opposing players may logically tap the ventral rather than the dorsal system, statements about the precision of the judgements that can be made via the ventral system should be made reservedly from laboratory-based simulation studies. The video simulations used in most laboratory studies of anticipation are typically captured from a fixed camera position with no panning of the camera to provide vision following the ball (or object) after it has been struck by the opponent through to its precise landing position on the court. Consequently, less than perfect judgements of actual landing position from this kind of display cannot be taken as an absolute measure of the
precision capability of the ventral system. More appropriate comparisons could be drawn from in-situ studies involving occluding goggles where the capacity exists for the participant to continuously monitor the ball in flight through to its final landing position.

In their section on the evidence for ventral contributions to affordance perception, van der Kamp et al. note that most studies of visual anticipation in sport require participants to make judgements about either the type of action the opponent is producing or the outcome of the opponent’s action rather than a response regarding their own action. The authors contend that responses about self action selection may be more appropriate than responses about the actions of the opponent as these would link closer to an affordance for action than the more prevalent perceptual measures. In practice, we (e.g., Abernethy & Russell, 1987) and others (e.g., Goulet et al., 1989) have opted for measures of accuracy of predicting opponent’s actions rather than the participant’s own actions for largely pragmatic reasons. As any given perceptual display (e.g., a serve hit by an opponent to the receiver’s left) may have multiple possible response options (a return backhand drive down-the-line, a return forehand drive cross-court, a deep lob etc) determining what does and does not constitute a correct movement response is extremely difficult/subjective whereas the determination of a correct perceptual judgement (was the serve going to the left or right?) is straightforward. Relatedly, if one opts to only measure the participant’s own choice of movement response and this turns out to be in error, it is not possible to then determine whether the locus of the error is poor pick-up of advance information from the opposing player or simply poor response selection strategy. For these reasons adopting the approach of attempting to measure whether a player has selected an appropriate action, as van der Kamp et al. advocate, is not without its difficulties and drawbacks.

In summary, the work of Goodale and Milner has significantly influenced thinking about the functional role of different visual pathways in the brain, and the propositions now advanced by van der Kamp et al. (2008) provide an important extension of this thinking to the
domain of visual anticipation. By following the leads suggested by van der Kamp et al., and utilising experimental protocols encapsulating full interception, researchers interested in expert anticipation may be better able to not only understand the significance of existing findings in expert anticipation, but to also establish whether the pick-up of advance (pre-release) information is ventrally-based, how ventrally-processed information informs a response, the nature and scope of information processed via the dorsal pathway, and, importantly, the interaction between the two pathways. As this understanding develops, movement scientists will be in a better position to develop efficacious approaches to perceptual training and motor skill acquisition.

REFERENCES


APPENDIX C

SEEKING TO DEVELOP A MORE EFFECTIVE AND VALID METHOD FOR THE ASSESSMENT OF CRICKET BATTING PERFORMANCE

The following appendix is a short position paper seeking to develop and validate a more effective means of evaluating cricket batting performance. A number of these measures were used in Experiment II of this thesis.
The accurate evaluation of performance in an open interceptive task such as cricket batting is difficult, particularly when looking to do so in a relatively controlled scientific environment. Successful performance necessitates not only accurate bat-ball interception, but also the ability to adjust this response according to the changing positions of opposition fielders attempting to stop the ball and prevent runs being scored. The open nature of the task leads to the fact that many different responses are possible for any given delivery, making difficult the effective categorisation or evaluation of how good a response may be.

Mann et al. (2007) assessed cricket batting performance through a scale-based coach rating of performance. This method was employed in every trial in an attempt to allow for the many degrees of freedom in this open task; however the scoring was highly subjective on the part of the coach, and it lacked clear guidelines for scoring. Clearly research performed examining a task like cricket batting would benefit from an approach that allows for the open nature of the skill, yet it is as objective as possible with clear operational definitions to guide scoring.

Müller and Abernethy (2008) used a simple categorical tool as a means of evaluating interceptive skill in a hitting task. In this method the quality of bat-ball contact (QoC) is categorised as good, bad, or none, with performance evaluated as a percentage of good, or of all bat-ball contacts. This tool may be useful when the aim is to simply intercept a ball with an implement; however it may fail to effectively allow for important elements of expertise in a task such as cricket batting. It does not possess the ability to assess performance in a task where the aim may be to manipulate the quality of the interception to both hit the ball as hard as possible, and to strategically position a ball when hit.

In the game of cricket, batters attempt to hit a ball projected towards them by bowlers, with the primary goal to score runs which is more likely to occur if the ball is hit, as hard as possible, away from ten fielders. The batter continues to play on until they are dismissed, typically (but not exclusively) occurring if the ball after being hit is caught by a
fielder, or if it is missed and it breaks a wicket being protected by the batter. Hence in an attempt to better evaluate interceptive skill in cricket batting, it is desirable to build on the quality of contact tool advocated by Müller and Abernethy (2008) by using additional evaluations for the aggressiveness of the attempted interception, and the likelihood that a batter may be dismissed on any given trial.

**OPERATIONAL DEFINITIONS**

Three separate primary measures of interceptive skill were evaluated; the *quality of bat-ball contact*, *forcefulness of bat-swing (FoBS)*, and *likelihood of dismissal (LoD)*. The approach was to replicate the QoC tool validated by Müller and Abernethy, and to extend this categorical protocol to evaluate the remaining two primary measures (see Table A-3 for operational definitions). All three primary measures require a degree of subjectivity on the part of the person rating performance, however the use of only three categories for each score aids in minimising the degree of judgement required.

The FoBS score provides an assessment of how hard the ball is likely to have been hit, depending on whether there has been full, partial, or no follow-through of the bat after the anticipated point of bat-ball contact. An evaluation of FoBS provides a score reflecting the likelihood that any bat-ball contact will result in runs being scored. The temporal precision required of a faster, more aggressive bat-swing renders its successful execution more difficult, however it is likely to result in an increase in the number of runs scored as the ball has a greater chance of being hit between fielders, and away from the pitch. In contrast, even if there is good bat-ball contact, low bat-swing forcefulness will result in the ball not travelling far rendering it difficult for the batter to score runs, as the ball is easily stopped by fielders. Hence the *interaction* between quality of bat-ball contact and FoBS is of importance.

Any concurrent measurement of QoC and FoBS may aid in assessing the chance of runs being scored, however it fails to assess the remaining objective of a cricket batter: to avoid
being dismissed. Hence a score reflecting the likelihood of being dismissed may reflect the participant’s success in achieving this concurrent objective. Such a score must allow for the primary means of dismissal such as being bowled (the wicket being protected by the batter is hit), caught (a fielder catches a ball hit to them without hitting the ground), or being adjudged leg-before-wicket (the ball hits the batter’s legs and the umpire decides the ball would have hit the wicket).

The numerous different ways a batter can be dismissed renders the assessment of LoD in many cases difficult. Although it is simple to judge whether the batter is bowled, for other dismissals such as leg-before-wicket or caught, a certain degree of subjectivity is required. Video footage recorded directly behind the bowler is used to determine the LoD. In the case of leg-before-wicket, the video footage is viewed to determine whether the ball hit the batter’s legs in front of the stumps; if this is the case the batter is a chance of being dismissed (irrespective of any other qualifying laws). In the case of being caught, both the batter and judge are provided with the exact location of ten fielders,\(^1\) and as a result the scorer must make a subjective assessment of whether the ball was hit towards one of the fielding locations without the ball hitting the ground. Once again if this is the case, the batter has provided a chance of being dismissed. As a result, this score does not provide a definitive score of whether a dismissal would have occurred; rather, it attempts to assess that such an event may have been possible.

In addition to the three primary measures of performance, a secondary composite measure of all three primary measures was calculated to provide an assessment of overall batting performance for each trial. The formula for calculation of this measure is provided in Figure A.4, and the possible scores resultant from such a system are shown in Table A-4.

\(^1\) In this protocol, the batter and judge are provided with a schematic diagram of a cricket field demonstrating the hypothetical location of all ten fielders. This diagram is available on a 0.64 x 0.51 m poster on a wall adjacent to the participant throughout testing.
Importantly, the calculation used to assess performance relies on the product rather than the addition of the component scores. This ensures that a zero is scored for trials where there is no bat-ball contact, and for trials where the batter is definitely dismissed, both key tenants deemed necessary to ensure face validity for the scoring system. While any trial with minimal FoBS may not result in runs being scored, successful interception is executed and hence it was considered important that these cases should not result in a score of zero.

Table A-3. Operational Definitions for Categorical Scores of Primary Measures used to Assess Performance for Each Trial

<table>
<thead>
<tr>
<th>Primary measure</th>
<th>Score</th>
<th>Operational definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality of Contact</td>
<td>2</td>
<td>Ball contacts the bat face and travels in a direction consistent with the pre-contact plane of bat motion.</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Ball contacts the bat face but deflects in a direction inconsistent with the pre-contact plane of bat motion.</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>Ball does not make contact with the bat.</td>
</tr>
<tr>
<td>Forcefulness of bat-swing</td>
<td>2</td>
<td>Complete follow-through of bat swing after anticipated point of bat-ball contact.</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Incomplete follow-through of bat swing after anticipated point of bat-ball contact.</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>No follow-through of bat swing after anticipated point of bat-ball contact, or no attempt is made to hit the ball.</td>
</tr>
<tr>
<td>Likelihood of dismissal</td>
<td>0</td>
<td>No foreseeable chance of batter being dismissed.</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Ball is hit towards one of ten nominated fielding positions without the ball hitting the ground (chance of being caught), or ball does not hit bat and hits batter on the legs in front of the wicket (chance of being adjudicated leg-before-wicket).</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Ball hits the wicket being protected by the batter.</td>
</tr>
</tbody>
</table>

Batting performance = \[ \text{Quality of contact} \times (\text{FoBS} + 1) \times (2 - \text{LOD}) \]

Figure A.4. Formula used to calculate score for batting performance on each trial
Table A-4. All Possible Categories Across the Three Primary Measures, Sorted by Calculated Score for Batting Performance.

<table>
<thead>
<tr>
<th>Contact</th>
<th>Forcefulness of bat-swing</th>
<th>Likelihood of dismissal</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>High</td>
<td>Low</td>
<td>12</td>
</tr>
<tr>
<td>Good</td>
<td>Moderate</td>
<td>Low</td>
<td>8</td>
</tr>
<tr>
<td>Good</td>
<td>High</td>
<td>Moderate</td>
<td>6</td>
</tr>
<tr>
<td>Some</td>
<td>High</td>
<td>Low</td>
<td>6</td>
</tr>
<tr>
<td>Good</td>
<td>Moderate</td>
<td>Moderate</td>
<td>4</td>
</tr>
<tr>
<td>Good</td>
<td>Low</td>
<td>Low</td>
<td>4</td>
</tr>
<tr>
<td>Some</td>
<td>Moderate</td>
<td>Low</td>
<td>4</td>
</tr>
<tr>
<td>Some</td>
<td>High</td>
<td>Moderate</td>
<td>3</td>
</tr>
<tr>
<td>Good</td>
<td>Low</td>
<td>Moderate</td>
<td>2</td>
</tr>
<tr>
<td>Some</td>
<td>Moderate</td>
<td>Moderate</td>
<td>2</td>
</tr>
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<td>Good</td>
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<td>High</td>
<td>0</td>
</tr>
<tr>
<td>Some</td>
<td>High</td>
<td>High</td>
<td>0</td>
</tr>
<tr>
<td>Some</td>
<td>Moderate</td>
<td>High</td>
<td>0</td>
</tr>
<tr>
<td>Some</td>
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<tr>
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<td>High</td>
<td>Moderate</td>
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<tr>
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<td>High</td>
<td>High</td>
<td>0</td>
</tr>
<tr>
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<td>Moderate</td>
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<td>Moderate</td>
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<tr>
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<td>Low</td>
<td>Low</td>
<td>0</td>
</tr>
<tr>
<td>None</td>
<td>Low</td>
<td>Moderate</td>
<td>0</td>
</tr>
<tr>
<td>None</td>
<td>Low</td>
<td>High</td>
<td>0</td>
</tr>
</tbody>
</table>

VALIDITY

Ratings for the three primary measures were performed on video footage of 250 balls from a one-day international match, demonstrating a moderate correlation between the calculated batting performance and runs scored per ball ($r_s = .52; p < .001$). When considering the QoC alone, only a low linear correlation exists between QoC and the number of runs scored per ball ($r_s = .24; p < .001$), most likely a reflection of the high occurrence of good bat-
ball contacts in this sample (80% of trials), yet only a relatively low percentage of these contacts resulted in runs. There was also a high likelihood of runs still being scored even if only some bat-ball contact occurred (Figure A.5a). The rating of FoBS more accurately reflects the number of runs scored per ball ($r_s = .44; p < .001$; Figure A.5b). The LoD exhibits no relationship with the number of runs scored ($r_s = -.12; p = .068$; Figure A.5c), however it does correlate highly with the occurrence of dismissals ($r_s = .77; p < .001$).

The composite score for batting performance cannot claim to provide a complete means of predicting the number of runs scored on any given trial; however it appears to represent a marked improvement on the QoC categorical rating used alone. It is worth noting that when considering the analysis across all 250 trials, the batting performance score correlates only marginally better than FoBS with runs scored per ball, however support for the former scoring method can be put forward on the consideration of face validity alone. There is little point in employing a tool to evaluate interceptive skill if it does not even account for the occurrence of interception. In this sample the score for aggressiveness has correlated moderately well with the runs scored because good bat-ball contact occurred for the majority (80%) of trials.

The score assessing LoD is a good predictor of whether the batter is actually dismissed, but it does not predict the number of runs that are likely to be scored. This effect is largely a result of the frequency of occurrence; in 250 trials only ten times was the batter deemed a chance of being dismissed. Again on simple account of face validity and keeping in mind the goals of the batting task, there seems good reason to maintain a measure of the chance of dismissal. This factor encourages play which minimises the likelihood of dismissal, and subsequently tempers the score for any trial where dismissal is likely.
Figure A.5. Average runs scored per ball and percentage of all runs scored across 250 balls of a one-day international match for each category of (a) quality of contact, (b) forcefulness of bat-swing, and (c) likelihood of dismissal.
RELIABILITY

Reliability of the three primary scores and the secondary composite score was assessed on a selection of 192 trials performed within an experiment examining the effect of visual blur on cricket batting. Intra-rater reliability was first assessed comparing scores performed live and on a first review of video footage (2 weeks later), demonstrating a strong correlation for batting performance ($r_s = .84; p < .001$), in conjunction with strong correlations for QoC ($r_s = .86; p < .001$), FoBS ($r_s = .72; p < .001$), and LoD ($r_s = .68; p < .001$). When the live assessments were compared to a second video review (a further month later), comparable correlations are found for all of batting performance ($r_s = .84; p < .001$), QoC ($r_s = .86; p < .001$), FoBS ($r_s = .67; p < .001$), and LoD ($r_s = .64; p < .001$). Strong correlations were also found when comparing across subsequent video ratings: batting performance ($r_s = .85; p < .001$); QoC ($r_s = .87; p < .001$); FoBS ($r_s = .84; p < .001$); and LoD ($r_s = .82; p < .001$).

REFERENCES


Participant interviews were conducted following data collection for Experiments II & IV (experiments performed concurrently). Following are the transcripts of these exit interviews. Questions/comments from interviewer are in italics.
PARTICIPANT 1

1. *Compared to how you would normally bat, do you think you needed to change the way you batted with the introduction of blur? If so, please explain this in as much detail as possible.*

Definitely. Probably shortening of the backlift and less movement of the feet.

*So did you even have to do that in the first one we did today (+1.00)?*

Yes to a degree. To a degree.

*With the introduction of blur, was there any visual information that you would usually rely upon that you couldn’t see? If so, please explain this in as much detail as you can.*

Yep. The lack of ability to see the release of the ball. The lack of ability to see the seam of the ball. And the lack of ability to see the seam in the bowler’s hand.

2. *With the introduction of blur, was there any additional or different visual information that you used that you wouldn’t usually use? If so, please explain this in as much detail as possible.*

It made me concentrate more on watching the ball all the way underneath my eyes, and then as I played the shot I was actually watching where I hit the ball whereas when I get into the bat sometimes I don’t do that. So I’d say it was something I could use especially if I had the blurred vision like I did last week, I had to train myself to watch the ball – I could almost see my hands coming through and then looking up at the shot and then when I was batting without the blur I made sure I tried to do that as much as possible. So it made me train my eyes to see more.

*Ok so you found that with them you were, it was more changing the way you watched the ball onto the bat?*

Yep, the habit. It made me get out of bad habits really.

*Which deliveries were easiest to face?*
The ones down the leg.

Why was that?

Probably because the ball is line with your body most of the way. I found the further the ball got away from your body the harder it was to keep track of it, judging distance and things like that.

3. If you were to give advice on how to pick the line of these three bowlers, so if you were to explain to someone else how to pick up the line of these three bowlers as early as possible, what would you say? Firstly for Bowler 1, if you were to try to explain to someone how to pick up the line, or how to pick up his action really, what would you say?

He’s probably [inaudible] really through his true action so I wouldn’t have too much advice for someone like him ‘cause his action is quite pure. But for someone like Bowler 2 who is side-arm you can see in the drop of his front shoulder, and you can see in the angle of his arm on how late he is going to let it go ‘cause he varies it quite a lot.

So he drops his shoulder when he is going to bowl on the off-side?

Yep he changes the angle of his arm.

Bowler 3?

Yeah he’s a fairly front-on bowler as well so with him he tended to be fairly true as well.
PARTICIPANT 2

1. Compared to how you would normally bat, do you think you needed to change the way you batted with the introduction of blur? If so, please explain this in as much detail as possible.

You had to. As it got worse I think you had to premeditate your foot movements a little bit at times to get forward to push your weight - that made it a little bit easier. And also with the last one, face up a little bit more front-on, I found that helped a little bit. I don’t know why, but it did seem to help a little bit, just gave you a little better depth perception I found.

2. With the introduction of blur, was there any visual information that you would usually rely upon that you couldn’t see? If so, please explain this in as much detail as you can.

Yeah, the bowler’s wrist was a big one, I’d say that, and the seam – I’d try look at the seam of the ball and as soon as any sort of blur you can’t see it at all.

Even the lightest level you couldn’t see the wrist position?

Yep, no way.

Anything else?

Not really.

Ball flight?

Not being able to see the ball the whole way was the big killer. Towards the end you could only see it for the last two, three, four metres maybe tops, so obviously being able to watch the ball the whole way was the big killer.

3. With the introduction of blur, was there any additional or different visual information that you used that you wouldn’t usually use? If so, please explain this in as much details as possible.
To start with, the angle of the bowler’s arm. You relied more upon that than just the
simplistics of the wrist and the seam of the ball so you took more into the timing that they let
the ball go as to whether it would be short or full. And the angle of the arm as to whether it
would be leg-side or off-side.

  So you wouldn’t usually use that?

Not really, not really.

  So you are more so looking for wrist?

Yeah.

4. If you were required to explain to another batter how to anticipate the line they
were bowling as early as possible, what advice would you give them for each
bowler? So for Bowler 1 to start with, what advice would you give to another
batter to pick him up?

With normal vision obviously?

Yeah.

Really watch for release point, that’s the biggest thing. If he’s really going to bend his
back or sort of or put in a little bit more, you can really see the angle of it.

  The angle of his arm?

Yeah and also the, it’s hard to put, he leans back into his action which results in the
shoulder starting back more. Front arm was a big one, as to whether they would pull down or
across was a big one.

  For Bowler 1?

Yeah, yeah especially cause he sort of pulls in quite a lot and then for an effort ball
sometimes he’ll bring it more to the side instead of straight down. Bowler 3, he’s got a pretty
straight up-and-down action so it’s a bit hard to really give any information about that. He’s is
sort of more angle of the arm again whether it’s almost part the perpendicular or a little out
there as to where the ball’s really going to go. Bowler 2, because he’s almost like a slinger, yet
again really where the ball comes from as in angle of arm as to where the ball ends up.

So you think he changes his angle for different lines?

Yep, but the problem is with that comes, then you can tell possibly where he is trying
to put the ball as to whether it ends up, where he releases it. Because even if he might try and
bowl it outside off, if he hangs on to it for too long, of course it’s going to drag down the leg
side. So he was a little bit hard in that respect, you could get information out of it, the angle of
the arm, but the release point was the key thing, so other than that not a great deal.
PARTICIPANT 3

1. Compared to how you would normally bat, do you think you needed to change the way you batted with the introduction of blur? If so, please explain this in as much detail as possible.

Yeah I played off the front foot a lot more, tried to drive a lot more.

Why was that?

You can’t pick it up until late and when you’re on the back foot bloody you’d get out LBW or something like that.

OK. Anything else?

Uh, nah, don’t think so.

How about your backswing? Was there any change in your backswing?

Probably a bit shorter, if anything. Just don’t have time to see the ball.

2. With the introduction of blur, was there any visual information that you would usually rely upon that you couldn’t see? If so, please explain this in as much detail as you can.

Oh, I just couldn’t see it come out of the hand as clear, you know, sort of try to pick it up off the pitch a bit more, yeah.

3. With the introduction of blur, was there any additional or different visual information that you used that you wouldn’t usually use? If so, please explain this in as much detail as possible.

Oh, I tried to watch the body a lot more to see whether their, like their actions to see if they were going to push it sort of to off-side or leg-side.

Was that with the goggles or without?

Probably both. Yeah. Had to do anything to try to pick up the ball a bit earlier.

Was that not something you’d usually use?
Oh, not as much as I had to try to do. Yeah.

4. If you were required to explain to another batter how to anticipate the line they were bowling as early as possible, what advice would you give them for each bowler? So for Bowler 1 to start with, what advice would you give to another batter to pick him up?

Uh, watch his hand to see which way it was pointing, towards the off-side or the leg-side. Like I was sort of trying to, trying to pick him up.

OK How about Bowler 2?

His action when he, cause he bends his back right back you can see him drag it across more I think. Like when he’s going to come to leg-side he sort of yeah falls away a bit I think in his action.

OK. And Bowler 3?

He’s a bit harder actually. Ah, probably out of the hand a bit more as well to see whether he’s pushing towards leg-side or something like that. The hand is the important thing I think.
PARTICIPANT 4

1. *Compared to how you would normally bat, do you think you needed to change the way you batted with the introduction of blur? If so, please explain this is as much detail as possible.*

[Problem with tape recorder – part of interview inaudible – dot points are the recollections of the interviewer]

- Felt that he did need to change the way he batted because he couldn’t see the advance information, he couldn’t see the seam on the ball, so he had to change the way he batted.
- Shorter balls were easier, and fuller balls were harder. Thought this may have been something to do with peripheral vision, not being able to see it early enough and pick up the length when it was full, so difficult to adjust to the shot.
- Felt that he had to concentrate more with the blur, and that it was maximal with any level of blur. So not correlated, as soon as there was any blur he had to concentrate more.
- Playing balls later off the pitch.

2. *With the introduction of blur, was there any visual information that you would usually rely upon that you couldn’t see? If so, please explain this in as much detail as you can.*

Obviously I watch the seam from the hand, obviously couldn’t see that with the blurred vision.

*With all of them? So even the first one today [+1.00]?

Yep. Yeah. So I like to use the seam angle to give me some visual cues whether it’s going to be an outswinger, inswinger for the seam bowlers. So yeah that was probably the
main one that I found a little bit off-putting. And also I like to watch their face early on at the top of their run-up, OK when they start. That’s just my cue to switch on. And then as they progress into their delivery stride then look at the hand and at the seam position.

*Anything else?*

That’s about it. I look at the position on the crease, but even though it was blurred I’ve got an idea if they are going a bit wider on the crease or they are a bit straighter on.

*OK so you could see the ball out of the hand? You lost that did you with the blur? Even with the lightest blur.*

Even with the lightest blur I lost it yeah. So if for example if someone bowled a leg-cutter or an off-cutter I couldn’t be able to tell you. I could see it coming out of the hand but I couldn’t tell the axis it was coming on.

3. *With the introduction of blur, was there any additional or different visual information that you used that you wouldn’t usually use? If so, please explain this in as much details as possible. Did you rely on anything that you wouldn’t usually use?*

I’m just trying to think. Not really, as I said I tried to narrow my focus just to the arm, so obviously I probably took in less cues because obviously with my blurred vision I thought, well, I can’t see different things so I probably instead of focusing on two or three things at once, I probably just focussed on the one thing.

4. *If you were required to explain to another batter how to anticipate the line they were bowling as early as possible, what advice would you give them for each bowler?*

Good luck! Well I thought, do I nominate the bowler?

*Yeah*

Well for Bowler 4 I could probably tell a little bit more by the position on the crease. When he tried to bowl leg-side he probably tries to go a little wide on the crease and angle it
down where as when he tries to bowl outside off he is a bit straighter in his delivery. I thought Bowler 1, the left armer, tended to fall over a little bit more when he tried to push it across to the off-side. Whereas Bowler 3 was probably the hardest one because I found he was inconsistent and that made it harder for me because he came out wide, and I thought OK this will go down leg, but actually it was outside off-stump. So I found him probably the hardest of the three, I don’t know whether my results will show that, but if someone is more consistent, they’re obviously harder to pick, and I found that was magnified when I had the blurred vision as well.
PARTICIPANT 5

1. Compared to how you would normally bat, do you think you needed to change the way you batted with the introduction of blur? If so, please explain this is as much detail as possible.

Well you probably did, had to watch the ball a lot closer. You couldn’t exactly see the ball out of the hand, so you had to watch the ball until it comes closer.

OK so when you couldn’t see it out of the hand, you were picking it up quite late?

Yeah, about half way down the pitch. I also probably changed the backswing, the way you lifted the bat up, because you have less time to react, you obviously have less time to swing the bat through.

So how did you change it?

I probably shortened the backswing.

OK. Did you move it earlier, or just shorten it?

Shorten the backswing, so the bat had less space to move.

2. With the introduction of blur, was there any visual information that you would usually rely upon that you couldn’t see? If so, please explain this in as much detail as you can.

Probably the bowlers hand you couldn’t see as much. So if there was variety, variation out of the hand you couldn’t see it. The slower ball was tough.

Could you see the slower ball in that last one [+1.00]? That was the lightest amount of blur, that one just then.

Yeah I could sort of pick the slower ball up then.

Anything else? Any other visual information you rely on?

Seam position...I couldn’t really see that.

What about with the last one? Could you see the seam position then do you think?
Not clearly. Not clearly out of the hand.

And that’s something you’d usually rely on when you’re batting?

Yeah. Especially against spinners.

3. With the introduction of blur, was there any additional or different visual information that you used that you wouldn’t usually use? If so, please explain this in as much details as possible.

Not that I can think of. Not really.

4. If you were required to explain to another batter how to anticipate the line they were bowling as early as possible, what advice would you give them for each bowler? So for Bowler 1 to start with, what advice would you give to another batter to pick him up?

Good question. Probably try and watch his body position through the crease, how open it is or closed it is.

OK so if it was open he was more likely to...?

I’d say he’s more likely to spray it off-side.

OK, that’s alright. How about Bowler 2?

Just go leg-side!

There’s nothing in his body that you could really pick up to give away?

Not that I know consciously, there might be something there.

Absolutely, that’s a good point. How about Bowler 3? Anything?

His wrist position sort of changes it up a bit, but again that was when I could see obviously.

OK. Before you were talking about the bowling-machine was easier to bat against than the bowlers when it was really blurred. Why’s that?

The bowling-machine had a set position that it was coming out of, you knew where it was coming from, you could probably roughly guess the angle of the ball - the head was what
it was going to come down at. Whereas the bowlers, you know, there’s also movement in their body when they’re running in, there’s a lot of different variables I would say, to change it up.

OK. You commented on that after the blurriest one, how about the one, the lightest blur you just batted in. Was there as much of a difference between the bowlers and the bowling-machine?

No, there wasn’t as much of a difference there. You can still make bodies out a lot more, but it’s still different, it’s always easier batting against a bowling-machine, because you’ve got a set point that it’s coming out of.

So you even find that even when it’s not blurred at all?

Yeah when I have like normal vision, it’ll be easier to bat against the bowling-machine.
PARTICIPANT 6

1. *Compared to how you would normally bat, do you think you needed to change the way you batted with the introduction of blur? If so, please explain this is as much detail as possible.*

Yeah, cause you’ve got to watch the ball a lot harder and you’ve got to actually watch the bowler’s action. It helps, but with Bowler 2 it’s pretty hard cause his action comes out wider, compared to Bowlers 1 and 3.

*Anything else you might have had to change the way you batted?*

No not really.

*How about back swing or bat movements or anything like that. Did that change at all?*

Nup. No.

2. *With the introduction of blur, was there any visual information that you would usually rely upon that you couldn’t see? If so, please explain this in as much detail as you can.*

Yeah their wrist position and the release.

*OK. What do you usually look at that for?*

Just to pick up the ball and all the, like the ball in the hand and wrist.

*Are you looking for line there, or length, or whether they’re going to swing it in, or cut it?*

Especially with the ball at first whether it’s going to swing or if they’re holding it in different positions for cut, or the slower ball.

*OK, so you couldn’t see that as well?*

Couldn’t see it at all.

*How about with the lowest level? Could you still see it with them?*

It was a while ago. I couldn’t see the seam position.
3. With the introduction of blur, was there any additional or different visual
information that you used that you wouldn’t usually use? If so, please explain this
in as much details as possible.

Ah, not really, no.

Were you needing to pick up the ball in the air later, say?

With the bad lenses, yeah, you couldn’t see it at release so you had to pick it up as late
as possible.

So with the bad ones today, they were the ‘2’s’, could you see it out of the hand there
do you think? Or were you able to get it in the air?

Yes and no. On some you could but some you have to pick it up half way down.

4. If you were required to explain to another batter how to anticipate the line they
were bowling as early as possible, what advice would you give them for each
bowler? So for Bowler 1 to start with, what advice would you give to another
batter to pick him up?

It would be easiest if you watched the whole arm rather than just the wrist position.

‘Cause he seemed to follow through in a straight line, if you get what I mean.

So he’ll follow through where it’s going?

Yeah, like, tends to, but not straight all the way. But, Bowler 2, he lets go a bit round
arm and you tend to lose a heap of [inaudible] with the goggles.

Right. So with Bowler 2, what information, was there anything there do you think to
help pick up the line early?

I watched his front shoulder on a couple, and one that I picked up ‘off’ it went ‘off’.

His leading shoulder towards second slip.

And for Bowler 3? Anything there?

Have a bigger sightscreen! No, he’s the same as Bowler 1 really, in that corridor. He’s
just straight down rather than round.
Which was harder to face the bowling-machine or the bowlers with the blur?

The bowlers, cause with the bowling-machine you can read it if it’s going to go short and that, because you can see it going up. But with Bowler 2 you don’t know where it’s going, short, wide or full.
PARTICIPANT 7

1. Compared to how you would normally bat, do you think you needed to change the way you batted with the introduction of blur? If so, please explain this in as much detail as possible.

I needed to bat more safely. I needed to restrict all my shots, so I cut down on everything pretty much more.

OK, so a more defensive mindset?

Yep.

Anything else, like the way you executed?

I thought, when my vision was blurred my footwork sort of struggled because I didn’t know really, probably, know where the ball was so I couldn’t use my feet with my vision as much.

2. With the introduction of blur, was there any visual information that you would usually rely upon that you couldn’t see? If so, please explain this in as much detail as you can.

Well I tried to watch his action a bit more when it was blurred, and also when it cut out, and I tried to see if he was dragging it or if he was opening up and splaying it down off, but nah, it wasn’t there.

So just facing the bowlers, this is without the goggles, was there any information you would usually look for that you couldn’t see?

Ah, the ball! I was picking it, the more blurred it was the more I looked closer at the pitch, and obviously when my vision got clearer I looked at his hand again so the ball was alright.

What did you find harder with the blur, the bowling-machine or the bowlers?
Probably the bowlers. Cause, well, they bowled quicker than the machine, as well as there were a lot of things to take in as well, including action and everything. But when the bowling-machine was on all you do is look for the hole where it came out and so there’s no arms to lose it in and no movement.

3. With the introduction of blur, was there any additional or different visual information that you used that you wouldn’t usually use? If so, please explain this in as much details as possible.

Probably I had to watch it harder than I would normally, and, nah, pretty much I looked at the same spots as I would without blurred vision.

Okay. You tried to watch it harder and concentrate?

I really tried to concentrate on where it was.

4. If you were required to explain to another batter how to anticipate the line they were bowling as early as possible, what advice would you give them for each bowler? So for Bowler 1 to start with, what advice would you give to another batter to pick him up?

I’d say look at the ball release just before it cuts off, ’cause that’s probably the most determinant factor of where it’s going - is the last part you see. So, depending on where his arm is and where it came from I suppose, so the angle determines where it goes, so just watch that.

Okay. Was there any difference across the three bowlers for that? So say for Bowler 2, the other left-hander?

Probably against Bowler 1, I’ve practiced against him a lot so I had a better idea than the other two. Oh and also swing, didn’t come into it as well, ’cause some of them swung so it also altered there. For the other bowlers they were pretty easy.

Okay. If you were to pick up swing information before ball release, what would you usually look for?
Oh, seam on the ball. You can probably factor it into how he’s holding it, but obviously you’d have to look out for that one.

*Were you able to see that information with the lenses in do you reckon?*

Not as well as I could have. But yeah swing you pick up mainly in the air not by the hand or you can’t tell by his action.

*Sure. Do you think can pick up that information better now that you’re wearing, since you got these lenses [habitual lenses] last season? Does it make much difference?*

For sure. I reckon it was actually like batting with an impairment. Yeah you had to squint as well. Now as soon as you get them everything is clearer, so it makes it a lot easier probably.
PARTICIPANT 8

1. *Compared to how you would normally bat, do you think you needed to change the way you batted with the introduction of blur? If so, please explain this as much detail as possible.*

Did I change the way I batted with the contacts in?

*Yeah.*

Yeah, I think playing off the back foot was a lot harder. I’m not too sure why, but I seemed to be propping up on the front foot and then when I dropped back on the back foot I’d lost it there for whatever reason, I had a lot of trouble timing the ball. On the front foot I didn’t find it as bad. I’d guess it’s more in terms of, off the front foot, if you come straight down the deck you’re an even chance either way, whereas off the back foot the ball’s got more time to either move sideways off the pitch, so if it’s blurred and you’re having an each way guess, which you are a lot of the time, coming forward seems to be easier than playing back.

*OK, so fuller balls or shorter balls easier?*

Fuller balls much easier, I thought.

*Did you have to change anything else in the way you executed your batting?*

No, not really, I tried to bat as normal as possible I think.

*OK. Backswing was the same?*

Yep. Probably the only thing that differed was the foot straight down the pitch and like I just said to accommodate that straight ball you’re sort of having an each way bet of where you’re going, so if you look at it from straight on there wouldn’t be a lot of lateral movement of that front foot, you’re probably going straight down the deck most times.
2. With the introduction of blur, was there any visual information that you would usually rely upon that you couldn’t see? If so, please explain this in as much detail as you can.

Are we talking about with the glasses on as well?

No, this is all without the goggles actually.

Yeah, actually, had a heap of trouble picking up slower balls, so I guess anything wrist related, I couldn’t pick it up. That was, I’m not sure probably it was bowling-machine as well as it was against the bowlers, but yeah I couldn’t see anything so I guess it’s that distance thing. But most of the other things like arm going across the body and all that type of stuff with swingers, I tried to follow that, but any wrist changes I just couldn’t pick it up at all.

3. With the introduction of blur, was there any additional or different visual information that you used that you wouldn’t usually use? If so, please explain this in as much details as possible.

I’m not too sure. You’re certainly watching harder for anything that can help you in terms of line, I definitely noticed when I put the bat down and had to pick off or leg I was looking for anything that I could to give me an indication of which way it was going. So, I think, where their shoulders were and all those kinds of cues I was trying to get an indication of whether it was going down leg or down the off side. So certainly more awareness of what they were actually trying to do, whether it helped or not I’m not sure.

4. If you were required to explain to another batter how to anticipate the line they were bowling as early as possible, what advice would you give them for each bowler? So for Bowler 3 to start with, what advice would you give to another batter to pick him up?

I think the thing with Bowler 3, I noticed probably throughout, was his shoulder position, so he tended to - I think - open up a little more down the off-side, where as his shoulder position was closed when I thought it was going down the leg-side. So that was the
main thing I was using, but I think also arm position and proximity to his ear so if it was there a bit wider or a bit straighter I was trying to work with that as well.

*Ok so if it was out wider, that was...*

He tended to spray quite a few so if it was out wider it was either down leg-side or quite a way down leg-side, whereas if it was up straighter, it was normally his straighter ball. Same with Bowler 5, like he got in really close with his, and he bowled a lot of balls which were straight [inaudible], he didn’t spray as many. The left armer [Bowler 1], he was actually quite tough to pick up, he had quite a quick, quite a good release action. So, he gave me a good look at the ball, but his movement until it got blacked out, I really had a lot of trouble picking it up. It was a lot quicker than the other two, cause the other two were the more conventional into the bowling position there and gave you a good look at the ball where as he was sort of there, and it was gone before I knew which way it was going.
PARTICIPANT 9

1. Compared to how you would normally bat, do you think you needed to change the way you batted with the introduction of blur? If so, please explain this is as much detail as possible.

It depended whether it was behind the net or not.

OK, these ones will be without the goggles, so facing the bowlers and the bowling-machine.

I was just trying to play pretty much as straight as I could, got to take a big step forward a play it from there pretty much.

OK. Anything else?

Not that I can think of.

So you were saying earlier that you looked at their body and tried to see in which direction it was going to give yourself some idea and then...

Yep that was more with the second contacts, the hardest ones. I sort of just watched the body and sort of started tilting forward, unless they let go of the ball a bit later then it was going to be shorter, or they went fuller. So, it just gave me a brief idea of where it was.

Did you change your backswing at all?

No.

It was all the same?

Yep.

So the main change was that big step forward?

Yep.

You wouldn’t usually do that?

Oh, I don’t think I do. I don’t think I’d go straight forward, id usually play from where I am. So, it sort of just started from there. Because I saw it so late.
2. With the introduction of blur, was there any visual information that you would usually rely upon that you couldn’t see? If so, please explain this in as much detail as you can.

I’m a big ball watcher, so all the way in the run-up I look at the ball, so it was pretty tough there.

What level, so that first pair you had on Monday, what we call a +1.00, could you see the ball OK in the hand when they were coming in?

Yep.

Alright, so how about today, those first ones today, the +3.00 they were the hardest?

Yeah, no they were the hardest, couldn’t see a thing until about, sort of a metre or two away. So that was it, that was tough.

Alright, the +2.00’s, the ones you have in now.

Yep it would have just been another dot, a bit further away.

Is there any other visual information you couldn’t see that you usually rely on?

I think, the shoulders worked, ’cause it was just a little blurred, for how far away you actually get. So it was just that a little bit ’cause when I was looking at the body I was just looking at the [inaudible], so it was just looking pretty [inaudible].

3. With the introduction of blur, was there any additional or different visual information that you used that you wouldn’t usually use? If so, please explain this in as much details as possible.

I think I used the twisting of the body, so it was actually, if the arm was coming around, I thought for the left armer, I thought it was going leg-side. A few of those ended up being way off-side though. I mean, I tried to use that but it didn’t probably work as well with him.

4. If you were required to explain to another batter how to anticipate the line they were bowling as early as possible, what advice would you give them for each
bowler? So for Bowler 5 to start with, what advice would you give to another batter to pick him up?

Probably just look straight at the shoulders. Just cause he comes straight back over, so, just the angles gives a big clue.

Was it any different for Bowler 2, the left hander?

Yeah he sort of swung around a bit more.

Did that make it harder?

Yeah.

OK, but still shoulders?

Yep.

And Bowler 2, the other right hander?

Yeah I think he actually swung it a bit, so that was a bit tough when they go off and you think that’s where the ball’s going to be.

Yeah we were just looking at the initial line of the ball, so he was just shoulders?

Yep.
PARTICIPANT 10

1. *Compared to how you would normally bat, do you think you needed to change the way you batted with the introduction of blur? If so, please explain this in as much detail as possible.*

   Yes. Not much for the easiest ones, I thought that was pretty similar to normal batting. But particularly with the hardest ones I thought I had to change my ways ’cause you didn’t pick up the ball anywhere as near as early. You kind of saw it half way down so you had to wait until you picked it up and make a quick movement, shorten your backlift, that kind of thing.

   *OK, so shorter backlift, anything else?*

   I don’t know, it just made it a bit harder just not being able to see the ball as clearly, but in terms of changing the way I batted I think the only thing was I had to just kind of move a bit later ’cause I didn’t see the ball as early.

2. *With the introduction of blur, was there any visual information that you would usually rely upon that you couldn’t see? If so, please explain this in as much detail as you can.*

   Yeah definitely. As the bowler is running in, I usually kind of watch, just watch the bowler running in, ’round about their face, not overly focussing on anything. But, it made it hard, just a bit disconcerting, I don’t know whether it affected what I was picking up, but as they actually released it you couldn’t see the bowler clearly so you couldn’t really pick up the ball in their hands. So that was tough, ’cause you didn’t know what it was doing. And then also, you didn’t pick up the ball for the more severe lenses until it was a little way down the pitch.
Ok, so, when you’re saying you’re watching the bowler come in and their face, so you’re watching their face, is that just like a soft focus? So you’re not watching for information from their face, that’s just your central point of vision?

No, I’m not actually good at that! I’ve heard guys talk about watching the bowler running in and picking up little cues, but I don’t think I do that, I don’t do it consciously anyway. I more, just watching them running in, preparing to face up to the ball. If anything I pick up balls probably, sorry pick up information, just before they release it, but I don’t know, it’s probably sub-conscious. I don’t know.

Sure, so with the easiest, with the softest lenses, you could see all that you needed do you think?

Yeah, pretty much. Like, I was actually surprised it didn’t really affect batting much at all, but the others, they made it harder.

3. With the introduction of blur, was there any additional or different visual information that you used that you wouldn’t usually use? If so, please explain this in as much details as possible.

I think, the most severe ones, I actually did watch the bowler more. Particularly for the, is this just the batting, or when the net was up?

Ah, without the net for the moment.

Oh, not much, but probably I actually did watch the bowler’s body a little more while they were releasing it because I could not pick the ball up out of their hand so, like, I wasn’t as focussed as I was when I was, focussed on the ball coming out of the hand cause I couldn’t have been. So I probably just watched the body a bit more and tried to pick up things off that. I don’t know if I did it very successfully.

And so you were saying earlier that you were surprised that you could still bat with the easiest contact lenses, so, it looked like it was going to be tough, but you ended up batting alright?
Appendix D  Participant exit interviews

It didn’t look too tough, but it was just kind of like, when you look down the other end, oh wow its blurry, this is going to be hard, but then I still managed to pick the ball up OK. Probably not quite as well but I think it would have made me watch it more when it got closer to me. Because usually you pick the ball up pretty well as they release it, so then maybe you relax your eyes, or relax something a bit, whereas when you don’t quite get it, it almost makes you a bit more alert. That might have been what it was.

4.  

Ok so this is with the goggles on and the net across. If you were required to explain to another batter how to anticipate the line they were bowling as early as possible, what advice would you give them?

Um, I found it harder, for Bowler 2 it think he’s a bit more of a side-on bowler, so I found that a bit easier to pick up cues from him cause he kind of turned his body side-on, like that kind of jump in to, and rotate, so you could pick up the line a bit from that. So you just, watching his, I think shoulders come through, would probably be my advice. But also, just imagining, when you don’t have the bat in hand I found it a lot harder. A lot easier when I actually imagined I was batting, like just standing there trying to pick the line...

Yeah, you wanted to move...

I imagined I had a bat in my hand, and just did my little pre-movement, I found that a little bit easier, because that’s what I usually do.

So once we take away that movement, it was really hard to do?

Yeah.

Ok, anything else? Anything else you noticed?

Oh, as I said to you before, I was actually surprised how well I hit them with the worst lenses, the hardest lenses, on the bowling-machine particularly. Like, I didn’t smash them but just considering how little I could see, like I was surprised at times that I found the middle of the bat. I don’t know why that was, it was just kind of like, I wasn’t really sure where the ball was but it tended to find the bat which was interesting.
Ok, alright, so that wasn’t really a conscious thing, you just ended up being at the right place?

Yeah well I did, as I said before, shorten by bat lift cause I thought I had to, that was after I hit the first few I worked that out, but once I’d done that it was more just trying to take the bat to the line of the ball and I managed to do it sometimes even when I wasn’t too sure where the ball was.
APPENDIX E

PARTICIPANT CONSENT FORM FOR EXPERIMENT I
PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM

Blur and Batting Performance

Participant selection and purpose of study
You (i.e. the research participant) are invited to participate in a study of batting performance with contact lens-induced blur. We (i.e. the investigators) hope to gain a better understanding of:

a) Vision in cricket batting
b) Acceptable levels of blur that optometrists can advise batsmen can tolerate, and
c) Better methods of training

You were selected as a possible participant in this study because you:

a) Are a grade cricketer, and/or
b) Are a member of the UNSW cricket team

Description of study and risks
If you decide to participate, we will fit you with contact lenses to blur your vision to pre-determined levels. You will then undergo appraisal by a suitably accredited coach viewing footage of you facing balls delivered by a bowling machine. Overall, 200 balls will be faced.

The only discomfort you are expected to face may be a period of adjustment to the contact lenses being worn for the study. This adjustment period is normal, and may last until the lenses are removed. Lenses will be worn for a period of time during which 200 balls will be faced (estimated to be 2 hours maximum).

The risk of being struck by a ball is less than the risk a cricket training session or match presents. This is because a full set of protective cricket gear will be worn, and the balls faced will be no faster than medium pace. The risk of contact lens-related effects will be minimal, as disposable lenses will be worn and discarded after use. It is hoped that improved methods of batting training will be learned from this study.

We cannot and do not guarantee or promise that you will receive any benefits from this study.
PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)
Blur and Batting performance

Confidentiality and disclosure of information
Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission, except as required by law. If you give us your permission by signing this document, we plan to discuss the results in written and oral presentations. In any publication, information will be provided in such a way that you cannot be identified.

Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (phone 9385 4234, fax 9385 6648, email ethics.sec@unsw.edu.au).

Your consent
Your decision whether or not to participate will not prejudice your future relations with the University of New South Wales. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

If you have any questions, please feel free to ask us. If you have any additional questions later, Chief Investigator, David Mann, 0402 154 121 will be happy to answer them.

You will be given a copy of this form to keep.

You are making a decision whether or not to participate. Your signature indicates that, having read the information provided above, you have decided to participate.

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Signature of Research Participant...............................................................................
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Signature of Witness.................................................................................................
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(Please PRINT name)...................................................................................................
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Date................................................................................................................................
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Nature of Witness........................................................................................................
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Signature(s) of Investigator(s)..................................................................................
DAVID MANN .................................................................................................
NEILSEN DE SOUZA ....................................................................................
DAMIEN WATSON .....................................................................................
SCOTT TAYLOR ..............................................................................................
REVOCATION OF CONSENT
Blur and Batting Performance

I hereby wish to WITHDRAW my consent to participate in the research proposal described above and understand that such withdrawal WILL NOT jeopardise any treatment or my relationship with The University of New South Wales.

……………………………………………………………
Signature Date

……………………………………………………………
Please PRINT Name

The section for Revocation of Consent should be forwarded to the Chief Investigator, David Mann.
Rm 3.007, 3rd Floor North Wing Phone: 0402 154 121
Rupert Myers Building, Fax: 02 9313 6243
Gate 14, Barker St, Email: d.mann@unsw.edu.au
Kensington.
PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM

Refractive blur and performance in an interceptive task with the availability of advance kinematic information

In these studies we will be examining your batting performance, facing both bowlers and a bowling machine in our cricket testing facilities at the Australian Institute of Sport. As a part of this testing, in some cases your vision will be clear, however in others we will put contact lenses in your eyes to make your vision blurred. We are interested in how your batting performance and technique changes with the blurred vision, along with the influence that blur has on the ability to detect essential information from the body of the bowler.

Across the two testing sessions you will participate in two different studies as follows;

Study 1 – Blur and Batting

In this study you will be batting as you would normally against three bowlers, and also against a bowling machine. You will be batting on an indoor court, imagining you are batting in a one-day match with a set field.

For each of the contact lens conditions you will be facing 30 deliveries from the bowlers (including 6 practice deliveries) and 30 deliveries from the bowling machine (including 6 practice deliveries). Rather than facing a real ball, you will be facing a softer ‘incrediball’ which acts much like a real ball.

Study 2 – Blur and anticipation

In this study we will be looking at your ability to detect the line of the ball from early information from the bowler’s body. You will be facing the same three bowlers again with a soft ‘incrediball’, and you will be wearing a special pair of goggles which allow us to block your vision at certain points in the bowling delivery.

When batting in this study, for some of the deliveries you will see all of the bowler coming in to bowl along with all of the ball flight, however for others you will see the bowler coming in to bowl, and the goggles will block your vision as soon as the ball is let go - you still need to try hit it! You will be standing behind a net however which stops the ball from hitting you should you miss it. When the bowler comes in to bowl you won’t know whether vision is going to block out or not – it will be random.
For this study you will face 24 deliveries (6 of these practice) where you are actually batting and trying to hit the ball. There will be a second set of 24 deliveries (again 6 of these practice) where you will be standing still and calling out the line of the ball (off or leg side) as early as possible.

You will be batting with all protective gear, including a helmet. Bowlers will not be bowling towards your body, rather either on the off- or leg-side. They will not bowl short, and you will be facing a special ball which acts like a cricket ball but is much softer, very similar to an ‘incrediball’. The risks will otherwise be the same as those you would typically experience batting in a game or training session.

Whilst you will be able to gain some valuable batting practice, we cannot and do not guarantee or promise that you will receive any benefits from this study.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission, except as required by law. You will be videotaped whilst batting, and may be identifiable on the video. This video will only be viewed by members of the research team, and will not be available to other players, coaches, or selectors. If you give us your permission by signing this document, we plan to publish the results in scientific journals and to present it at scientific conferences. In any publication, information will be provided in such a way that you cannot be identified.

Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (phone 9385 4234, fax 9385 6648, email ethics.sec@unsw.edu.au). Any complaint you make will be investigated promptly and you will be informed out the outcome.

Your decision whether or not to participate will not prejudice your future relations with the University of New South Wales or the Australian Institute of Sport. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

If you have any questions, please feel free to ask us. If you have any additional questions later, David Mann (0402 154 121) will be happy to answer them. If you have any concerns with respect to the conduct of this study, you may contact the secretary of the AIS Ethics Committee (Dr. John Williams) on 02 62 14 1816 or (Ms Helene Kay) on 02 62 14 1577.

You will be given a copy of this form to keep.
THE UNIVERSITY OF NEW SOUTH WALES and AUSTRALIAN INSTITUTE OF SPORT

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)

Refractive blur and performance in an interceptive task with the availability of advance
kinematic information

You are making a decision whether or not to participate. Your signature indicates that, having
read the information provided above, you have decided to participate.

……………………………………………………                                              .…………………………………………………….
Signature of Research Participant                                                                        Signature of Witness
……………………………………………………                                              .…………………………………………………….
(Please PRINT name)     (Please PRINT name)
……………………………………………………                                              .…………………………………………………….
Date       Nature of Witness

REVOCATION OF CONSENT

Refractive blur and performance in an interceptive task with the availability of advance
kinematic information

I hereby wish to WITHDRAW my consent to participate in the research proposal described above and
understand that such withdrawal WILL NOT jeopardise any treatment or my relationship with The
University of New South Wales, or the Australian Institute of Sport.

……………………………………………………                                              .…………………………………………………….
Signature                       Date
……………………………………………………
Please PRINT Name

The section for Revocation of Consent should be forwarded to David Mann, Skill Acquisition, Australian
Institute of Sport, Bruce, ACT 2617, AUSTRALIA.
APPENDIX G

PARTICIPANT CONSENT FORM FOR EXPERIMENT III
PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM

Anticipation across the perception-action coupling spectrum

You are invited to participate in a study looking at how we are best able to test expert anticipation and decision making in sport. We hope to learn both the best type of visual display, and the best response type to use when looking to test and train anticipation in athletes. You were selected as a possible participant in this study because you participate in the ACT First Grade competition, or in a grade below this.

If you decide to participate, you will be facing at different times each of videos and live bowlers whilst wearing special goggles which allow us to black out what you see for certain periods of time. You will need to anticipate the direction in which the ball is going either through a verbal response, moving towards the ball, shadowing a response, or actually attempting to hit the ball. We will inform you which response you need to make for each delivery. For certain deliveries we will be blacking out the view of a section of the ball flight, and at times final parts of the bowler’s run-up. The experiment should require you to participate for approximately two hours.

You will be batting with all protective gear, including a helmet. Bowlers will not bowl short, and you will be facing a special ball which acts like a cricket ball but is much softer, very similar to an ‘incrediball’. The risks will otherwise be the same as those you would typically experience batting in a game or training session.

Whilst you will be able to gain some batting practice, we cannot and do not guarantee or promise that you will receive any benefits from this study.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission, except as required by law. You will be videotaped whilst batting, and may be identifiable on the video. This video will only be viewed by members of the research team, and will not be available to other players, coaches, or selectors. If you give us your permission by signing this document, we plan to publish the results in scientific journals and to present it at scientific conferences. In any publication, information will be provided in such a way that you cannot be identified.

Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (phone 9385 4234, fax 9385 6648, email ethics.sec@unsw.edu.au). Any complaint you make will be investigated promptly and you will be informed out the outcome.
Your decision whether or not to participate will not prejudice your future relations with the University of New South Wales or the Australian Institute of Sport. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

If you have any questions, please feel free to ask us. If you have any additional questions later, David Mann (0402 154 121) will be happy to answer them. If you have any concerns with respect to the conduct of this study, you may contact the secretary of the AIS Ethics Committee (Dr. John Williams) on 02 62 14 1816 or (Ms Helene Kay) on 02 62 14 1577.

You will be given a copy of this form to keep.
THE UNIVERSITY OF NEW SOUTH WALES and AUSTRALIAN INSTITUTE OF SPORT

PARTICIPANT INFORMATION STATEMENT AND CONSENT FORM (continued)

Is the perception of kinematics used to enhance performance in the execution of an interceptive task?

You are making a decision whether or not to participate. Your signature indicates that, having read the information provided above, you have decided to participate.

……………………………………………………                                              .…………………………………………………….
Signature of Research Participant                                                                        Signature of Witness
……………………………………………………                                              .…………………………………………………….
(Please PRINT name)                                                                                     (Please PRINT name)
……………………………………………………                                              .…………………………………………………….
Date       Nature of Witness

REVOCATION OF CONSENT

Is the perception of kinematics used to enhance performance in the execution of an interceptive task?

I hereby wish to WITHDRAW my consent to participate in the research proposal described above and understand that such withdrawal WILL NOT jeopardise any treatment or my relationship with The University of New South Wales, or the Australian Institute of Sport.

……………………………………………………                                              .…………………………………………………….
Signature                       Date
……………………………………………………
Please PRINT Name

The section for Revocation of Consent should be forwarded to David Mann, Skill Acquisition, Australian Institute of Sport, Bruce, ACT 2617, AUSTRALIA.