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Interception in the Presence of Ball-Swing: Exploring the Development of Visual-Motor Expertise in Cricket Batting

Vishnu Sarpeshkar

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Abstract

Precise visual-motor coordination underpins success in fast-ball sports. Previous studies highlight significant differences in both the gaze and kinematic behaviour of skilled and lesser-skilled performers when carrying out interceptive actions (e.g., predictive eye movements and temporal coupling between the body and the hitting implement). However, much of what we know is based largely on studies that adopt case-study designs and/or simplified task environments, making it difficult to generalise the findings to the wider population and to the challenging tasks actually encountered in the performance environment. This is particularly true when seeking to intercept targets that follow a curved or *swinging* flight-path rather than a straight trajectory. Successful interception in the presence of ball-swing requires remarkable spatio-temporal precision, and helps to test performance at the limits of human performance. Therefore, the aim of this thesis is to establish a comprehensive understanding of the development of visual-motor expertise using interception in the presence of ball-swing as a model of a highly demanding interceptive task.

The four experimental chapters in this thesis collectively report the findings of one large-scale experiment that assessed the visual-motor behaviour of cricket batters *in situ*. In the experiment, four groups of batters, who systematically differed according to their level of batting skill and age, attempted to hit balls projected by a hybrid ‘ProBatter’ ball-machine. Crucially, balls travelled at speeds that reflected those experienced during competition and ball-swing was introduced to manipulate task difficulty. Batters wore a portable eye tracking system to record their gaze direction, and high-speed video footage was used to analyse kinematic behaviour.

Kinematic behaviours have been shown to underpin success and distinguish batters of different skill levels when hitting a ball. However, little is known about how widely these findings generalise to actions performed in more representative task conditions (e.g., faster ball-speeds and swinging flight-paths). Therefore, the first experimental chapter (Chapter 2) aims to examine the development of timing and movement coordination when hitting a ball in these conditions. Kinematics were compared when batters intercepted balls that followed a (i) straight flight-path only, and (ii) random mixture of straight and swinging flight-paths. Results revealed skill-based differences in interceptive performance when hitting straight balls, with the performance of all batters decreasing in the presence of ball-swing (particularly when the ball swung *away* from the batter). Ball-swing delayed the timing of most key moments in the hitting action, with batters increasing the velocity of bat-swing to overcome those delays. Knowledge that the ball *could* swing (hitting straight balls mixed with swinging trajectories) also altered the batting kinematics, highlighting the potential impact of top-down cognitive influences on kinematics and performance.

Eye movement strategies also underpin skill in interception, yet almost all studies of gaze in interception have employed case-study designs that may fail to accurately capture the behaviour of the wider population. The second and third experimental chapters sought to examine the gaze behaviour of batters when intercepting balls that followed a straight trajectory (Chapter 3) and a combination of straight and swinging trajectories (Chapter 4). Results revealed strong markers of expertise (e.g., the prevalence of predictive saccades towards bat-ball contact) but also failed to support some existing measures (e.g., that better batters make earlier saccades to ball-bounce). Ball-swing reduced interceptive performance as a result of both increased uncertainty and the greater spatio-temporal precision required for interception. It revealed new markers of expertise that were not present when facing only straight trajectories and showed that batters make specific visual-motor adaptations in an attempt to account for the swinging ball (e.g., oblique predictive saccades).

Vision and motor actions work in a coordinative fashion and so the examination of gaze and kinematics in isolation may overlook critical interactions that underpin expertise in interception. The final experimental chapter (Chapter 5) examines for the first time the relationship between gaze and kinematics when intercepting a fast-moving ball. Results revealed skill-related differences in visual-motor coordination: for skilled batters the anticipatory saccades towards ball-bounce were temporally related to the batter’s kinematics (initiation of bat-downswing), but for the lesser-skilled batters saccades were related to an external event (moment of ball-bounce). Moreover, kinematic behaviour differed when predictive saccades were not performed, providing evidence that a functional interaction between gaze and kinematics helps to support successful interception.

Collectively, the results establish a clearer picture of the strategies that underpin skilled interception, with skill-based differences in gaze and kinematics found to be evident by late adolescence and sustained into adulthood when hitting straight and swinging targets. Interception in the presence of ball-swing was found to significantly influence not only batting performance but also visual-motor behaviour. The experimental series establishes a comprehensive understanding of the development of visual-motor expertise, providing a foundation for the development of talent identification and training paradigms designed to detect and improve skill in batting.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications during candidature

Peer-Reviewed Papers

SARPESHKAR, V. & Mann, D. L. (2011). Biomechanics and Visual-Motor Control: How it has, is, and will be used to reveal the secrets of hitting a cricket ball. *Sports Biomechanics*, 10(4), 306-323.

Conference Presentations

SARPESHKAR, V. (2012). Establishing the relationship between gaze behaviours and skilled interceptive actions: an example from cricket batting. *UQ HMS 'Straddie' Conference*, Moreton Bay Research Centre, Brisbane, Australia.

SARPESHKAR, V., Mann, D. L., Spratford, W., Abernethy, B. (2015). The influence of swing on the timing and coordination of a front-foot defensive shot among cricket batters across skill and age. 5th *World Congress of Science & Medicine in Cricket*, Luna Park, Sydney, Australia.

Presentations at Coaching Seminars

SARPESHKAR, V. (2013). *Keep your eyes off the ball: Secrets of cricket batting*. Cricket Australia – Sport Science and Sports Medicine Department, Brisbane, Australia

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Keywords

visual-motor control, expertise, interception, gaze behaviour, kinematics, cricket batting, development, fast-ball sport

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List of Abbreviations used in the Thesis

QoC – Quality of Contact

FoBS – Forcefulness of Bat-swing

SD – Standard deviation

% $\text{Gaze}_{\text{ahead}}$ – The percentage of ball-flight where gaze was directed ahead of the ball in flight

% $\text{BBC}_{\text{fixation}}$ – The percentage of trials where gaze is directed towards the ball at the moment of bat-ball contact

% $\text{BBC}_{\text{lagging}}$ – The percentage of trials where gaze is positioned behind the ball at the moment of bat-ball contact

% $\text{BBC}_{\text{post-contact}}$ – The percentage of trials where gaze is directed towards the future location of the ball, based on the path of bat-swing, at the moment of bat-ball contact

iBS – Initiation of bat-backswing

iFFS – Initiation of front-foot stride

pBH – Peak bat-height

cFFS – Completion of front-foot stride

iDS – Initiation of bat-downswing

BBC – Bat-ball contact

iFFS-iBS – Time between the initiation of front-foot stride and the initiation of bat-backswing

cFFS-iDS – Time between the completion of front-foot stride and the initiation of bat-downswing

cFFS-BBC – Delay in time between the completion of front-foot stride and bat-ball contact

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‘*Don’t ever let somebody tell you you can’t do something. Not even me, all right? You got a dream, you got to protect it. People can’t do somethin’ themselves, they want to tell you you can’t do it. If you want somethin’, go get it. Period’.*

Chris Gardner (Will Smith) in *The Pursuit of Happyness* (2006)

CHAPTER 1

THE DEVELOPMENT OF VISUAL-MOTOR EXPERTISE DURING AN INTERCEPTIVE ACTION

‘*When you’re curious, you find lots of interesting things to do.*’

Walt Disney

From the time a child reaches out to pick up his or her favourite toy, essential motor skills such as those involved in interception (including hitting and catching skills) begin to develop. To successfully intercept a target, the performer needs to accurately perceive the relative motion of a target (if it is moving), and respond by effectively organising the relative movement of their limbs to ensure that the position of an end-effector (e.g., the hands or a bat) coincides with the spatial and temporal coordinates of the target (e.g., a ball) at the moment of arrival (Montagne, Fraisse, Ripoll, & Laurent, 2000). Successful interception thus demands the complex coordination of the neuromuscular and visual systems to position the end effector at the right place at the right time, allowing for the execution of everyday activities such as picking up a glass of water, swatting flies, or catching a ball. However, when examining interceptive tasks in a sporting environment such as returning one of Rodger Federer's 200 km.h^{-1} serves in tennis, or hitting one of Brett Lee's 160 km.h^{-1} deliveries in cricket, the spatial and temporal constraints that need to be conquered to ensure successful interception can, at times, appear near impossible.

Fast-ball sports are commonly used as an exemplar task to examine the visual-motor strategies that underpin goal-directed interceptive behaviour and decipher the boundaries of human performance (see Walsh, 2014). Particularly, striking tasks typically observed in baseball and cricket batting generally require the performer to act upon a moving target that usually entails overcoming severe spatial and temporal constraints. For instance in these tasks, performers will often have less than 600 ms to predict the future arrival location of the ball, with optimal interception demanding remarkable spatial and temporal precision (Peper, Bootsma, Mestre, & Bakker, 1994; Regan, 1997; Tresilian, 2004a). Examinations of skill-based differences in the gaze and motor actions of performers in those tasks have provided valuable (and at times highly influential) insights into the strategies that allow performers to not only predict the future arrival location of the ball, but also be positioned at the right place at the right time (e.g., Land & McLeod, 2000; Weissensteiner, Abernethy, & Farrow, 2011). Moreover, there is growing interest in the literature to also determine at what stage of development these skill-based differences are likely to be acquired (e.g., Weissensteiner, Abernethy, Farrow, & Müller, 2008). The knowledge gained from these studies can help establish a theoretical foundation from which to explore the development of visual-motor expertise, whilst also promoting opportunities for the purposes of talent identification and/or development.

Knowledge of the visual-motor behaviour that allows performers to account for the severe spatio-temporal constrains encountered in fast-ball sports continues to progress our understanding of the strategies that promote successful interception. Surprisingly however, very little is known about how performers may account for variations in the contextual environment that is typically experienced during competition. For instance, opponents in fast-ball sports often seek to gain an advantage by employing a variety of different strategies that attempt to further exaggerate the performer's perceived spatial and temporal constraints of the task. One such strategy that is commonly used by pitchers in baseball, bowlers in cricket, and free-kick takers in soccer is to manipulate the ball's flight-path so that it follows a curved (or *swinging*) trajectory. The increased spatial and temporal demands imposed by swinging trajectories are thought to lead to a misperception of the future arrival location, and time, of the ball, ultimately reducing interceptive proficiency (Craig, Bastin, & Montagne, 2011; Craig, Berton, Rao, Fernandez, & Bootsma, 2006). With previous studies reporting that a cricket ball could potentially swing up to 800 mm under ideal conditions (e.g., Barton, 1982), it is conceivable that adaptations in the visual-motor behaviour of performers are essential in order to overcome the increased spatial and temporal constraints of the task. Furthermore, simply being aware that a ball *could* swing may also influence the visual-motor behaviour of performers when intercepting balls that follow a straight-flight-path (e.g., Gray, 2002). Until now, very little is known about *how* performers are able to (if at all) adapt their visual-motor strategies to account for the presence of ball-swing. This provides an efficacious model from which to better understand how skilled performers develop expertise in interception (for a review, see Sarpeshkar & Mann, 2011).

Existing studies examining the development of visual-motor expertise in interception have predominantly focused on understanding the skill-based differences in visual (e.g., Land & McLeod, 2000) and motor behaviour (e.g., Weissensteiner et al., 2011). However, considering that vision and motor actions work together in a coordinative fashion, the independent examination of vision and motor actions may overlook critical interactions between the two that could help to underpin expertise in interception. As a result, heeding to the calls of previous studies to examine the critical relationship between gaze and motor actions (e.g., Abernethy, 1993; Sarpeshkar & Mann, 2011) may provide a higher level of understanding, and appreciation of the visual-motor strategies that underpin successful interception. Although previous studies reveal that gaze is closely coupled with the motor actions when intercepting a *stationary* target (see Land, Mennie, & Rusted, 1999), very little is known if a similar relationship exists when intercepting a *moving* target. Understanding the nature of this relationship between gaze and the interceptive action may help extend the literature and provide a deeper knowledge of the intricate coordination of visual-motor control required for successful interception.

This introductory chapter seeks to explore the existing literature surrounding the visual-motor behaviour of performers when intercepting a fast-moving target. The first section (Section 1.1) focuses on understanding the development of visual-motor expertise when performing an interceptive task and looks to uncover the strategies that underpin successful interception. The second section (Section 1.2) seeks to specifically explore the task of cricket batting – the task of interest throughout the thesis – particularly observing the spatio-temporal demands of the batting task and the unique visual-motor behaviour of the batters to promote successful performance. The third section (Section 1.3) explores the current knowledge regarding swinging flight-paths in sport, with an emphasis on the perceptual influences of ball-swing on the ability of the performers to accurately predict the future arrival location of the target. Finally, the fourth section (Section 1.4) seeks to highlight the significant gaps in the current understanding of the development of visual-motor expertise in interception, before establishing a foundation and purpose for the experimental series that is subsequently reported in this thesis.

1.1. Visual-Motor Control during Interception

The visual system, as a key part of the central nervous system, is the dominant system for information pick-up for perception and decision-making. Visible light from the surrounding environment is projected onto the retina, where a vast network of receptors and cells convert light into electrical signals and transmits this information to the Primary Visual Cortex (V1) in the brain (Kandel, Schwartz, & Jessell, 2000). It is the interpretation of this information that builds a representation of the surrounding environment and enables the development of an effective goal-directed movement strategy.

1.1.1. Initial Principles Governing Visual-Motor Control

Interest in understanding the process of how information is detected and its subsequent influence on action can be traced back to notable philosophers such as Plato, Aristotle and Descartes (Williams, Davids, & Williams, 1999). The foundations of visual-motor control have largely been influenced by cognitive psychology and information processing, with the conception that action is a predetermined sequence of movements that is initiated once the actor has perceived the necessary information. Early studies that have explored skilled interception reveal that experts tend to display a more consistent movement time than the novices do when executing actions across varying task constraints (for an example using table tennis, see Tyldesley & Whiting, 1975). Tyldesley and Whiting (1975) and Schmidt (1975) supported the notion of the *operational timing hypothesis*, which proposes that the remarkably consistent movement times observed by expert performers is evidence for a pre-determined motor plan. That is, movement is initiated once the performer has calculated the necessary variables for the task and the time remaining before the target's arrival at the optimal interception point. This form of *predictive* movement control suggests that continuous visual information obtained during movement execution may be redundant as the performer has *a priori* knowledge of the time taken to execute a movement, thus reducing the processing demands on the performer to simply determining when to initiate the movement of fixed duration (also see Zelaznik, Wade, & Whiting, 1986).

Recent findings exploring movement control have embraced the contrasting notion that visual information is continuously used *throughout* the movement and not simply at the start of the movement. In other words, movement is controlled by maintaining an ongoing, rather than a discrete, coupling between visual perception and action. Lee and colleagues (1983) observed that when performers jumped to intercept a falling target, their knee and elbow angles varied to modify movement times, in a *prospective* 'online' control of movement, to coincide with the arrival of the ball. Furthermore, variations in the movement initiation time (i.e., the *visual-motor delay*) of around 55-130 ms prior to contact were observed, which is much faster than the commonly accepted visual simple reaction time delay of 200 ms observed in laboratory settings (Carlton & Carlton, 1987; Lee et al., 1983; McLeod, 1987). Similarly, Bootsma and van Wieringen (1990) reported that the temporal accuracy of expert table tennis players performing a forehand drive was greater at the moment of bat-ball contact than it was at movement initiation. This suggests that performers were utilising visual information throughout movement execution to ensure bat-ball contact was made with optimal spatial and temporal precision.

There has been recent interest in identifying how vision might aid the prospective control of movement, considering the increasing belief that the brain does not predict the future arrival location of a target (see Montagne, 2005). *Tau*, or time-to-contact, has been proposed to be critical in providing fundamental information that is used to estimate time-to-contact by obtaining optical information on the ball's relative expansion on the retina, instead of calculating on the basis of the target's velocity and distance (see Lee et al., 1983; Savelsbergh, Whiting, & Bootsma, 1991; Tresilian, 1999). Although previous studies have supported the role of tau in determining time-to-contact (e.g., Savelsbergh, Whiting, Burden, & Bartlett, 1992), there has been growing concern that tau cannot be the sole explanation for the timing of actions and that other perceptual sources of information must be just as useful to determine time-to-contact (see Heuer, 1993; Judge & Bradford, 1988; Wann, 1996).

1.1.2. Perception-Action Coupling and Visual-Motor Control

The visual system obtains perceptual information from the surrounding environment to identify and locate the target of interest, before the necessary signals are generated to perform the desired motor action. This coupling between perception and action thus forms the cornerstone from which a greater understanding of the strategies that underpin successful interception can be obtained. The theory of a dual-pathway for vision (Goodale & Milner, 1992; Milner & Goodale, 1995) presents two discrete but interacting parallel neural pathways processing visually guided information regarding the performer’s actions (*dorsal* stream), and the visual perception of the performer’s surrounding environment (*ventral* stream). The dorsal pathway is known for utilising instantaneous information from the surrounding environment in an *egocentric* manner for the online control of movements. For example, the dorsal pathway is critical in the execution of a striking action to ensure the target is struck at the right place at the right time with the right amount of force. In contrast, the ventral pathway recognises objects of interest in an *allocentric* manner and enables the creation of a perceptual and cognitive representation of the visual array. For instance in striking tasks such as tennis, the ventral pathway is responsible to consciously help distinguish between the effectiveness of a ‘cross-court’ or ‘down-the-line’ shot to win the point (for more information, see Abernethy, Mann, & Bennett, 2008; Milner & Goodale, 1995; van der Kamp, Rivas, van Doorn, & Savelsbergh, 2008). Critically, both the ventral and dorsal streams are organised in a parallel, but integrated manner when promoting successful interception. Although empirical evidence is needed, it is speculated that novices may rely more so on the ventral stream to ensure movement execution, whereas experts are better able to utilise the dorsal stream as movement control becomes highly automatized (Abernethy, Maxwell, Masters, van der Kamp, & Jackson, 2007; van der Kamp, Oudejans, & Savelsbergh, 2003).

Understanding this critical coupling between perception and action through the integration of the dorsal and ventral pathways helps to better assess visual-motor expertise when performing an interceptive task. Any separation of this interdependency between perception and action may result in a failure to capture the true essence of skilled performance (Gibson, 1979). Van der Kamp et al. (2008), and now more recently Panchuk, Davids, Sakadjian, MacMahon, and Parrington (2013), argue that our current knowledge of expertise in interceptive tasks may in fact be biased as many studies remove the performer from their competitive environment in their experimental designs. This is proposed to result in an over-emphasis on the ventral and under-emphasis on the dorsal stream contributions to performance. Mann, Abernethy and Farrow (2010a) highlighted this issue when examining the anticipatory ability of skilled and lesser-skilled cricket batters through an *in situ* temporal occlusion study. Batters were asked to predict the direction of ball-flight when vision was occluded at three different timeframes (at the moment of ball-release; 50 ms following ball-release, and no occlusion), and under four different conditions (verbal; lower-body movement only; full-body movement with no bat; full-body movement with bat). As the specificity of the coupling between perception and action increased with each condition, skilled batters improved their ability to anticipate the direction of the ball, even when vision was occluded at the moment of ball-release. The findings support the need to maintain ecological validity and the critical coupling between perception and action in order to fully appreciate the advantage enjoyed by expert performers (for a similar finding on the visual search strategies of soccer goalkeepers, see Dicks, Button, & Davids, 2010). This point will be further addressed in section 1.2.3.

1.1.3. Central and Peripheral Vision and Perception-Action Coupling

The interdependency between perception and action illustrates how our actions are influenced by our perception of the world. Accurate perception however is reliant on the actor moving their eyes in a manner that allows the area of greatest visual interest (i.e., the target) to fall on the fovea (i.e., central vision) where a greater density of photoreceptors and ganglion cells provides a sharp, high resolution image of the surrounding environment in full colour. Consequently, performers seek to move their eyes in a manner that ensures foveal fixation is maintained on the target, allowing for an accurate intake of information and an enhanced perception of the environment (Hyönã, 2011). When the target does not fall on the fovea (i.e., peripheral vision), the disproportionate representation of photoreceptors provides less clarity and lacks the resolution required for an accurate representation of the environment (Goldstein, 2009). Peripheral vision may thus provide conflicting responses with noticeable distortions in spatial position and motion detection (Levi, 2008; Pelli & Tillman, 2008).

The poorer ability to integrate features via peripheral vision may lead to misperception of the environment through misdirection and illusions. Although classical perceptual illusions such as the Ponzo illusion and Müller-Lyer illusion provide an interesting insight into how the brain processes information, a more dynamic environment provides a better foundation from which to examine the integrative ability (or lack thereof) of peripheral vision. Magic has been a relatively untapped source of examination for perceptual processing, with the sleight of hand tricks providing an interesting example of how perceptual processing is often misdirected towards central vision, whilst the crux of the illusion occurs in peripheral vision (for an interesting read, see Otero-Millan, Macknik, Robbins, & Martinez-Conde, 2011; though also see Kuhn, Tatler, Findlay, & Cole, 2008). Similarly during competition, inducing misdirection in the performer's perception of the future arrival location of the ball provides a large advantage to the opponent. This is particularly evident with the illusion of the '*breaking curveball*' commonly reported by baseball batters. The 'curveball' occurs when spin is imparted on the ball resulting in a net transverse force that leads to lateral deviations in the ball's flight-path (Mehta, 1985), with many baseball batters claiming that the ball curved 'suddenly' or 'sharply' making it very difficult to hit (see Bahill & Karnavas, 1993; Watts, Bahill, & Griffing, 1991). When examining this phenomenon, Shapiro, Lu, Huang, Knight, and Ennis (2010) observed that when the target (a vertically descending disk) was foveally tracked, central vision was able to separate first- (descending disk) and second-order (internal spinning) motion to detect that the object was descending vertically. However, when tracked peripherally (by fixating at a separate target adjacent to the descending disk), participants integrated first- and second-order motion to interpret the descending disk to have adopted a curved trajectory. The authors concluded that this sudden break in ball-flight reported by the baseball batters is due to the ball transitioning into peripheral vision following a period of foveal tracking. This is supported by previous studies that show that the gaze strategies of baseball batters begins with smooth tracking for the first two-thirds of ball-flight, before shifting their gaze ahead of the ball towards bat-ball contact, and then batters '*continue to follow the ball with peripheral vision letting the ball catch up to the eye*' (Bahill & Baldwin, 2004, p. 262) so that images of the ball and bat are within central vision as contact is being made (the influence of swinging ball trajectories on perception will be further explored in section 1.3.2). Although the exact role of peripheral vision during interception is still unclear, successful interception may be reliant on performers effectively gathering perceptual information from foveal *and* peripheral vision (Bahill & LaRitz, 1984; Land & McLeod, 2000).

1.1.4. Visual-Motor Behaviour when Performing Interceptive Actions

Examinations into the visual-motor behaviour of performers when carrying out an interceptive action provide an interesting insight into the visual strategies that acquire perceptual information and ultimately guide a motor action. Particularly, examining the skill-based differences in the gaze and movement behaviour (through *kinematic* analysis) of performers can help determine the underlying processes involved in the planning, organisation and execution of skilled movements. Remarkably, some skill-based differences in visual-motor behaviour can be observed *prior to* ball-release. Previous studies examining the anticipatory ability of performers reveal that prior to ball-release, skilled performers are able to differentiate kinematic variations in their opponent's body to anticipate their intentions (e.g., Abernethy, 1990; Müller & Abernethy, 2006; Savelsbergh, Williams, van Der Kamp, & Ward, 2002; Singer, Cauraugh, Chen, Steinberg, & Frehlich, 1996). For example, Singer et al. (1996) reported that when returning a serve in tennis, expert performers produced a definitive scan that began in the proximal segments of the opponent's body and gradually moved towards the distal body segments to coincide with the moment of racquet-ball contact. Novice performers on the other hand, were more scattered and generic in their scan of their opponent's body before maintaining fixation on the distal body segments. Moreover, performers were also found to couple the initiation of their motor action with the kinematics of the opponent prior to ball-release. Hubbard and Seng (1954), and recently Ranganathan and Carlton (2007) observed that baseball batters established a 'rhythm' by coupling the initiation of their front-foot movement with the moment of ball-release. It was proposed that this ability to anticipate the opponent's future intentions, and prepare their actions prior to ball-release, allows skilled performers to move into an optimal position from which to intercept their target earlier; giving the impression of *having all the time in the world* (*cf.* Bartlett, 1947).

Examinations of visual-motor behaviour *following* ball-release have also revealed skill-based differences in the gaze and kinematic behaviour of performers. When a target is in motion, such as a ball in flight, commensurate movement of the eyes (and head) can permit the maintenance of foveal fixation on the target as it moves through the visual field (termed *smooth tracking*). However, performers do not, and perhaps cannot, abide by the common coaching adage to '*keep your eyes on the ball*' throughout ball-flight (Bahill & LaRitz, 1984; Land & McLeod, 2000). Instead, a subconscious rapid eye movement seeks to quickly shift foveal fixation from one point in the visual field to another (termed a *saccade*). A common type of saccade that is initiated when performing an interceptive action is an *anticipatory saccade*, whereby performers shift their gaze ahead of the target to a predicted location in the visual field where they believe the target will be in the future (e.g., Land & McLeod, 2000). The landmark study by Land & McLeod (2000) examined the gaze behaviour of cricket batters of three different skill levels and found that batters foveally tracked the ball for the initial portion (50-80%) of ball-flight before initiating an anticipatory saccade towards the predicted location of ball-bounce. Furthermore, it was reported that more skilled batters initiate this saccade earlier than lesser-skilled batters do, which was interpreted to reflect the superior anticipatory ability of the skilled batters to predict the future location of the ball. It is also interesting to note that similar to baseball batting (e.g., Bahill & Baldwin, 2004; Bahill & LaRitz, 1984), cricket batters too were not tracking the ball up to the moment of bat-ball contact. Instead, their gaze fell behind the path of the ball not long after it bounced. This suggests that perhaps maintaining foveal fixation is very difficult, if at all necessary, at the moment of bat-ball contact to promote successful interception. However, recent findings by Mann, Spratford, and Abernethy (2013) observed that two of the world's best cricket batters adopted a unique sequence of eye movements that suggested that batters initiated a second anticipatory saccade that directed their gaze towards the predicted location of bat-ball contact, and then maintained gaze at that location as they hit the ball. The gaze behaviour of performers specific to cricket batting will be further explored in section 1.2.2.

Understanding skill-based differences in the *kinematic* behaviour of performers has been challenging though because the same hitting outcome can be achieved by a number of different movements/actions. However, recent studies have helped to uncover some common kinematic parameters that promoting successful interception. When examining the striking motion in interceptive tasks such as returning a serve in tennis, or batting in baseball and cricket, the kinematic chain of events from this full-body movement seeks to promote the summation and transfer of forces from the lower limbs through to the trunk, further to the arms and then to the end effector striking the target (see Sarpeshkar & Mann, 2011; Zatsiorsky, 1998). In general, previous studies examining the kinematic behaviour of performers reveal that the skilled performers are better than the lesser-skilled performers in achieving, for example, a: (i) shorter duration of time between the moment of ball-release and the initiation of foot movement (Abernethy, 1981; Hubbard & Seng, 1954), (ii) faster angular velocity of bat-swing (Abernethy & Russell, 1984), and (iii) decreased variability in the timing of the initiation and completion of bat-swing (Bootsma & van Wieringen, 1990). Recently, Weissensteiner et al. (2011) also showed that skilled cricket batters are better than lesser-skilled batters in synchronising the timing of the completion of their foot stride with the initiation of their bat-downswing. By doing so, skilled batters were able to establish a stable foundation from which they could effectively facilitate bat-downswing (Abernethy, 1981) and use this forward momentum to shift their centre of mass forward and effectively transfer the summated forces to the ball. The kinematic behaviour of performers specific to cricket batting will also be explored in section 1.2.1.

1.1.4.1. Limitations in the current understanding of visual-motor behaviour.

Clearly, the aforementioned findings of skill-based differences in visual-motor behaviour have provided important insights into the strategies that underpin successful interception. However, there are three major concerns with the existing literature that limit the conclusions that can be drawn from those findings:

(i). The support for skill-based differences has largely been made on the basis of studies that employ very low sample sizes, making it difficult to determine whether these findings are truly representative of the wider population. For example, the highly influential paper by Land and McLeod (2000) examined the eye movements of only three cricket batters each of a different skill level.

(ii). Existing studies have generally examined performance in simplified task environments that may not necessarily replicate the spatio-temporal demands typically experienced during competition. For instance, the paper by Bahill and LaRitz (1984) reported the gaze behaviour of a baseball batter hitting a plastic ball that moved along a string to a fixed (and therefore predictable) location relative to the batter, while Taliep, Galal, and Vaughan (2007) reported skill-based differences in the head position of cricket batters when performing a shadow movement to video-projected footage.

(iii). Studies have typically examined skill-based differences at only one particular stage of development. This not only makes it difficult to make valid comparisons across different studies, but also very little is known about the age at which these skill-based differences in visual-motor behaviour are likely to be acquired (e.g., Benguigui & Ripoll, 1998; Dorfman, 1977).

Collectively, these studies may not provide an accurate reflection of the findings they seek to represent, warranting the need for a more comprehensive examination of the development of visual-motor expertise. As a result, there is a clear need to examine the visual-motor behaviour associated with skilled interception by using (i) a larger number of participants, (ii) an environment that more closely replicates competition, and (iii) a broader range of skill and age groups.

Another critical oversight of previous examinations is the relative paucity of studies that examine the link between gaze and kinematics when performing an interceptive action. In other words, the exclusive examination of the performer's gaze behaviour may have overlooked its critical relationship with motor actions, thus falling short in capturing the true essence of why these differences may exist. When intercepting a stationary target (a teapot), Land et al. (1999) observed that gaze generally preceded the motor action, providing perceptual information that allowed for the continuous guidance, monitoring and feedback of the task; concluding that gaze was quite strongly coupled with the motor actions (also see Land & Hayhoe, 2001). However when intercepting *moving* targets, performers need to account for the visual-motor delay inherent of the neuromuscular system to alter movements on the basis of visual feedback (approximately 150 ms; see Saunders & Knill, 2003). Considering the immense spatio-temporal demands of fast-ball sports, performers may need to organise their movements by adopting a visual-motor strategy that prospectively allows them to predict where the target will be in the near future rather than in the present (see Sarpeshkar & Mann, 2011). Until now, very little is known about the nature of this relationship when intercepting a fast-moving target, though previous studies suggest that performers may be able to rely on previous experiences to prepare their gaze and action based on the predicted future location of the target (e.g., Diaz, Cooper, Rothkopf, & Hayhoe, 2013; Land & Furneaux, 1997).

It is clear that successful interception relies on the complex coordination of gaze and kinematics. Establishing a clearer understanding of the skill-based differences in visual-motor behaviour can help foster greater knowledge of how skilled performers develop expertise in interception. The next section seeks to explore the unique spatio-temporal demands experienced during the fast-paced interceptive task of cricket batting; a task that forms the foundation for the experimental work undertaken throughout the thesis.

1.2. Cricket Batting: Visual-Motor Behaviour and Successful Performance

Cricket batting is an open motor task that requires batters to choose from a wide repertoire of shots to hit an oncoming ball away from 11 opposing fielders located within an oval/circular field. The demands imposed on a batter begin with the laws of the game, which state that the width of a bat should not exceed 108 mm to hit a ball with a circumference no greater than 229 mm (Marylebone Cricket Club, 1993). Batters at the elite level must also overcome a large spectrum of ball-speeds, ranging from 75 km.h^{-1} (≈21 m.s^{-1}; often delivered by 'spin' bowlers who aim to impart spin on the ball to promote lateral deviations following ball-bounce) to 160 km.h^{-1} (≈45 m.s^{-1}; frequently delivered by 'fast' bowlers). Furthermore, the batting task takes place on an uneven turf playing surface that may not necessarily have consistent rebound characteristics, with the batter typically hitting the ball after it has bounced on this surface. Success in the task therefore depends on the batter's ability to hit the ball to score 'runs' whilst minimising the likelihood of being dismissed (such as the ball being caught by one of the opposing fielders, or having the ball hit the stumps located behind the batter).

1.2.1. Spatio-Temporal Demands of Cricket Batting

When hitting a ball in cricket, the batter sometimes has less than 600 ms to judge the future arrival location of the ball, with optimal interception being within a spatial accuracy of ± 3 cm (due to the width of the bat; Land & McLeod, 2000; McLeod & Jenkins, 1991), and within a temporal window as small as 2-5 ms (Regan, 1992; Tresilian, 2004a). Furthermore, batters must also contend with the possibility of the ball following an array of different flight-paths (straight or swinging) and trajectories (that cause the ball to bounce at different locations in relation to the batter). To counter this, the batter often needs to choose from one of two response options: to (i) step *forward* to hit the ball immediately after it bounces to minimise the possibility of lateral deviations following ball-bounce (termed a *front-foot shot*), or (ii) step *backward* to hit the ball well after it has bounced to ensure additional ball-flight information is available following ball-bounce to correct for any lateral deviations in ball-flight (i.e., termed a *back-foot shot*; see Figure 1.1).

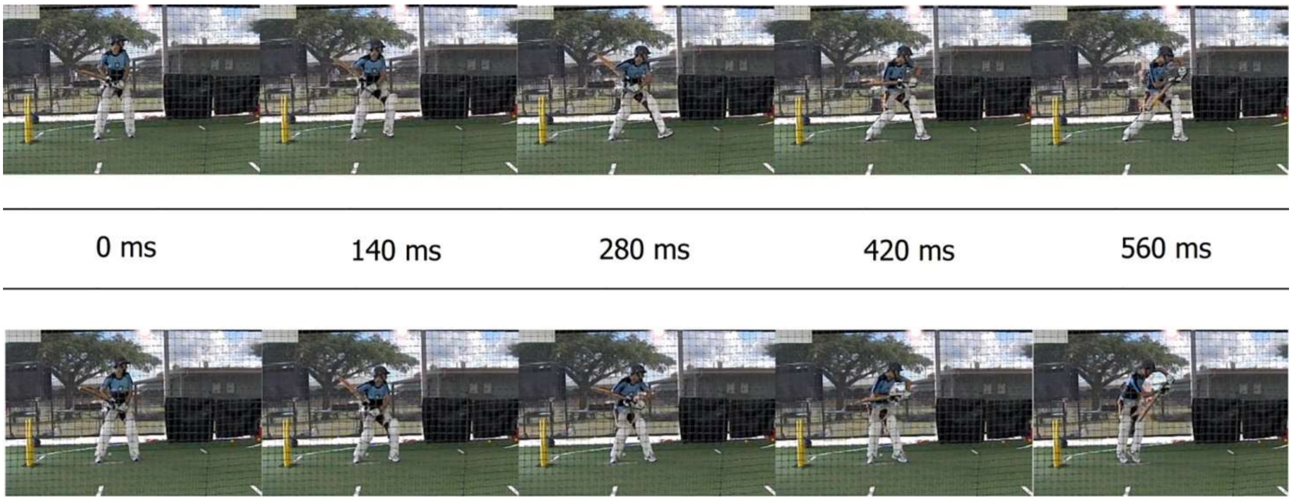

Figure 1.1. Images depicting the temporal sequence of the key phases of movement following ball-release for the front-foot (top panel) and back-foot shot (bottom panel).

Early analysis of batting behaviour reported the overall movement of the batter as if it were a single complete movement with no temporal overlap between decision making and motor execution (Glencross & Cibich, 1977). However, Abernethy (1984) showed that the behaviour of skilled batters consisted of at least two discrete phases of movement: (i) lower-body movement and, (ii) bat-downswing. It is believed that the first phase of movement serves as a positioning role for batters to utilise early ball-flight information to move towards an optimal position from which to hit the ball. Ranganathan and Carlton (2007) observed similar behaviours among baseball batters where batters coupled the initiation of their front-foot movement with ball-release, while the step duration varied with different ball velocities (also see Hubbard & Seng, 1954). Similarly, Thomlinson (2009), reported that almost all skilled cricket batters initiated their front-foot movement at similar times following ball-release, with stride distance and duration varying in relation to the location of ball-bounce relative to the batter. Weissensteiner et al. (2011) showed that the coupling between the completion of lower-body movements and the initiation of bat-downswing may be a distinctive characteristic of skilled performance. More specifically, skilled batters showed a shorter duration of time between the completion of their front-foot stride (as the batter stepped forward) and the initiation of their bat-downswing, with this inter-limb coordination becoming more proficient with age (Weissensteiner, 2008). The authors proposed that the coordination of upper- and lower-body segments reflects an efficient means by which skilled batters could establish a strong, stable base of support before transferring their energy to a controlled downswing of the bat (Abernethy, 1981).

The second phase of movement allows the batter to swing their bat forward to hit the ball towards the desired location. Compared to other fast-ball sports (e.g., baseball and tennis), the bat-speed generated by cricket batters is considerably slower (e.g., Marino, 1989; Stuelcken, Portus, & Mason, 2005). However, this does not necessarily correlate to the batters altering their bat-swing more readily as a result of unexpected deviations in ball-flight. McLeod (1987) examined the minimum time necessary for batters to correct their bat-swing to unexpected deviations in ball-flight to ensure successful interception. This was achieved by examining the visual-motor delay of cricket batters attempting to hit balls that, at times, deviated laterally as a result of bouncing on wooden dowels placed under the playing surface. The results revealed that batters needed to initiate their corrections at least 190 ms prior to bat-ball contact. This encompasses the visual processing delays comparing the predicted and modified flight-path of the ball, as well as delays attributable to overcoming the inertia, impulse and direction of the relatively heavy wooden bat (see Sarpeshkar & Mann, 2011). Because the batter must make some form of prediction for where the ball will be at contact when they commence their backswing, this suggests that cricket batting may require batters to adopt a hybrid form of predictive *and* prospective movement control to promote successful interception. It is believed that the prospective control of movement is attainable up to 190 ms prior to bat-ball contact, after which a predictive form of control may be necessary for the batter to judge the future arrival location of the ball; as it is very difficult to alter the bat-swing once it is initiated (see Diaz, Phillips, & Fajen, 2009; Katsumata & Russell, 2012; Tresilian, 2005).

Although the batters may not be able to alter their bat-swing immediately prior to bat-ball contact, anecdotal observations of skilled performers suggests that batters may be able to make fine adjustments to their bat-swing to manoeuvre the ball away from the opposing fielders. For example, Sir Donald Bradman, generally considered to be the best cricket batter ever to play the sport, is famously known to have practiced the ability to make fine online alterations to his bat by using a cricket stump to repeatedly hit a golf ball against a corrugated iron tank[1] (see Fraser, 2005; Glazier, Davids, Renshaw, & Button, 2005). This idea is supported by Bootsma and van Wieringen (1990) who persuasively argued that the visual-motor delay could be considerably shorter than 190 ms as performers could alter distinct parameters of their existing motor action to promote a

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[1] To understand the difficulty of this task, a golf ball has a diameter of 42.7 mm and a cricket stump has a diameter of 38.1 mm. This form of training continues to be used regularly among young cricket batters to help develop their visual-motor control and in turn, their ability to successfully hit the ball.

continuous regulation of their bat-swing as late as is permissible by the sensorimotor system, without necessarily initiating a new action (see Dewhurst, 1967; Johansson & Westling, 1984). This behaviour can also be observed in everyday activities such as the minute alterations in wrist position when picking up a glass of water, or beer, to avoid spilling a drop. However, this conjecture surrounding the usefulness of late ball-flight information to promote successful interception continues to be the topic of considerable debate in the literature (see Hayhoe, Mennie, Sullivan, & Gorgos, 2005; Mann et al., 2013).

1.2.2. Gaze Behaviours and Successful Performance

It is well established that when performing an interceptive task, batters do not abide by the common coaching adage to *keep your eyes on the ball*. Instead, cricket batters, like baseball batters, generally track the ball through a combination of smooth pursuit tracking and anticipatory saccades (e.g., Bahill & LaRitz, 1984; Land & McLeod, 2000). Although smooth tracking alone would allow batters to maintain foveal fixation on the ball throughout ball-flight, it is uncertain what the exact role of an anticipatory saccade may be, despite collective agreement that they are associated with success in interception (Diaz, Cooper, Rothkopf, et al., 2013; Mann et al., 2013). Bahill and LaRitz (1984) proposed that batters initiated a saccade to ensure foveal fixation was maintained when the target was moving too quickly for smooth tracking. To explore this hypothesis, Croft, Button, and Dicks (2009) examined the saccadic behaviour of sub-elite cricket batters by systematically varying the velocity of the ball to determine the threshold below which a saccade was no longer produced. They found that saccades were produced irrespective of the velocity of the ball and concluded that a saccade is not produced because the ball is moving too quickly (also see Mann et al., 2013).

More recently, Diaz, Cooper, Rothkopf, et al. (2013) suggested that prediction was a fundamental aspect of visual perception and that saccadic eye movements were likely to be based on learnt internal models of ball-flight characteristics that directed gaze ahead of the target in anticipation of a predicted event (also see Land & Furneaux, 1997). They examined the eye movement strategies of naïve performers in an immersive virtual racquetball environment where the ball speed and elasticity following ball-bounce were manipulated. It was reported that the spatial (within about 1.5° visual angle) and temporal accuracy of these saccades (maintaining an average duration of 170 ms between ball-bounce and the ball's arrival at the gaze location) is consistent with the use of an experience-based model to not only predict the future location of ball-bounce, but may also in turn help predict where (and when) the ball is likely to arrive (also see Diaz, Cooper, & Hayhoe, 2013; Diaz et al., 2009; Hayhoe et al., 2005). Empirical evidence is still required to determine how this strategy may differ across different skill and age levels, and whether these behaviours observed in the virtual environment accurately represent those observed *in situ*.

Recently, Mann et al. (2013) shed new light on the gaze behaviour of elite and lesser-skilled cricket batters and called these earlier conclusions into question. They examined the eye and head movement strategies of two of the world's best cricket batters and two club-level batters to determine whether differences in interceptive performance were the result of a superior gaze strategy adopted by the elite batters. Two important additions were made to the findings reported by Land and McLeod (2000). First, the elite batters used their eyes to guide their head so that it was aligned with the position of the ball throughout most of its flight. That is, the batters moved their head in a fashion that retained the position of the ball within a single egocentric direction relative to the head. By knowing where the ball would arrive relative to their head, it was proposed that batters might be able to simplify the task to one where time-to-contact was needed to successfully hit the ball (see Lee et al., 1983; Oudejans, Michaels, Bakker, & Davids, 1999). Second, the elite batters were found to not only produce an anticipatory saccade towards ball-bounce, but also to produce a second anticipatory saccade towards the likely location of bat-ball contact. Although Land and McLeod (2000) had proposed that batters were generally unable to track the ball in the final moments prior to bat-ball contact, Mann et al. (2013) reported that the elite batters frequently performed a saccade towards bat-ball contact or tracked the ball up to the moment of bat-ball contact. The authors concluded that the elite batters appeared to be doing whatever was necessary to direct their gaze towards the predicted location of bat-ball contact. Consistent with Diaz, Cooper, Rothkopf, et al. (2013), this suggests that learnt internal models of ball-flight may allow the skilled batters to direct their gaze towards the predicted future arrival location of the ball. As a result, batters could then maintain foveal fixation on the ball prior to bat-ball contact, facilitating online alterations to bat-swing as late as would be permissible (see Ripoll & Fleurance, 1988; Spering, Schütz, Braun, & Gegenfurtner, 2011). These findings collectively helped Mann et al. (2013) propose three possible roles for anticipatory saccades: to (i) facilitate tracking after the moment of ball-bounce, as it prevents the batter from having to direct their gaze down towards ball-bounce, and then back up again to accurately track the ball after it bounces, (ii) allow the batter to compare predicted and actual ball-flight trajectories, and (iii) promote a better detection of, and correction for, unexpected changes in the flight-path of the ball (also see Hayhoe et al., 2005).

A growing body of work continues to highlight the distinctive skill-based differences in the gaze behaviour of batters when hitting a fast-moving ball. However when examined in isolation, this may not provide a clear picture of how these differences may influence the batter's motor actions. For instance, Land and McLeod (2000) showed that skilled batters initiated their saccade towards ball-bounce earlier than the lesser-skilled batters did. However, it is unclear what functional advantage an earlier saccade might provide in facilitating successful interception. Examining this critical relationship between gaze and kinematics when performing an interceptive task can help foster a more comprehensive understanding of the coordinative fashion in which gaze and motor actions work together to underpin expertise in the interception of a fast-moving target.

1.2.3. The Mode of Delivery Influences the Visual-Motor Behaviour of the Batters

As mentioned earlier, it is essential to maintain ecological validity and the critical coupling between perception and action in order to fully appreciate the expert advantage in interceptive actions. In the case of cricket batting, this means examining the visual-motor behaviour of batters in an environment that closely replicates that experienced during competition. While the use of 'live' bowlers would be ideal, maintaining experimental control is difficult due to the large natural variations in the bowler's kinematics and ball-flight characteristics. Furthermore, the physiological and workload demands placed on the bowler over a prolonged bowling session could limit the quality of the bowling and can also be potentially dangerous to their health. As a result, researchers have welcomed the introduction of ball-projection machines as they provide tight experimental control whilst also ensuring a large volume of balls could be delivered. However, recent comparisons of batting behaviour when facing a bowling machine and a live bowler have questioned whether the gaze and movement strategies of batters are comparable between these two delivery methods, and whether bowling machines can be an adequate substitute in promoting the development of batting skill (for more information, see Pinder, Davids, Renshaw, & Araújo, 2011a; Pinder, Renshaw, & Davids, 2009; Renshaw, Oldham, Davids, & Golds, 2007).

The kinematic behaviour of the bowler prior to ball-release has been shown to provide critical information for the batters to anticipate the time and location of ball-release

(Barras, 1988). Furthermore, the batters can also use this information to help determine the type of delivery (see Müller & Abernethy, 2006; Müller, Abernethy, & Farrow, 2006) and also organise the initiation of their movement prior to ball-release (see Hubbard & Seng, 1954; Ranganathan & Carlton, 2007). This information however, is absent when facing a bowling machine. Batters are often only cued by the person feeding the machine by raising their arm prior to dropping the ball into the machine. Furthermore, the lack of kinematic information when facing a bowling machine means that batters often ‘park’ their gaze at the opening of the machine where the ball is projected (see Renshaw et al., 2007). With the machine head also clearly visible to the batter, any changes to the angle of release can be easily detected and allow batters to make early predictions regarding the location of ball-bounce, often resulting in premediated movement actions (Figure 1.2).

Differences in the gaze and kinematic behaviour of batters when facing a live bowler and a bowling machine have also been observed following ball-release. Pinder (2012) reported that developmental level cricket batters were able to foveally track the ball for a longer duration of ball-flight, and produced more accurate predictive saccades, when facing live bowlers compared to a bowling machine. When facing the bowling machine, batters typically let the ball ‘wash’ over the retina during early ball-flight, resulting in batters directing their gaze behind the ball for the majority of ball-flight (see Croft et al., 2009; Land & McLeod, 2000). There is also overwhelming evidence to suggest that the absence of advance information from the bowling machine influences the kinematic behaviour of the batters (see Cork, Justham, & West, 2008, 2010; Pinder et al., 2009; Renshaw et al., 2007). Specifically when facing a bowling machine, batters showed significant delays in the timing of the movement initiation following ball-release (*cf.* Hubbard & Seng, 1954; Ranganathan & Carlton, 2007), and the time between the completion of front-foot stride and the initiation of bat-downswing (*cf.* Weissensteiner et al., 2011). They were also found to adopt a shorter stride length and a lower velocity of bat-downswing (see Pinder et al., 2011a). Collectively, it is proposed that prolonged use of the bowling machine may significantly change the visual-motor behaviour of batters and may be detrimental towards skill development, particularly for developmental-aged batters (see Pinder et al., 2009; Renshaw et al., 2007).

Advancements in technology have allowed researchers and coaches alike to move a step closer towards replicating match-like conditions whilst maintaining a degree of experimental control. The hybrid *ProBatter* system (ProBatter Sports, Milford, CT) is a ball-projection machine that is located behind a large screen that displays a life-sized video projection of an approaching bowler before a ball is projected through the screen towards the batter (for more information, see Portus & Farrow, 2011). The ProBatter machine is programmed to show a series of different video recordings of a particular bowler (recorded live during competition) so that the ball-flight seen for that delivery is the same as that actually bowled in the video footage. This ensures that any kinematic information offered by the bowler's action matches the actual ball-flight. Mann et al. (2013) reported that the ProBatter machine provides: (i) experimental control that is not available with 'live' bowlers *in situ*, (ii) advance information of the bowler's kinematics to the batter (unlike a ball-projection machine), and (iii) assurance that batters cannot predict the direction of the ball based on any changes in the machine's angle of release (Figure 1.2). Furthermore, the machine can also be automated by programming a predetermined sequence of different deliveries, allowing for both experimental randomisation and a more realistic batting experience. Although the ProBatter machine has considerably more face validity for the assessment of batting behaviour than when using conventional ball-projection machines, a full validation of the system is yet to be performed to determine whether the visual-motor behaviour observed when facing the ProBatter are similar to those seen when facing a 'live' bowler *in situ*.

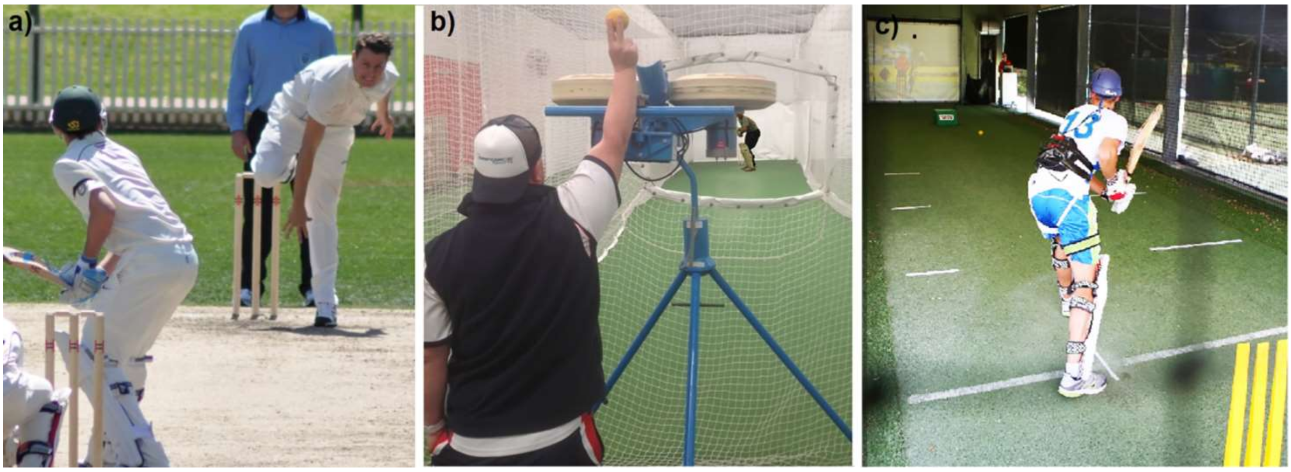

Figure 1.2. Exemplar images of a batter facing (a) bowler, (b) bowling machine, and (c) ProBatter respectively.

It is apparent that the open striking task of cricket batting presents an ideal vehicle from which to examine the visual-motor strategies that underpin successful interception. In addition to overcoming the severe spatio-temporal constraints experienced during the task, batters can also be required to develop visual-motor strategies that account for the (possibility of) lateral deviations in ball-flight. The next section seeks to explore the occurrence of ball-swing in sport, particularly focusing in on the factors that promote ball-swing and its subsequent influence on batting performance and visual-motor behaviour.

1.3. Interception in the Presence of Ball-Swing

A significant gap in the current knowledge base surrounding the visual-motor behaviour of performers during an interceptive task is the gaze and movement strategies that promote successful interception of a target that follows a swinging flight-path. Intercepting targets that follow a curvilinear rather than straight flight-path is commonly encountered in daily life such as when catching a Frisbee, or judging the distance of a car turning from around the bend. They are also commonly employed in many ball-sports where opponents seek to mislead the performer's perception of the future arrival location of the ball. To understand how swinging flight-paths influence the performer's perception of the target's trajectory, it is important to first examine the factors that lead to an object adopting a swinging trajectory.

1.3.1. Physics of Ball-Flight

The use of unusual flight-paths (such as swing) was originally considered to be a form of cheating because it was assumed that foreign objects were used to illegally manipulate the surface of the ball (see Woolmer, Noakes, & Moffett, 2008). However, scientific testing, for example using aerodynamic wind tunnel testing or computer simulations, has shown that simple physics can cause an object to follow a swinging flight-path. The curved trajectory of an object can be explained through *Bernoulli's Principle*. Bernoulli's principle states that the faster a fluid (such as air) flows across a surface, the more pressure it exerts (Bernoulli, 1738); which is a remnant of Newton's Second Law of Motion: '*The acceleration of an object is parallel and directly proportional to the net force acting upon it, and is inversely proportional to the mass of the object*'. An object can thus adopt a curved trajectory as a result of pressure differentials between turbulent (lower pressure) and laminar (higher pressure) airflow, which in an attempt to maintain equilibrium, gives rise to the '*Magnus force*'.

1.3.1.1. Magnus forces.

Magnus forces were first described by Isaac Newton in 1672 after watching the behaviour of the ball during a tennis match (Mehta, 1985). After much investigation, Magnus forces were found to be produced when a spinning object moving through the air creates a whirlpool of rotating air around itself and experiences a force that is perpendicular to the line of motion (see Mehta & Pallis, 2001; Walker, 1999). For example, when a soccer ball is in flight, a very thin layer of air, known as the boundary layer, surrounds the surface of the ball. If the ball was to be moving while rotating in a clockwise direction around the vertical axis, a whirlpool of fast moving air would be created on the left-hand side of the ball increasing the ball's velocity, whereas these motions would be opposed on the right-hand side of the ball decreasing the ball's velocity. As a result, this causes the boundary layer to separate from the ball asymmetrically; that is, earlier on the left-hand side but later on the right-hand side. Consequently, the air pressure on the left-hand side of the ball is higher than it is on the right-hand side of the ball. In an attempt to return to equilibrium, this results in a force that is perpendicular to the line of motion. In other words, the ball will deviate laterally from left to right (also see Mehta, 1985; Mehta & Pallis, 2001; Walker, 1999). This type of behaviour can be witnessed in many sporting activities such as the free-kicks taken by David Beckham in soccer, or the 'drift' achieved in Shane Warne's magical delivery that dismissed Mike Gatting in the 1993 Ashes series[2].

1.3.1.2. Laminar vs. turbulent airflow.

Laminar and turbulent airflow can also be achieved in the absence of spin. Critically, the nature of airflow around an object is greatly influenced by the drag forces encountered as a result of friction as it moves through the air. The relative drag forces experienced by an object in flight is dependent on its velocity, smoothness of the surface, density of the air, temperature and altitude (Walker, 1999). For example, the wings on an aircraft do not spin[3], yet their design generates lift by creating an asymmetrical airflow around the wing as the aircraft moves through the air. That is, lower pressure on the top surface and higher pressure on the bottom surface (e.g., NASA, 2010). Similarly, a ball can achieve comparable properties throughout its flight.

A cricket ball for example, is made out of cork and four pieces of leather, weighing 156 g in total. The ball has a primary seam consisting of six rows of 60-80 stitches along its equator and a secondary seam consisting of internal stitching along each hemisphere and at right angles to each other (Mehta, 2005). The primary seam, which is raised above the surface of the ball, clearly separates the ball into two hemispheres. As the ball is being used in normal play, constant collisions with the bat and the bounce of the ball on an

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[2] The 'drift' from left to right observed in ball-flight is one of the signature characteristics that led to the delivery being coined *the ball of the century*.

[3] As I have noticed from my cherished window seat on frequent flights between Brisbane and Sydney.

abrasive surface slowly deteriorate the surface of the ball. As a result, cricket players are often seen applying moisture (either through saliva or sweat) to one hemisphere of the ball and rubbing it heavily on their trousers in an attempt to polish and restore the ball's condition. This is to promote a shiny smooth surface on one side of the ball (resulting in laminar airflow), whilst maintaining a rough abrasive surface on the other (resulting in turbulent airflow). When the ball is in flight, the resultant air pressure on the shiny side of the ball is higher than it is on the rough side of the ball, resulting in a force that is perpendicular to the line of motion (Figure 1.3; Bearman & Harvey, 1976; Walker, 1999). This gives rise to the phenomenon referred to in cricket as *swing* (see Barton, 1982; Mehta, 1985, 2005; Mehta, Bentley, Proudlove, & Varty, 1983; Mehta & Pallis, 2001). Interestingly, by merely changing the orientation of the cricket ball, the primary seam can further disrupt airflow to one side of the ball causing it to swing in the opposite direction. In other words, it is also possible for a cricket ball to swing towards the shiny smooth side (termed *reverse swing*; for more information, see Mehta, 2005).

The notion of a swinging ball in cricket, whether it is the ability of the bowler to cause the ball to swing, or the ability of the batter to overcome its increased spatio-temporal demands to successfully hit the ball, are often considered to be some of the toughest skills to grasp (see Woolmer et al., 2008). The lateral deviations of a cricket ball gives rise to two potential types of deliveries: (i) *outswing* (whereby the shiny side of the ball is towards the batter, thus causing the ball to swing *away* from the batter), and (ii) *inswing* (whereby the shiny side of the ball faces away the batter, thus causing the ball to swing *in towards* the batter; e.g., Cricket Australia, 2005, see Figure 1.3). Wind tunnel tests by Mehta (2000) reported that at a velocity of 30 $m.s^{-1}$ ($\approx$108 $km.h^{-1}$) and with the seam angled at 20° to the oncoming airflow (all comfortably within human achievement), a maximum side force of about 30% of the ball's own weight could be experienced, potentially deviating the ball laterally by approximately 800 mm (see Barton, 1982).

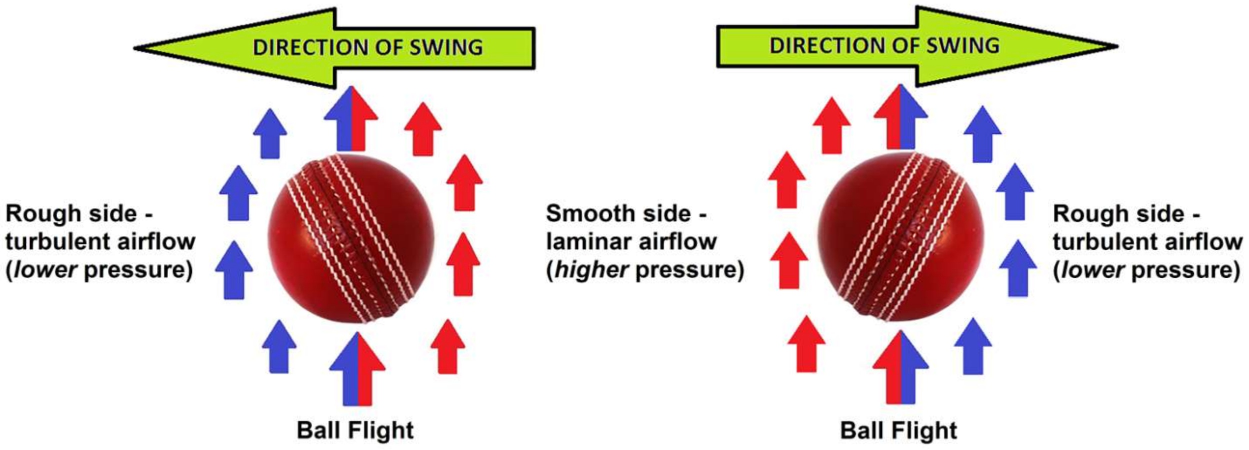

Figure 1.3. Illustration of the pressure differentials created through laminar and turbulent airflow causing the ball to swing.

1.3.2. Visual Perception and Ball-Swing

The extensive body of work examining the aerodynamic and physical properties of a target that follows a swinging flight-path, surprisingly, has not necessarily translated to a clear understanding of its influence on the visual-motor behaviour of the performers attempting to intercept the swinging target. In other words, it is not yet clear whether the visual-motor strategies that underpin successful interception of a target that follows a *straight* flight-path also help performers to successfully intercept a target that follows a *swinging* flight-path. A critical distinction that performers need to make when intercepting a target that follows a swinging trajectory, compared to a straight trajectory, is that they need to account for the continuous lateral deviation in the target's flight-path when predicting its future arrival location. This is clearly a very challenging task. Craig et al. (2011) recently examined the ability of recreational soccer goalkeepers to predict the future arrival location of balls following a straight and swinging trajectory in an immersive virtual-reality environment. It was reported that the interceptive proficiency of the performers was significantly reduced when intercepting the swinging balls compared to the straight balls. This observation is consistent with the idea that the type of informational variables that performers rely on when intercepting targets that follow straight flight-paths (*viz*. changes in target size and bearing angle) may be less reliable if the target follows a swinging flight-path (Craig et al., 2009). This has led to the hypothesis that fundamental limitations within the visual system may restrict the performer's ability to predict the future arrival location of a swinging target, thus explaining the poorer interceptive performance (see Craig et al., 2006; Port, Lee, Dassonville, & Georgopoulos, 1997). With these behaviours observed in a virtual environment, it would be useful to determine whether performers adopt similar strategies *in situ* to fully appreciate the influence of ball-swing on visual-motor behaviour (i.e., maintain the critical coupling between perception and action; see Mann et al., 2010a).

Although Craig et al.'s hypothesis suggests the performers may not be able to predict the future arrival location of a swinging ball, there is reason to believe that performers may be able to adapt their gaze behaviour to account for ball-swing. Early examinations of eye movements in a virtual environment have shown that performers can incorporate horizontal elements to their saccades when shifting their gaze between two distinctive locations (i.e., *oblique saccade*; see Viviani, Berthoz, & Tracey, 1977). Mrotek and Soechting (2007) observed that when a section of a target's swinging trajectory was briefly occluded in a virtual environment, performers were able to account for the target's curvature and initiated a saccade towards the predicted location from where the target was likely to re-emerge. Although this behaviour has not yet been reported during an interceptive task *in situ*, it is consistent with the idea that performers could utilise existing memory representations of ball-flight trajectories to shift their eyes towards the anticipated location of a target through the shortest possible route (see Becker & Jürgens, 1990; Diaz, Cooper, & Hayhoe, 2013).

Previous studies have also shown adaptations in the movement strategies of performers that may allow them to be positioned at the right place at the right time when intercepting a swinging target. Lenoir, Vansteenkiste, Vermeulen, and de Clercq (2005) examined the influence of ball-swing on the movement coordination of volleyball players, and observed that players organised their movements through a ball-related reference frame. That is, they continuously coupled the position of their body to the changing heading direction of the ball to ensure that their arrival location coincided with the arrival of the ball. This evidence of *movement reversals* (i.e., the ongoing alteration of position in space with continuing ball-flight information; see Casanova, Borg, & Bootsma, 2015; Craig et al., 2011; Montagne, Laurent, Durey, & Bootsma, 1999) suggests that performers are able to extract perceptual information from ball-flight as it unfolds to constantly modify the timing and coordination of their movement in an online manner (Peper et al., 1994). This may be slightly different in hitting tasks such as cricket batting however, as batters need to, at some point, predict the future arrival location of the ball because altering the bat-swing may be too difficult once the movement is initiated (see section 1.2.1; McLeod, 1987; Sarpeshkar & Mann, 2011).

The visual-motor behaviour of performers may also be significantly influenced by the *direction* of ball-swing, which has received very little scientific attention. The perceptual information specifying the future arrival location of a target is thought to be similar irrespective of the direction of ball-swing (see Craig et al., 2011; 2006; Lenoir et al., 2005). However, it can be argued that this could be task specific. For example, in tasks where the performer stands front-on with their opponent directly in front of them (such as a soccer goalkeeper facing a penalty shot), the direction of ball-swing should not influence their ability to intercept the target as the perceptual information specifying the future arrival location of the ball is mirrored. However, in other tasks where the performer is *not* positioned directly in front of their opponent (e.g., a baseball batter standing to one side of home plate), perceptual information is no longer mirrored and so ball-swing in one particular direction may be more challenging to intercept than the other. This is consistent with the anecdotal observations of cricket batters who claim that a ball that swings *away* from them is more difficult to hit than a ball that swings *in towards* them (e.g., Woolmer et al., 2008). Considering that the alignment between the performer and the opponent is seldom symmetrical during competition, it is reasonable to expect that the direction of ball-swing will have a significant influence on the visual-motor behaviour and interceptive proficiency of the performers.

It is also important to consider that the *possibility* of ball-swing may not only influence the visual-motor behaviour of performers when intercepting a target that follows a swinging flight-path, but may also extend to the uncertainty generated when intercepting a target that *does not* swing. The contextual environment in which an action is performed is known to influence how that action is accomplished (e.g., Todorović, 2010). For instance, Tijtgat et al (2010) examined the timing and coordination of movement when catching balls travelling at different ball-speeds under different contextual environments. They found that when the ball-speeds were blocked together, performers were able to scale the initiation of their hand movements to that individual ball-speed. However, when the ball-speeds were randomised, hand movements were initiated at a similar time irrespective of the ball-speed. This predetermined motor action was thought to allow performers to prepare for the most difficult type of ball-speed (i.e., the fastest ball-speed) which then allowed sufficient time to compensate for the slower ball-speeds in an ‘online’ manner. Similarly, Gray (2002) examined the influence of the prior sequence of pitches on the bat-swing of college-level baseball batters of different skill levels. The results showed that the bat-swings of the lesser-skilled batters were significantly influenced by the sequence of preceding pitches, significantly decreasing their interceptive performance. On the other hand, the skilled batters were able to combine the knowledge of the previous sequence of pitches with the perceptual ball-flight information to modify their bat-swing and successfully hit the ball. This shows that the range of possible outcomes can influence the way that the action is performed. As a result, examining the visual-motor behaviour of performers in the presence of ball-swing represents an ideal model from which to better understand how skilled performers account for contextual information to facilitate successful interception.

1.3.3. Folklore Surrounding Ball-Swing in Sport

From curved free-kicks in soccer to curveballs thrown in baseball, opponents attempt to mislead the performer's perception of the future arrival location, and time, of the ball. Interestingly though, much of our current understanding of swinging flight-paths in sport are based on anecdotal observations, with relatively limited scientific evidence confirming and/or challenging those observations. For example, the anecdotal reports of the rising fastball and breaking curveball are synonymous with baseball folklore, where batters claim that the ball either rises suddenly (against expected gravitational forces) just prior to reaching the batter, or adopts a sharp curve mid-flight as it approaches the batter (Bahill & Karnavas, 1993). Despite scientific studies explaining the misperception in the ball's flight-path (Shapiro et al., 2010), along with aerodynamic studies refuting that such trajectories exist (Briggs, 1992), many sportspeople are adamant that such a phenomenon exists.

The sport of cricket is also steeped with folklore when exploring the swing of a cricket ball. From the environmental conditions that are conducive to swing, to the actual colour of the ball used during competition, much of what we know, or at least what we think we know, is based on the anecdotal observations and reports by cricket players and spectators. Coaches of developing batters are also observed to advocate coaching strategies based on observations of skilled performers. For instance, the common coaching adage to *move late, move quickly* is thought to encourage batters to delay the initiation of their front-foot stride and bat-backswing to sample as much of ball-flight as possible, before increasing their stride speed and the angular velocity of bat-downswing to compensate for this delay (see Bradman, 1958; Cricket Australia, 2005). With very little scientific basis behind the modification of batting behaviours, examining the visual-motor adaptations of performers to the increased spatio-temporal demands of hitting a swinging ball can shed new light on the strategies that underpin successful interception in the presence of ball-swing. It is hoped that the findings from such studies can help establish a foundation from which researchers and coaches alike can work towards a more comprehensive understanding of the development of visual-motor expertise to help develop training paradigms designed to improve batting skill and/or an effective criteria for the purposes of talent identification.

1.4. Thesis Outline

1.4.1. Rationale for the Thesis

It is clear that successful interception requires precisely coordinated visually guided movements that effectively guide the timing and coordination of the motor action. Previous studies have shown that differences in the gaze and kinematic behaviour of performers underpins success and effectively distinguishes skilled from lesser-skilled performers; yet the support for these findings are largely made on the basis of studies that use very low sample sizes (e.g., Land & McLeod, 2000; Mann et al., 2013). So, a valid question to ask might be, *can the studies adopting a case-study design accurately reflect the skill-based differences in the visual-motor behaviour of performers across a wider population?* It could be argued that these studies may be too sensitive to individual variations in the actual participants tested to reflect the population findings they seek to represent. At this point there is insufficient evidence to verify whether these findings can be replicated using a larger sample of participants. Moreover, these studies reporting skill-based difference have generally done so when examining performers at a particular stage of their development. In other words, *it is unclear the age at which these skill-based differences in visual-motor behaviour are likely to emerge*, making it difficult to compare the findings across different studies because some studies have tested developmental level players (e.g., Croft et al., 2009) while others have tested adults (e.g., Land & McLeod, 2000; Mann et al., 2013). If expert-like visual-motor behaviour is found to emerge at an early age, then this would provide evidence that it is a skill that is acquired early in development. On the other hand, if these differences are found later in age, then a greater accumulation of experience and/or maturation is likely to be necessary for the development of expert-like behaviour. This clearly warrants a more comprehensive examination of the gaze and kinematic behaviour of a greater number of performers, and across a broader range of skill and age levels, to truly comprehend the development of visual-motor expertise and establish a clearer understanding of the expert advantage.

This chapter also clearly highlights the importance of examining skilled performers in an environment that more closely replicates that experienced during competition. Existing studies often make inferences about skill-based differences in visual-motor behaviour after either removing the performer from their natural environment (e.g., through virtual environments) and/or by examining performance under simplified task constraints (e.g., hitting slower and more predictable ball-flight trajectories). These changes make it difficult to generalise the findings to the more challenging tasks encountered in the performance environment. Particularly, very little is known about how performers might account for the increased spatio-temporal demands imposed when intercepting a target in the presence of ball-swing. In other words, *can the same visual-motor strategies that allow performers to intercept a target that follows a straight flight-path also help performers to successfully intercept a target that may (or may not) follow a swinging flight-path?* This raises three interesting questions: (i) how does simply being aware of the *possibility* of ball-swing influence the interceptive performance and visual-motor behaviour of performers when hitting a target that follows a straight flight-path, (ii) what specific adaptations (if any) in gaze and movement coordination are performed to promote successful interception of a target in the *presence* of ball-swing (compared to straight flight-paths), and (iii) does ball-swing in one particular *direction* alter the interceptive proficiency and visual-motor behaviour of performers more than ball-swing in the other direction?

It is also clear that understanding skilled interception through the examination of gaze and kinematic behaviour in isolation may not capture the true essence of the expert advantage. Considering the coordinative fashion in which gaze and motor actions work together, examining the critical relationship between the two can help to better understand expertise in interception. Although gaze has shown to be closely coupled with kinematics when intercepting a stationary target (Land et al., 1999), there is almost no evidence to suggest that this relationship holds when intercepting a fast-moving target. In addition to the paucity of studies outlining the nature of this relationship, very little is known whether any specific gaze and kinematic variables in the hitting action are coupled, and whether this coupling underpins skilled performance. By heeding to the calls of previous papers to understand this relationship between eye movements and motor actions (e.g., Abernethy, 1993; Phillips, Davids, Renshaw, & Portus, 2010; Sarpeshkar & Mann, 2011), a deeper understanding of the functional interaction between the two to promote successful interception can be established.

The overarching aim of the experimental series presented in this thesis is to establish a comprehensive understanding of the development of visual-motor expertise using interception in the presence of ball-swing as a model of a highly demanding interceptive task. Notably, the thesis aspires to extend the current knowledge base by examining the gaze and kinematic behaviour of cricket batters, who systematically differed in their level of batting skill and/or age, when hitting a ball that follows a straight and swinging flight-path. It does so by overcoming several limitations of previous investigations: using (i) a larger number of participants, (ii) a broader range of skill and age groups, and (iii) an environment that more closely replicates that experienced during competition. This thesis also provides the first examination of the critical relationship between gaze and kinematics when hitting a fast-moving target to help better understand the intricate coordination of visual-motor control that forms the cornerstone for skilled movements. It is expected that the findings from this experimental series will shed new light on the strategies that underpin the development of visual-motor expertise in interception, whilst also establishing a foundation for the purposes of talent identification and/or developing appropriate training protocols to improve performance.

1.4.2. Scope of the Thesis

The visually demanding, time-stressed interceptive task of cricket batting was chosen to be examined throughout the thesis[4], as it allows for the examination of the key aims of the thesis without necessarily manipulating the constraints of the task beyond what is commonly experienced during competition. Specifically, differences in the visual-motor behaviour of cricket batters can be readily examined as the sport is played across a wide spectrum of skill and age groups, while it is also not uncommon for batters to have to account for (the possibility of) lateral deviations in ball-flight. With the gaze and movement strategies of cricket batters bearing similarities with other interceptive tasks such as baseball batting, soccer goalkeeping and returning a serve in tennis, findings from studies of those tasks can be drawn on to aid in the understanding of the visual-motor strategies that underpin expertise in interception. Increasing scientific interest in visual-motor control, in addition to a growing body of work on the aerodynamic properties of balls in sport, ensures that current knowledge is readily available for the integration of key principals from these disparate scientific fields to explore the development of visual-motor expertise when performing an interceptive action in the presence of ball-swing.

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[4] The idea of studying the sport of cricket as part of my education was very tempting indeed!

In accordance with previous studies that recommend examining skilled performers in their natural environment (e.g., Farrow & Abernethy, 2003; Gibson, 1979), experimentation performed in this thesis aimed to replicate the spatio-temporal demands commonly experienced during competition to maximise ecological validity. This was achieved in three different ways. First, batters were able to maintain the critical coupling between perception and action by physically hitting a ball that was projected towards them (see Mann et al., 2010a). Second, the use of the hybrid ProBatter ball-projection machine allowed batters to couple their actions with, and utilise advance kinematic information from, the bowler's body for a more realistic batting experience that is not attainable when using conventional ball-projection machines. Third, a considerably faster ball-speed was used (i.e., ≈33 $m.s^{-1}$, or 119 $km.h^{-1}$) compared to the ball-speeds used in most previous studies (< 28 $m.s^{-1}$, or 100 $km.h^{-1}$; e.g., Croft et al., 2009; Land & McLeod, 2000; Pinder et al., 2009; Renshaw et al., 2007; Weissensteiner et al., 2011) to more closely replicate the temporal constraints experienced during competition. Collectively, it is believed that the findings from the experimental series of studies presented in this thesis may provide the most accurate representation of the development of visual-motor expertise when intercepting a fast-moving target to-date.

1.4.3. Thesis Structure

This thesis collectively reports the findings of one large-scale experiment that examines both the gaze and kinematic behaviour of performers when intercepting a fast-moving target *in situ*. These findings, organised into four experimental chapters, are written and presented in a manner that would ensure each chapter is suitable for submission in a peer-reviewed scientific journal, in accordance with the recommendations by the University of Queensland School of Human Movement and Nutrition Sciences Postgraduate Review Panel. This is likely to result in a degree of repetition in some sections of the methods across the experimental chapters (i.e., participants, experimental design and procedure), however other sections of the methods provide information specific to each experimental chapter. This, although increases the length of the overall thesis, allows for each experimental chapter to independently report and disseminate the findings.

To systematically examine the development of visual-motor expertise, the first experimental chapter in this thesis (Chapter 2) seeks to investigate only the movement strategies of performers across different skill and age levels when hitting balls that follow a straight and swinging flight-path. This investigation was performed first to establish the link between kinematic behaviour and interceptive performance when facing balls that follow straight and swinging trajectories to provide a foundation from which to then explore their association with gaze of batters. The findings from Chapter 2 help to establish whether skill-based differences in the timing and coordination of movement would emerge early or later in development, whilst also helping to better understand the movement strategies that performers use to account for the *possibility*, *presence*, or *direction* of ball-swing.

The second and third experimental chapters seek to establish a more comprehensive understanding of the visual gaze behaviour used by performers when hitting a block of balls that follow a straight trajectory (Chapter 3) and balls that follow a combination of straight and swinging trajectories (Chapter 4). The results help to identify the eye and head movement strategies that underpin successful interception when hitting straight trajectories, and whether the same strategies promote successful interception when hitting swinging trajectories. Furthermore, the findings help to determine whether the gaze strategies previously reported when hitting swinging balls in virtual environments extend to those observed *in situ*. By examining the visual-motor behaviour of performers in an environment that more closely replicates that experienced in competition, a clearer understanding of the development of visual-motor expertise and the expert advantage in interception can be established.

The final experimental chapter (Chapter 5) draws from the findings of the previous chapters to provide the first examination of the relationship between gaze and kinematics when intercepting a fast-moving target. The concurrent examination of both gaze and kinematics can help determine *if* a close relationship is likely to exist between the two, and if it does, how it might contribute towards skilled performance. It is proposed that the findings can provide a foundation to gain a deeper understanding, and appreciation, of the coordinative fashion in which gaze and kinematics interact with each other to underpin expertise in interception.

And finally, Chapter 6 assesses the experimental results individually, and collectively, to shed new light on the current literature regarding the development of visual-motor expertise when performing an interceptive action in the presence of ball-swing. The theoretical and practical implications of these findings are discussed, along with further considerations that seek to establish a foundation for future research and/or practical applications in developing exciting avenues for the purposes of talent identification and/or training paradigms designed to enhance batting performance.

CHAPTER 2

PERCEPTUAL INFLUENCES OF SWINGING FLIGHT-PATHS SHAPE THE TIMING AND COORDINATION OF DYNAMIC INTERCEPTIVE ACTIONS

Based on the review of the literature, there is conjecture regarding the influence of ball-swing on the visual-motor behaviour of performers during an interceptive action. In other words, there is a need to better understand how performers get to the right place at the right time when hitting targets that follow a swinging flight-path. By establishing the link between the performer's interceptive performance and their kinematics in the presence of ball-swing, this can provide a foundation from which to then explore its association with the batter's gaze.

'When the music changes, so does the dance.'

African proverb

2.1. Abstract

Successful interception relies on the use of perceptual information to accurately guide an efficient movement strategy that allows performers to be placed at the right place at the right time. Although previous studies have shed light on skill-based differences in the timing and coordination of movement when performing an interceptive action, very little is known about the movement strategies that may help performers account for the increased spatio-temporal demands of intercepting a target in the presence of ball-swing. The aim of this study was to examine the movement strategies of performers when intercepting a target in the presence of ball-swing. Movement timing and coordination was examined for 43 cricket batters who systematically differed in their level of batting skill and/or age when hitting a target that followed a straight and swinging flight-path. The results showed that (i) hitting a swinging ball led to significant delays in the timing of all kinematic moments and resulted in poorer interceptive performance when compared to hitting a straight ball, (ii) the possibility of ball-swing altered movement coordination and ultimately when the ball was hit even if the ball didn't swing, and (iii) hitting a ball that swung away was markedly harder to hit than a ball that swung in towards the performer. Differences in the synchronisation of the upper- and lower-body segments (i.e., movement coordination) were found across different skill (but not age) levels, suggesting that skill-appropriate movement strategies to account for the presence of ball-swing are evident by late adolescence and continue into adulthood. The results help establish a comprehensive understanding of the strategies that underpin successful interception in the presence of ball-swing.

2.2. Introduction

Successful interception relies on a performer accurately positioning an end effector (e.g., the hands or a bat) so that it coincides with the arrival position of the target (Lee, 1998). Fast-ball sports present an ideal task environment from which to explore the processes that support successful interception because skilled performers thrive despite the target often moving at excessively-fast speeds. Moreover, opponents often attempt to gain an advantage by manipulating the spatial and temporal constraints of the task. One possible strategy that opponents can use to exploit the boundaries of human capabilities (see Walsh, 2014) is to manipulate the flight-path of the target so that it follows a curved (or *swinging*) trajectory during flight. This for example, can be seen by a baseball pitcher throwing a curveball or a soccer free-kick being bent through the air. Recent studies examining the increased spatial and temporal demands imposed by swinging ball-flights suggest that performers may find it difficult to accurately perceive the future arrival location of the target when it follows a swinging rather than a straight flight-path, thus reducing their interceptive proficiency (Craig et al., 2011; Craig et al., 2006; Craig et al., 2009; Port et al., 1997). As a result, ball-swing represents an ideal model for a highly demanding interceptive task in which movement coordination can be examined to better understand how skilled performers develop expertise in interception (for a review, see Sarpeshkar & Mann, 2011).

Examining the motor actions performed during interceptive tasks (through kinematic analysis) offers an opportunity to better understand the strategies employed by skilled performers to overcome the, at times, complex spatial and temporal constraints. Previous studies have helped to identify a range of kinematic parameters that distinguish skilled from lesser-skilled performers in hitting tasks such as those performed in baseball, table tennis, and cricket. For instance, Weissensteiner et al. (2011) showed that skilled cricket batters were better than lesser-skilled batters in synchronising the timing of the completion of their front-foot movement with the initiation of their bat-downswing. By doing so, it is thought that skilled batters establish a stable foundation with their feet from which they could more effectively perform their bat-downswing (Abernethy, 1981). It is also hypothesised that skilled batters may be more consistent with this synchronisation, using this forward momentum to shift their centre of mass forward, position their head closer to the ball, and effectively transfer the summation of forces into the shot to successfully hit the ball. The isolation of these skill-based differences helps to further our understanding of how expertise can be developed in these fast interceptive actions (also see Abernethy &

Russell, 1984; Bootsma & van Wieringen, 1990; Hubbard & Seng, 1954; Taliep et al., 2007).

Skill-based differences in kinematic behaviour highlight the effective and efficient means by which skilled performers are able to coordinate their movement to be positioned at the right place at the right time. However, until now, these behaviours have generally been observed when intercepting targets that follow less-challenging *straight* flight-paths and it is not clear whether the same strategies promote successful interception when intercepting targets that follow a *swinging* flight-path. Swinging flight-paths arise as a result of pressure differentials around an object in flight that is either spinning (as is the case for a curving soccer ball) or has contrasting surface textures (such as the shiny and rough hemispheres of a cricket ball; for a comprehensive overview, see Mehta, 2009). This imbalance in pressure generates an additional force acting perpendicular to the object's flight-path, causing it to deviate in the direction of lower pressure (i.e., the Magnus effect; see section 1.3.1; Mehta, 1985; 2009; Walker, 1999). Although much is known about how a ball swings, surprisingly little is known about how performers might account for the continuous lateral deviation of the target in flight to facilitate successful interception (also see Casanova et al., 2015; Montagne et al., 1999; Peper et al., 1994). Craig et al. (2011) recently found that recreational soccer goalkeepers attempting to stop balls in a virtual environment were significantly worse when intercepting curving balls compared to balls following straight trajectories (15 vs. 57% of all targets). It was reasoned that the informational variables relied on when intercepting straight-trajectory targets (*viz*. changes in target size and bearing angle) may be less reliable for intercepting curving trajectories (Craig et al., 2009; Port et al., 1997). Moreover, it has been hypothesised that fundamental limitations within the visual system may prevent performers from obtaining accurate perceptual information specifying the target's rate of lateral deviation – and hence its future location – ultimately explaining the poorer performance associated with intercepting targets that follow a swinging flight-path (Craig et al., 2006; 2009).

Ball-swing could influence interceptive performance and movement behaviour in a number of different ways. First, the uncertainty generated by the *possibility* of ball-swing could in and of itself alter behaviour. That is, the possibility of ball-swing could alter not only how an action is performed when the ball swings, but also when it does not swing. Second, the *presence* of ball-swing increases the spatio-temporal precision required to hit a ball and therefore is likely to impact performance and how the action is performed. Third, the *direction* of ball-swing might be more difficult to intercept in one particular direction than another. That is, there is likely to be a difference in performance when the ball swings either in towards, or away from, the position of the performer.

2.2.1. Influence of the *Possibility* of Ball-Swing

The possibility of ball-swing may not only influence the performer’s ability to intercept swinging balls, but the uncertainty it generates could also influence the ability to intercept targets that *do not* swing. It is well established that the context in which an action is performed can influence how that action is accomplished (Todorović, 2010). For example, Tijtgat et al (2010) examined the timing and coordination of movement when catching balls that travelled at different speeds and found that, when the ball-speeds were blocked together, performers scaled the initiation of their hand movements to that individual ball-speed. However, when the ball-speeds were randomised, hand movements were initiated at a common time irrespective of the ball-speed. Similarly, Gray (2002) examined the influence of the prior sequence of pitches on the bat-swing of baseball batters of different skill levels. The results showed that the bat-swing of the lesser-skilled batters differed commensurate with the sequence of preceding pitches, significantly decreasing their interceptive performance. On the other hand, the skilled batters were able to combine the knowledge of the previous sequence of pitches with the perceptual information from ball-flight to adaptively modify their bat-swing parameters and successfully hit the ball. This suggests that the range of possible outcomes can influence the way that the action is performed. In the case of ball-swing, it is reasonable to expect that the *possibility* of ball-swing might alter the kinematics when attempting to hit a ball that follows a straight trajectory, with the effect expected to be more evident in the lesser-skilled when compared to the skilled performers.

2.2.2. Influence of the *Presence* of Ball-Swing

When intercepting targets that follow a swinging flight-path, it may be that the control of movement is less likely to be *predictive* and more likely to be *prospective*. When using predictive control, movements are planned on the basis of a prediction of the future location of the target (Tyldesley & Whiting, 1975); whereas when using prospective control, the movement is continuously modified on the basis of updated perceptual information as the task unfolds (Bootsma & van Wieringen, 1990). For example when examining the influence of swinging flight-paths on the movements of volleyball players, Lenoir et al. (2005) found that the players continuously coupled the position of their body with the changing heading direction of the ball to ensure that their position coincided with the ball at the moment of arrival (also see Casanova et al., 2015). The heading direction (or bearing angle) refers to the angle subtended at the performer by the current position of the ball and the current direction of displacement (Chardenon, Montagne, Laurent, & Bootsma, 2004; Chohan, Verheul, Van Kampen, Wind, & Savelsbergh, 2008). Such a strategy may help performers overcome the difficulty in predicting the future arrival location of a swinging ball, as the performer's final position will coincide with the position of the ball if they simply maintain a constant bearing angle with the ball up to the moment of contact (Montagne et al., 1999; Peper et al., 1994). However, in some interceptive tasks such as cricket and baseball batting, a degree of prediction may be necessary for successful interception. To ensure that the bat hits the ball, batters need to initiate their bat-swing at least 190 ms prior to bat-ball contact to account for the considerable inertia required to swing the bat; and in these tasks, it is very difficult for batters to alter their bat-swing once it is initiated (see McLeod, 1987; Sarpeshkar & Mann, 2011). As a result, a hybrid form of predictive *and* prospective movement control may be necessary when hitting swinging balls (see Diaz et al., 2009; Katsumata & Russell, 2012; Tresilian, 2005).

Currently, there is limited empirical knowledge exploring the kinematic behaviour of performers when intercepting a target in the presence of ball-swing. As a result, much of what we know, or at least what we think we know, about successfully hitting a swinging target in fast-ball sports is based on anecdotal evidence. For example, skilled cricket batters are said to *move late, move quickly* when hitting balls that follow a swinging flight-path, supporting the common coaching adage that encourages batters to delay the initiation of their stride and bat-swing to sample as much ball-flight information as possible before moving. In turn, batters are thought to compensate for this delay by increasing their stride speed and the angular velocity of bat-downswing (see Bradman, 1958; Cricket Australia, 2005). Skilled performers are also thought to counter any lateral deviation in ball-flight after bounce by hitting the ball immediately after it has bounced on the ground. Often coined *getting to the pitch of the ball*, skilled batters are thought to adopt a longer stride length to be positioned closer to the ball as it bounces so that they can make contact with the ball as soon after it bounces as possible (see Weissensteiner et al., 2011; Woolmer et al., 2008). By being closer to ball-bounce, batters are also able to position their head closer to the ball, and use a longer lever arm, to promote an effective summation of forces into the shot whilst also positioning their eyes closer to the ball prior to bat-ball contact (Taliep et al., 2007). As a result, successful interception when hitting a swinging ball may be associated with the batter modifying their bat-swing parameters, hitting the ball earlier and/or positioning their head closer to the ball. If these anecdotal observations are true, then skill-based differences in these kinematic behaviours are expected when batters hit swinging balls.

2.2.3. Influence of the *Direction* of Ball-Swing

The accuracy with which performers can intercept a swinging target may also vary depending on the *direction* of ball-swing. In situations where the performer stands front-on with their opponent directly in front of them (e.g., a soccer goalkeeper attempting to save a penalty), the direction of ball-swing should not influence their ability to intercept the target as the perceptual information specifying the future arrival location of the ball is mirrored (see Craig et al., 2011; 2006; Lenoir et al., 2005). However, in other instances where the performer is positioned asymmetrically relative to their opponent (e.g., a baseball batter standing to one side of the home plate), perceptual information is no longer mirrored and so one direction of ball-swing may be more challenging to intercept than the other. Until now, very little is known about how the direction of ball-swing influences the interceptive performance and the motor actions performed, though some predictions can be made on the basis of anecdotal observations. For example in cricket batting, where the batter is positioned asymmetrically relative to the bowler, it is claimed that a ball that swings *away* from the batter (termed *outswing*) is more difficult to hit than a ball that swings *in towards* them (termed *inswing*). Moreover, batters are thought to account for the out-swinging ball by adopting a shorter stride length but positioning their bat further forward of their body to hit the ball soon after it has bounced (see Woolmer et al., 2008). As a result, it is reasonable to expect that the increased difficulty in intercepting a target that swings away from the batter may lead to poorer performance and significant changes in movement compared to a target that swings in towards the batter.

The aim of this study was to examine the movement strategies used by skilled performers when intercepting a target in the presence of ball-swing. The timing and movement coordination of four groups of cricket batters, who systematically differed in their level of batting skill and/or age, were examined *in situ* when hitting balls that followed either (i) a straight flight-path only or (ii) a random mixture of straight and swinging flight-paths. Three separate analyses were performed. First, skill and age-related differences in interceptive performance and movement strategies were examined. Consistent with previous work, the skilled batters were expected to be more successful in their interceptive accuracy compared to the lesser-skilled batters (Hypothesis 1.1), an advantage underpinned by a closer and more consistent synchronisation of the timing between the completion of their front-foot stride and initiation of bat-downswing (e.g., Weissensteiner et al., 2011; Hypothesis 1.2). Furthermore, consistent with Daum, Huber, and Krist (2007) and Haywood, Greenwald, and Lewis (1981), these skill-based differences in the batter's kinematics and batting performance were also expected to emerge by late adolescence and continue into adulthood (Hypothesis 1.3). Second, kinematic behaviours were examined following the simple knowledge that the ball could swing. The possibility of ball-swing was expected to significantly alter the batter's movement coordination when hitting balls that followed a straight trajectory (Hypothesis 2.1). Specifically, the lesser-skilled batters were expected to be more likely than the skilled batters to adopt a predetermined movement strategy to initiate movement at a similar time following ball-release (e.g., Gray, 2002; Tijtgat et al., 2010; Hypothesis 2.2). Third, the influence of ball-swing on the performance and kinematic behaviour of the batters was examined. It was expected that the increased spatio-temporal demands of swinging flight-paths would result in more novice-like kinematic behaviour and would reduce the interceptive performance of the batters (Hypothesis 3.1). Specifically, a delay in the timing of the initiation of front-foot stride and bat-backswing was expected, which would then be compensated for by faster and shorter movements of the front-foot stride and bat-downswing (Hypothesis 3.2). Further, these changes were expected to be more pronounced for balls that swung away from the batter when compared to balls that swing in (Hypothesis 3.3).

2.3. Methods

2.3.1. Participants

A total of 43 male cricket batters were examined and were categorised into one of four groups that differed according to their level of batting proficiency ('skilled' or 'club') and their age ('adult' or 'youth'). The *adult skilled* group (13 batters, M_{age} = 25.1 years, age range: 19-37) consisted of batters who had represented their state/province at a senior level (four were members of the Australian national squad at the time of testing[5]). The *youth skilled* group (ten batters, M_{age} = 17.7 years, age range: 16-18) consisted of batters who had represented their state/province at an under-19 and/or under-17 level (four were members of the Australian under-19s national squad at the time of testing). The *adult club*

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[5] At the time of testing, two out of the four batters had represented their country in over 75 Test matches and sustained a batting average of 50 runs per innings; which at that time was a feat only achieved by 83 out of 2742 international batters since 1877.

(10 batters, M_{age} = 31.7 years, age range: 26-39) and *youth club* groups (10 batters, M_{age} = 21 years, age range: 18-23) consisted of lesser-skilled recreational players who played competitive club cricket for their local district and had not achieved any higher level representative selection. All batters provided informed consent to a protocol that was approved by the University ethics committee.

2.3.2. Experimental Design

All testing was conducted at an indoor batting facility designed to replicate the dimensions and ball rebound characteristics of a synthetic cricket surface. The facility housed a ProBatter ball-projection machine (PX-2-PB2005-87; ProBatter Sports, Milford, CT), which was used to project balls towards the batters (for more information, see Portus & Farrow, 2011; ProBatter Sports, 2015). The distance of the projection machine from the batter (≈17.68 m) and the height of ball-release from the ground (2.08 m [subtended angle of 6.66 deg]) replicated those dimensions typically experienced during competition. Furthermore, batters were offset slightly to the left of the location of ball-release (≈0.6 m [bearing angle of 1.94°]) to replicate the approach angle that the ball is commonly delivered from during competition[6].

The ball-projection machine was located behind a large screen (2.6 m x 3.5 m) which displayed a life-sized video projection (Hitachi CP-X809 LCD projector, Tokyo, Japan) of a cricket bowler in their approach towards the batter showing the bowler's full run-up, approach to the crease, ball-release, and follow-through. Mann et al. (2013) reported that the ProBatter machine provides three specific advantages when compared to the use of a live bowler or a bowling machine: (i) experimental control that is not available with 'live' bowlers, (ii) the video footage shows advance information of the bowler's kinematics which has been shown to be useful for movement coupling, and (iii) the projection screen prevents batters from noticing any changes in the angle of release of the projection machine and therefore the batter cannot artificially pick-up in advance the likely direction of the ball. The ProBatter machine was programmed to display a series of video recordings of one bowler (recorded live during competition) so that the ball-flight seen for that delivery matched that actually bowled in the video footage. This ensured that any

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[6] The laws of cricket prevent the bowler from delivering the ball from directly in front of the batter due to the presence of the stumps. As a result, the bowler must be position either to the left (termed '*over the wicket*'), or to the right (termed '*around the wicket*'), of the stumps at the point of release. In this experiment, the typical angle created from a bowler delivering the ball from over the wicket was replicated.

kinematic information in the bowler's action matched the actual outcome of ball-flight. At the moment of ball-release, a composite ball that is commonly used during training (and designed to act like a cricket ball; Jugs Inc., Tualatin, Oregon) was projected through a hole in the screen at a velocity of ≈33 $m.s^{-1}$ (119 $km.h^{-1}$). This ball-speed was chosen as it represented a speed commonly faced during competition, but one that was not too fast to be unsafe for the younger batters. Batters used their own cricket equipment (i.e., leg and thigh guards, gloves and cricket bat) and attempted to hit the ball projected towards them. Participants were instructed to bat as they would during competition; that is, to hit the ball in a manner that would enable them to score runs while also minimising the likelihood of being dismissed.

Prior to data collection, three areas on the playing surface were selected (i.e., *lengths*) to represent the different locations of ball-bounce relative to the location of the stumps (*viz*. *full*, *good*, and *short* length trials), with the batter standing ≈1 m in front of the stumps. In the full-length trials (or *deliveries*), the ball bounced 3.5-4.5 m from the stumps, a delivery that would typically require the batter to step forward to hit the ball. In the good-length trials the ball bounced 7.0-8.0 m from the stumps. This ball-length typically causes indecision as to whether the batter should step forward or backward to hit the ball, and so is commonly considered to be the most challenging ball-length from which to hit a ball in cricket (e.g., Woolmer et al., 2008). In the short-length trials, the ball bounced 9.0-9.5 m from the stumps and would typically require the batter to step backward to hit the ball (Figure 2.1; see Pinder et al., 2011a). The arrival location of the ball was also manipulated according to one of two different *lines*, causing the ball to be directed either close to, or away from the batter's body. These variations in line only served to prevent the batter from anticipating the future location of the ball and were of no particular experimental interest.

Participants attempted to hit balls that did, and did not, deviate laterally through the air (from now on referred to as *swing* and *straight* trials respectively). Swing was achieved by imparting sideward spin on the ball (for a similar technique, see Craig et. al 2011; 2006) to result in a ball that either swung in towards (i.e., *inswing*), or away from (i.e., *outswing*) the batter's body.

2.3.3. Data Collection

A high-speed video camera (Casio EX-F1, Tokyo, Japan; 300 Hz) located perpendicular to the batter (≈5 m from the batter in the sagittal plane) recorded footage of the batter's movements for each trial. A laser sensor was placed adjacent to the location of ball-release on the ProBatter machine so that when the ball was released, it triggered the illumination of a LED placed within the field of view of the video camera to signal the moment of ball-release (Figure 2.1). This allowed for the timing of movements to be determined relative to the moment of ball-release (for a similar set-up, see Weissensteiner et al., 2011). A short validation study established that there was a 12 ± 0.2 ms delay from the moment of ball-release to the moment the LED light was visible in the video footage. This time was subsequently accounted for in the movement times of the batters to reflect timing relative to the true moment of ball-release.

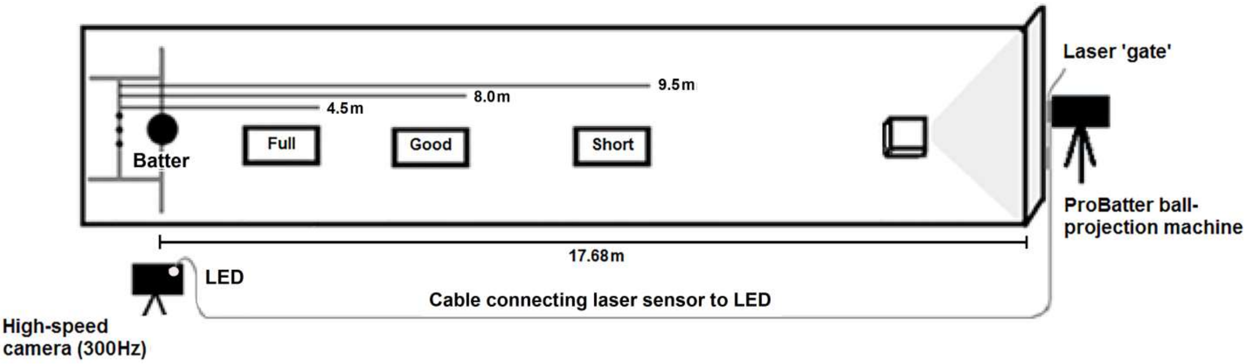

Figure 2.1. Schematic illustration of the experimental set-up. The laser detection device was placed adjacent to the release point on the ProBatter machine (obscured behind the screen), and when the laser was broken, it would trigger the LED to signal ball-release.

2.3.4. Procedure

Prior to the commencement of the experiment proper, batters were allowed a short warm-up (≈10-15 deliveries) to familiarise themselves with the ProBatter machine and the range of trials they were to face in the experiment. During the experiment proper, the participants batted in two separate counterbalanced blocks of trials. In the *blocked-straight* block of trials batters faced 18 deliveries that followed a straight flight-path only and were equally distributed across the three different lengths and two lines. In the *random* block of trials batters faced a mixture of straight (*random-straight*) and swinging deliveries (*random-swing*). Specifically, the random block consisted of 48 trials that were equally distributed to ensure 16 straight trials, 16 outswing trials and 16 inswing trials. In this block, the trials were distributed across two lines and only two lengths (full and good-lengths) because the ProBatter machine was unable to project short-length deliveries while imparting swing on the ball. The order of the trials within the blocks followed a predetermined but randomised sequence that started at a random position for each batter. Each batter took approximately one hour to complete the experiment.

2.3.5. Data Analysis

Manual inspection of the video footage from the high-speed video camera (Dartfish Classroom Plus, Dartfish Video Solutions, Fribourg, Switzerland, 2012) permitted the calculation of a series of key kinematic variables for each trial. For this study, only the front-foot defensive responses to good-length deliveries were analysed (representing 20.2% of all trials; Figure 2.2). A front-foot defensive shot is a common action where the batter moves forward on their front foot and hits the ball with minimal follow-through. Because of the difficulties in comparing the wide range of actions that a cricket batter can perform, the front-foot defensive shot is commonly relied on as an exemplar response to investigate the coordination of movement in batting (e.g., Pinder et al., 2011a; Renshaw et al., 2007; Stretch, Buys, Toit, & Viljoen, 1998; Stuelcken et al., 2005). A total of 442 out of 1200 possible good-length trials were analysed (37% of good-length trials): 333 trials were excluded because the batter did not swing their bat to hit the ball (28% of good-length trials); 335 trials because the batter played a shot other than a front-foot defensive shot (28% of good-length trials); and 90 trials because of technical difficulties with the video camera for three batters (8% of good-length trials).

2.3.6. Dependent Variables

A number of key variables were assessed to examine: (a) batting performance, (b) the timing and sequencing of key moments in the interceptive movement, (c) the duration of key movement phases, and (d) spatial measures of displacement and velocity.

(a). Batting performance: Interceptive performance was assessed in real-time for each trial by the primary investigator recording the *quality of bat-ball contact* (QoC; see Müller & Abernethy, 2008). The QoC provides a simple and validated categorical means of determining whether the batter successfully made contact with the ball. A score of two, one, or zero was given for each trial to represent ‘good’ (ball makes contact with the bat and travels in a direction consistent with the plane of bat motion), ‘poor’ (ball makes contact with the bat and travels in a direction inconsistent with the plane of bat motion) or ‘no contact’ (ball makes no contact with the bat) respectively (also see Müller & Abernethy, 2008). This allowed for the calculation of the *% of trials with ‘good’ bat-ball contact* (for a similar type of analysis, see Müller & Abernethy, 2006). Video footage of the batters was viewed after testing to determine which of the shots could be classed as front-foot defensive shots.

(b). Timing and sequencing of key moments in the movement: Six key moments were recorded relative to the moment of ball-release, *viz*. the moments of (i) *initiation of bat-backswing* (iBS), (ii) *initiation of front-foot stride* (iFFS), (iii) *peak bat height* (pBH), (iv) *completion of front-foot stride* (cFFS), (v) *initiation of bat-downswing* (iDS), and (vi) *bat-ball contact* (BBC; see Figure 2.2 for operational definitions of each key moment; also see Pinder et al., 2011a; 2009; Renshaw et al., 2007; Weissensteiner et al., 2011 for similar definitions). All timing data are reported as the *mean ± standard deviation* in milliseconds.

As a measure of movement coordination, the mean and the standard deviation of the time between two pairs of key events were calculated. First, the mean and standard deviation of the time between the initiation of front-foot stride and initiation of bat-backswing was calculated (*Time iFFS-iBS* and *SD iFFS-iBS*). A positive value indicates that batters moved their front foot first. Second, the time between the completion of the front-foot stride and initiation of bat-downswing was calculated (*Time cFFS-iDS* and *SD cFFS-iDS*). Weissensteiner et al. (2011) has previously shown that *Time cFFS-iDS* is shorter for skilled batters than it is for lesser-skilled batters because skilled batters initiate their bat-downswing immediately following the establishment of a stable base with their feet (also see Abernethy, 1981). The time measurement indicates the average time between the two events, whereas the SD measurement indicates how batters were able to reliably couple one event with the other.

(c). Duration of key movement phases: The duration of four key movement phases was calculated for each trial: (i) the *duration of backswing* (the time between the initiation of bat-backswing and peak bat-height), (ii) the *duration of downswing* (the time between the initiation of bat-downswing and bat-ball contact), (iii) the *duration of front-foot stride* (the time between the initiation and completion of the front-foot stride), and (iv) the delay from the completion of front-foot stride to bat-ball contact (*delay cFFS-BBC*). In addition, the *percentage of backswing relative to downswing* was also examined for each trial to determine the total percentage of bat-swing time spent in the backswing and downswing phases (see also Renshaw et al., 2007; Weissensteiner et al., 2011). This allows for a measure of the relative tempo of bat-swing to provide a representation of the changes in organisation of the two phases of bat-swing.

(d). Spatial measures of displacement and velocity: Distances in the video footage were calibrated using known distances in the horizontal direction (from the base of the stumps to the batting crease) and the vertical direction (from the base to the top of the

stumps). This calibration allowed for the calculation of the mean (and standard deviation) of six variables: (i) *Stride length* was calculated as the total distance covered from the initiation of front-foot stride to the completion of front-foot stride (mm), (ii) *stride velocity* was calculated as the distance of the front-foot stride divided by the duration of the front-foot stride ($m.s^{-1}$), (iii) *angular velocity of the bat-downswing* was determined by dividing the change in bat angle[7] by the time taken for the downswing ($rad.s^{-1}$), (iv) *displacement of peak bat-height* was measured as the highest vertical point from the ground reached by the bat during bat-swing (mm), (v) *location of bat-ball contact relative to the stumps* was the horizontal distance from the stumps to the position that bat-ball contact took place (mm), and (vi) the batter's *head position relative to bat-ball contact* was the horizontal distance from the batter's head to the position that bat-ball contact took place (mm; positive value indicates the batter's head is closer to the stumps at contact; Taliep et al., 2007). The timing and duration for all key phases of movement for a single participant showed high levels of intra- and inter-tester reliability (minimum 92% and 89% agreement respectively, with intra-tester coding performed six weeks apart).

2.3.7. Statistical Analyses

The experimental design allowed three specific analyses to be performed for each of the dependent variables. First, to establish skill and age-based differences in kinematics when facing straight trials, and to see whether they changed against straight trials that were co-presented with swinging trials, each of the dependent variables were analysed using a 2 (Skill: skilled, club) x 2 (Age: adult, youth) x 2 (Randomisation: blocked-straight, random-straight) ANOVA with repeated measures on the last factor. Second, to determine whether there were changes in movement coordination in the presence of ball-swing, a 2 (Skill) x 2 (Age) x 2 (Type of delivery: random-straight, swing) ANOVA with repeated measures on the final factor was performed. Finally, to see whether there were differences in movement coordination for the two different directions of swing, a 2 (Skill) x 2 (Age) x 2 (Direction of swing: outswing, inswing) ANOVA with repeated measures on the final factor was performed. Where the assumption of sphericity was violated, the Greenhouse-Geisser correction was used. Alpha was set at 0.05 for all comparisons. Partial eta squared (η_p^2) and Cohen's *d* values were calculated to indicate the effect size where appropriate.

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[7] Bat angle was determined by slope of the bat created, perpendicular to the ground, at the initiation of bat-downswing and at bat-ball contact.

A multivariate analysis of variance (MANOVA) was also performed encompassing each of the timing, coordination, duration and spatial kinematic measures. Variables found to be significant within the MANOVA were then subjected to a stepwise discriminant function analysis with the *F* value set between 0.05 and 0.15 (Tabachnick & Fidell, 2001). This allowed for the determination of the variable, or combination of variables that best predicted the batter's skill level, age group and each of the three comparisons (i.e., blocked vs random-straight, straight vs. swing, and direction of swing; for a similar analysis, see Weissensteiner et al., 2011). Cross-validation of the models was also performed to assess the accuracy of the model in predicting the same outcome variables for an independent dataset (Field, 2005).

Ball-release | **Initiation of bat-backswing** | **Initiation of front-foot stride** | **Peak bat height** | **Completion of front-foot stride** | **Initiation of bat-downswing** | **Bat-ball contact**

Ball-release	Moment of ball-release from the ProBatter machine (measured by the moment the LED is first illuminated in the view of the high-speed camera).
Initiation of bat-backswing	The first frame where the bat starts to move upward from the ground and continues on towards the peak bat-height (to differentiate the true backswing from any other preparatory movements).
Initiation of front-foot stride	The first frame where the front foot (i.e., the foot furthest from the stumps) is lifted off the ground to move the foot forward towards the ball (excluding any preparatory movements).
Peak bat-height	The highest point reached by the bat (between the moments of ball-release and bat-ball contact).
Completion of front-foot stride	The first frame where any part of the batter’s front foot makes contact with the ground following the initiation of front-foot stride.
Initiation of bat-downswing	The first frame where the bat starts to move downwards following peak-bat height and continues on towards bat-ball contact.
Bat-ball contact	The moment when bat-ball contact occurs. If contact is not achieved, then the moment of bat-ball contact is taken at the moment the bat was closest to the ball.

Figure 2.2. The chronological sequence of the front-foot defensive shot and the operational definitions for each key moment.

2.4. Results

2.4.1. Blocked-Straight vs. Random-Straight Trials

2.4.1.1. Skill and age based differences in kinematics.

In this section any differences in batting performance and movement kinematics are first established between the batters of different skill and age levels. This is done so for batting against all straight trials (blocked and random-straight).

2.4.1.1.1. Skill-related differences.

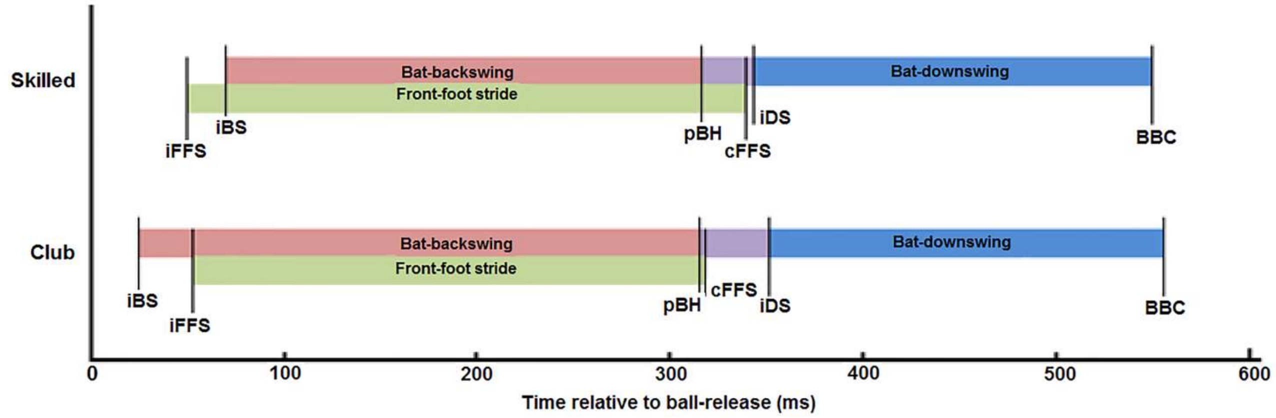

Figure 2.3. Timeline of the key movement phases for the skilled and club level batters in the blocked-straight and random-straight trials. The solid vertical lines represent the initiation/completion of each key phase of movement: iBS, initiation of bat-backswing; *iFFS*, initiation of front-foot stride; *pBH*, peak bat-height; *cFFS*, completion of front-foot stride; *iDS*, initiation of bat-downswing; *BBC*, bat-ball contact.

2.4.1.1.1.1. Batting performance.

The batting performance of the skilled batters was clearly better than it was for the club batters. There were no differences in the percentage of front-foot defensive shots played ($F(1, 36) = 0.13$, $p = .72$; $\eta_p^2 = .00$; skilled $M = 60.1\%$, $SD = 26.1$; club $M = 63.1\%$, $SD = 26.1$); however, the percentage of good bat-ball contacts was much higher for the skilled batters than it was for the club batters ($F(1, 28) = 26.74$, $p < .001$; $\eta_p^2 = .49$; skilled $M = 89.1\%$, $SD = 13.9$; club $M = 63.6\%$, $SD = 13.9$).

2.4.1.1.1.2. Movement kinematics.

There were very few systematic differences between the skilled and club batters in the *timing* of the key movements. Although the timing of the initiation of bat-backswing only approached significance across skill levels (*F*(1, 28) = 3.17, *p* = .086; η_p^2 = .1; skilled *M* = 70 ms, *SD* = 104*; club M* = 25 ms, *SD* = 97), the skilled batters relied on a backswing of shorter duration (*F*(1, 28) = 6.89, *p* = .01; η_p^2 = .2; skilled *M* = 246 ms, *SD* = 47; club *M* = 290 ms, *SD* = 47) resulting in a reduction in the percentage of time spent in backswing relative to downswing when compared to the club batters (*F*(1, 28) = 7.18, *p* = .012; η_p^2 = .20; skilled *M* = 50:50%, *SD* = 10; club *M* = 59:41%, *SD* = 10).

The strength of the coupling between the completion of front-foot stride and the initiation of bat-downswing proved to be a crucial difference between the skilled and club batters. Although there was no difference in the mean time between these two events for the skilled and club batters (time cFFS-iDS, *F*(1, 28) = 1.68, *p* = .205; η_p^2 = .06; skilled *M* = 3 ms, *SD* = 16; club *M* = 32 ms, *SD* = 15), there was a significant difference in the strength of the coupling between the two events (SD cFFS-iDS, *F*(1, 22) = 7.34, *p* = .013; η_p^2 = .25; skilled *M* = 25 ms, *SD* = 14; club *M* = 40 ms, *SD* = 14). A lower mean *time* between two events only shows that those events, on average, occur at a similar time. However, a lower *SD* between the events shows how consistent the link is between the two (the strength of the coupling).

2.4.1.1.1.3. Discriminant function for skill.

A stepwise discriminant function analysis was performed, following a MANOVA, to determine which variable(s) most strongly discriminated between skill levels and also how accurately group membership could be predicted. When facing balls that followed a straight flight-path, a significant discriminant function equation for prediction of skill group membership was derived (*D* = -3.22 + 0.06 * [*% good bat-ball contacts*] - 0.03 * [*SD cFFS-iDS*]; *F* = 15.35; *df* 2, 34; *p* < .001; group centroids: skilled = 1.0; club = -0.85). The predictors in the model were the ability to achieve a greater percentage of good bat-ball contacts and a lower SD in the time between the completion of front-foot stride and the initiation of bat-downswing, with the skilled batters being the most likely to do so. The model accurately predicted group membership for 81.1% of cases with 82.4% of skilled and 80.0% of club batters categorised correctly. Cross validation revealed successful classification of skill levels did not change.

2.4.1.1.2. Age-related differences.

There were no significant age-related differences in the likelihood of playing a front-foot defensive shot (*F*(1, 36) = 0.59, *p* = .45; η_p^2 = .02; adult *M* = 58.4%, *SD* = 26.1; youth

M = 64.7%*, SD* = 26.1) or in the percentage of good bat-ball contacts achieved for those shots (*F*(1, 28) = 1.21, *p* = .28; η_p^2 = .04; adult *M* = 73.7%*, SD* = 13.5; youth *M* = 79.1%*, SD* = 14.3). In addition, there were almost no differences between age groups for any of the kinematic measures, suggesting that differences in performance and movement kinematics are likely to be evident by late adolescence and are sustained into adulthood. The first exception was that the youth batters hit the ball slightly earlier than adult batters did (*F*(1, 28) = 24.34, *p* < .001; η_p^2 = .47; adult *M* = 557 ms*, SD* = 6; youth *M* = 547 ms*, SD* = 6). The second exception was that the standard deviation in the time between the completion of the front-foot stride and the initiation of the bat-downswing of the adult batters was larger than it was for the youth batters (SD cFFS-iDS, *F*(1, 22) = 6.42, *p* = .019; η_p^2 = .23; adult *M* = 39 ms*, SD* = 13*;* youth *M* = 26 ms*, SD* = 14). Although the skill x age interaction was not significant (*p* = .306), inspection of the results shows that this main effect of age is largely (though not exclusively) an effect of the high standard deviation of the adult club batters. The duration of the front-foot stride was found to become shorter with age for the club batters (*p* = .003, *d* = 1.88; primarily because of an earlier *completion* of movement), but longer with age in the skilled batters (*p* = .014, *d* = 1.36; primarily because of an earlier movement *initiation*, skill x age interaction, *F*(1, 28) = 17.61, *p* < .001; η_p^2 = .39). These changes naturally led to the stride velocity decreasing with age in skilled batters (*p* = .337, *d* = 0.52), but increasing with age in club batters (*p* = .038, *d* = 1.1; skill x age interaction, *F*(1, 28) = 5.33, *p* = .029; η_p^2 = .16).

2.4.1.1.2.1. Discriminant function for age.

A significant discriminant function equation was derived for the discrimination of age when facing the straight trials (*D* = -69.97 + 0.12 * [*timing of bat-ball contact*] + 2.58 * [*stride velocity*]; *F* = 14.93; *df* 2, 34; *p* < .001; group centroids: adult = 0.94; youth = -0.89). The predictors in the model were the earlier timing of bat-ball contact and finding no changes in stride velocity across skill level, with the youth batters being most likely to achieve such behaviour. The model accurately predicted group membership for 84.2% of cases with 88.9% of adult and 80.0% of youth batters categorised correctly. Cross-validation revealed that the same level of successful classification of age was maintained.

2.4.1.2. **Effects of randomisation.**

The mean results comparing each of the dependent variables when facing blocked-straight and random-straight trials are presented in Table 2.1. In this section, the main and interaction effects of randomisation are reported to determine whether the *possibility* of ball-swing influences the kinematic behaviour of the batters.

Table 2.1.

Descriptive Statistics across Skill and Age When Facing Blocked-Straight and Random-Straight Trials

		Blocked-Straight		**Random-Straight**	
		Adult	**Youth**	**Adult**	**Youth**
Batting performance (%)					
Good bat-ball contacts	Skilled	100.0 ± 0.0	91.7 ± 15.4	80.1 ± 25.3	83.3 ± 21.5
	Club	59.3 ± 34.5	75.0 ± 21.8	57.3 ± 17.1	61.4 ± 24.6
Front-foot defensive shots	Skilled	41.5 ± 32.5	60.0 ± 37.0	67.7 ± 29.5	71.2 ± 31.5
	Club	55.0 ± 36.3	55.0 ± 35.6	69.6 ± 22.1	72.8 ± 21.4
Timing and sequencing of key moments in the movement (ms)					
Initiation of bat-backswing	Skilled	60 ± 76	86 ± 55	68 ± 62	70 ± 49
	Club	-20 ± 124	45 ± 47	25 ± 75	56 ± 60
Initiation of front-foot stride	Skilled	26 ± 25	72 ± 71	28 ± 18	65 ± 63
	Club	38 ± 78	56 ± 73	61 ± 48	58 ± 63
Peak bat-height	Skilled	307 ± 40	327 ± 34	322 ± 36	317 ± 36
	Club	298 ± 95	325 ± 45	320 ± 42	315 ± 37
Initiation of bat-downswing	Skilled	336 ± 44	350 ± 33	358 ± 33	344 ± 33
	Club	357 ± 41	352 ± 36	350 ± 35	341 ± 33
Completion of front-foot stride	Skilled	351 ± 37	322 ± 52	341 ± 17	331 ± 58
	Club	255 ± 125	364 ± 53	303 ± 79	348 ± 40
Bat-ball contact	Skilled	555 ± 6	545 ± 12	558 ± 6	539 ± 8
	Club	564 ± 11	554 ± 5	551 ± 8	546 ± 4
iFFS-iBS	Skilled	34 ± 82	14 ± 57	40 ± 67	6 ± 51
	Club	-58 ± 133	0 ± 55	-37 ± 82	-8 ± 46
SD iFFS-iBS	Skilled	12 ± 15	23 ± 36	21 ± 14	26 ± 15
	Club	61 ± 34	47 ± 53	37 ± 22	19 ± 9
cFFS-iDS	Skilled	-15 ± 75	0 ± 47	-45 ± 77	-21 ± 57
	Club	-81 ± 143	-33 ± 51	-99 ± 109	-28 ± 55
SD cFFS-iDS	Skilled	25 ± 16	26 ± 34	33 ± 33	16 ± 5
	Club	45 ± 21	32 ± 15	53 ± 30	29 ± 12
Duration of key movement phases (ms)					
Duration of backswing	Skilled	247 ± 38	241 ± 42	253 ± 42	247 ± 39
	Club	318 ± 74	280 ± 45	296 ± 49	259 ± 48
Duration of downswing	Skilled	220 ± 44	195 ± 25	200 ± 34	195 ± 31
	Club	207 ± 40	202 ± 33	201 ± 37	205 ± 31
Duration of front-foot stride	Skilled	325 ± 37	249 ± 47	312 ± 18	267 ± 32
	Club	217 ± 62	307± 62	241 ± 56	290 ± 53
Delay cFFS-BBC	Skilled	204 ± 40	223 ± 48	217 ± 18	207 ± 57
	Club	309 ± 117	191 ± 52	249 ± 82	198 ± 37
Spatial measures of displacement and velocity					
Percentage of time spent in bat-downswing (%)	Skilled	50.4 ± 7.9	51.7 ± 8.3	48.2 ± 8.8	49.2 ± 7.6
	Club	33.3 ± 19.8	44.5 ± 7.9	41.0 ± 9.4	46.9 ± 7.7
Peak bat-height (mm)	Skilled	1681 ± 209	1487 ± 103	1537 ± 242	1482 ± 110
	Club	1463 ± 199	1526 ± 177	1421 ± 211	1463 ± 180
Stride length (mm)	Skilled	350 ± 76	301 ± 116	302 ± 37	306 ± 82
	Club	247 ± 77	274 ± 117	257 ± 74	238 ± 125
Angular velocity of bat-swing (rad/sec^{-1})	Skilled	9.8 ± 0.8	10.7 ± 1.1	9.7 ± 0.9	11.2 ± 1.4
	Club	9.5 ± 1.9	10.1 ± 1.5	9.3 ± 1.8	9.6 ± 0.9
Stride velocity (m/s^{-1})	Skilled	1.1 ± 0.2	1.1 ± 0.3	0.9 ± 0.1	1.1 ± 0.3
	Club	0.8 ± 0.4	0.8 ± 0.3	0.8 ± 0.3	0.8 ± 0.3
Location of bat-ball contact relative to the stumps (mm)	Skilled	1573 ± 251	1644 ± 380	1522 ± 274	1712 ± 338
	Club	1495 ± 225	1464 ± 253	1595 ± 280	1534 ± 206
Head position relative to bat-ball contact (mm)	Skilled	97 ± 65	115 ± 71	29 ± 67	131 ± 67
	Club	117 ± 92	80 ± 114	28 ± 133	105 ± 86

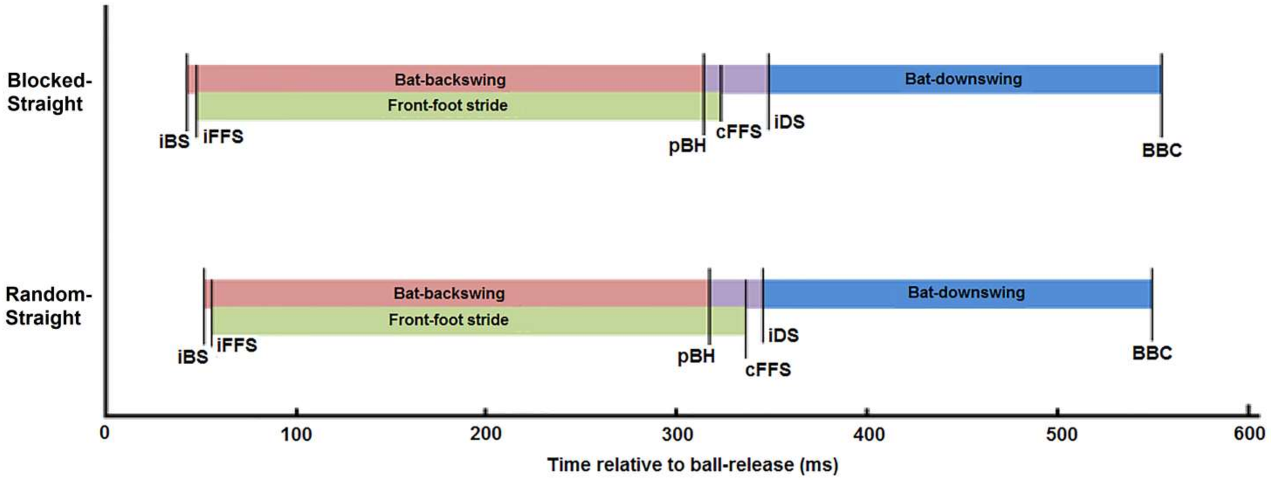

Figure 2.4. Timeline of the mean timing and duration of key phases of movement for Blocked-Straight and Random-Straight trials across skill and age. The solid vertical lines represent the initiation/completion of each key phase of movement: iBS, initiation of bat-backswing; *iFFS*, initiation of front-foot stride; *pBH*, peak bat-height; *cFFS*, completion of front-foot stride; *iDS*, initiation of bat-downswing; *BBC*, bat-ball contact.

2.4.1.2.1. Batting performance.

The possibility of ball-swing led all batters to play significantly more front-foot defensive shots compared to when the straight trials were presented in a blocked fashion (*F*(1, 36) = 10.25, *p* = .003; η_p^2 = .22; random-straight *M* = 70.3%*, SD* = 26.5; blocked-straight *M* = 52.9%*, SD* = 35.4). However, the effect of randomisation did not significantly influence the success of the front-foot defensive shots played (% of good bat-ball contacts *F*(1, 28) = 2.76, *p* = .108; η_p^2 = .09; random-straight *M* = 71.2%*, SD* = 21.8; blocked-straight *M = 81.5*%*, SD* = 22.9).

2.4.1.2.2. Movement kinematics.

The randomisation of the trials resulted in very few differences in the timing and duration of the key movement phases (Figure 2.4); however, it did result in clear differences in the spatial kinematics and ultimately when the ball was hit. As expected, the increased uncertainty when facing the random-straight trials led batters to alter their bat-swing. Specifically when facing the random-straight trials, batters lowered their peak bat-height (*F*(1, 28) = 5.25, *p* = .03; η_p^2 = .16; random-straight *M* = 1500 mm*, SD* = 205; blocked-straight *M* = 1539 mm*, SD* = 177), presumably to allow for a later initiation of bat-downswing if the ball were to swing. Contrary to expectations, batters when facing the random-straight trials used a slower stride velocity (*F*(1, 28) = 4.54, *p* = .04; η_p^2 = .14; random-straight *M* = 1.0 m.s^{-1}*, SD* = 0.3; blocked-straight *M* = 1.1 m.s^{-1}*, SD* = 0.3), primarily due to a delay in the completion of front-foot stride.

Batters were also found to hit the ball further forward from the stumps when facing the random-straight trials (*F*(1, 28) = 5.05, *p* = .033; η_p^2 = .15; random-straight *M* = 1591 mm*, SD* = 280; blocked-straight *M* = 1544 mm*, SD* = 284), and moved their head further forward to ensure it was closer to bat-ball contact (*F*(1, 28) = 4.21, *p* = .05; η_p^2 = .13; random-straight *M* = 73 mm*, SD* = 100; blocked-straight *M* = 102 mm*, SD* = 89; see Figure 2.5; an age x randomisation interaction [*F*(1, 28) = 12.25, *p* = .002; η_p^2 = .3] shows that this effect was largely because of changes in the movement of the adult batters). These changes meant that in the random-straight trials the batters decreased the delay from the completion of front-foot stride to the moment of bat-ball contact (*F*(1, 28) = 4.79, *p* = .037; η_p^2 = .15; random-straight *M* = 214 ms*, SD* = 61; blocked-straight *M* = 232 ms*, SD* = 75; Figure 2.4). Collectively, these results show that the simple knowledge that the ball could swing significantly altered the batter’s coordination of movement when hitting straight balls (also see Tijtgat et al., 2010), encouraging them to move further forward and hit the ball sooner after it bounced (Figure 2.5).

Figure 2.5. Exemplar video stills highlighting the batter’s movement coordination when facing blocked-straight trials (left; notice the batter hitting the ball later whilst positioning their head closer to the stumps); and random-straight trials (right; notice the batter hitting the ball earlier by making contact further away from the stumps whilst positioning their head closer to bat-ball contact).

2.4.1.2.3. Effects of randomisation mediated by skill and/or age.

Some of the effects of randomisation were mediated by the skill level and/or the age of the batters, though most were attributable to changes in the responses of only the adult club batters. In general, the findings suggest that the effects of randomisation tended to have a generalizable effect on most of the batters irrespective of their skill or age. When compared to the other three groups, the adult club batters in the blocked-straight trials used a front-foot stride of shorter duration so that they completed their front-foot movement earlier and made later bat-ball contact, but these group-based differences dissipated when facing the random-straight trials (skill x age x randomisation interactions for duration of front-foot stride, $F(1, 28) = 5.09$, $p = .032$; $\eta_p^2 = .15$; and for the timing of cFFS, $F(1, 28) = 5.41$, $p = .027$; $\eta_p^2 = .16$; skill x randomisation interaction for timing of BBC, $F(1, 28) = 4.32$, $p = .047$; $\eta_p^2 = .13$)[8]. This meant that against the random-straight trials, the adult club batters, but not the other groups of batters, decreased both their delay from the completion of the front-foot stride and the initiation of bat-downswing, and from the completion of front-foot stride and the moment of bat-ball contact (skill x age x randomisation interactions for time cFFS-iDS[9], $F(1, 28) = 7.43$, $p = .011$; $\eta_p^2 = .21$; and for delay cFFS-BBC, $F(1, 28) = 7.68$, $p = .01$; $\eta_p^2 = .22$). The propensity of the adult club batters to complete their front-foot stride very early in the blocked-straight but not random-straight trials is consistent with the idea that the responses against the blocked-straight trials were a result of a ‘pre-programmed’ movement rather than one that was altered ‘online’ based on the ball’s flight-path (Thomlinson, 2009). With the uncertainty of the ball’s flight-path when facing the random-straight trials, the adult club batters may have relied on a more ‘online’ control of movement when moving into position to play their shot (Bootsma & van Wieringen, 1990; Lee et al., 1983).

The one interaction effect that was not solely attributable to the adult club group was for the coupling between the initiation of the front-foot stride and the initiation of the bat-backswing (Figure 2.6). The skilled batters did not change the coupling between these two moments when facing the random-straight trials. However for the club batters, the

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[8] A significant main effect was also observed for the timing of bat-ball contact across skill ($F(1, 28) = 6.37$, $p = .018$; $\eta_p^2 = .19$; skilled $M = 549$ ms, $SD = 6$; club $M = 555$ ms, $SD = 6$), and the type of delivery ($F(1, 28) = 8.28$, $p = .008$; $\eta_p^2 = .23$; random-straight $M = 549$ ms, $SD = 7$; blocked-straight $M = 554$ ms, $SD = 9$). As this effect was overshadowed by a higher-order interaction, this, and other subsequent main effects that are superseded by an interaction will not be reported.

[9] This superseded the skill x age interaction observed for cFFS-iDS, ($F(1, 28) = 6.39$, $p = .017$; $\eta_p^2 = .19$).

coupling *improved* when facing the random-straight trials be at a similar level to that of the skilled batters (skill x randomisation interaction for SD iFFS-iBS, *F*(1, 22) = 4.44, *p* = .047; η_p^2 = .17.

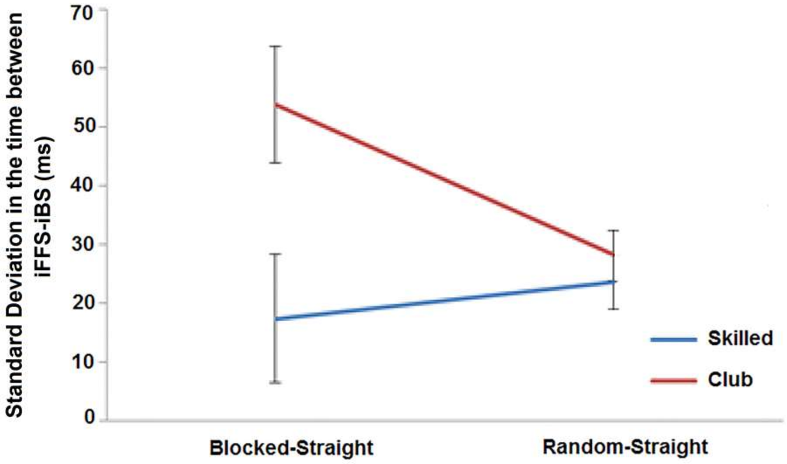

Figure 2.6. Mean standard deviation differences for iFFS-iBS as function of the batter's skill across blocked-straight and random-straight trials. Data are displayed with standard error bars.

2.4.1.2.4. Discriminant function for randomisation.

A significant discriminant function equation was derived that could discriminate between blocked-straight and random-straight trials (*D* = 0.97 * [*timing of bat-ball contact*] + 0.74 * [*head position relative to bat-ball contact*]; *F* = 7.48; *df* 2, 65; *p* = .001; group centroids: blocked-straight = 0.53; random-straight = -0.42). The predictors in the model for the random-straight trails were the ability of the batters to hit the ball earlier and position the head closer to the ball. The model accurately predicted group membership for 72.1% of cases with 70% of blocked-straight and 73.7% of random-straight trials categorised correctly. Cross-validation revealed the same level of successful classification of randomisation was maintained.

2.4.2. Straight vs. Swing

The mean results comparing each of the dependent variables when facing random-straight and random-swing trials are presented in Table 2.2. In this section, the main and interaction effects of swing are presented to determine whether ball-swing influences the batter's kinematic behaviour compared to when facing straight deliveries.

Table 2.2.

Descriptive Statistics across Skill and Age When Facing Random-Straight and Random-Swing Trials

		Random-Straight		**Random-Swing**	
		Adult	**Youth**	**Adult**	**Youth**
Batting performance (%)					
Good bat-ball contacts	Skilled	80.1 ± 25.3	83.3 ± 21.5	63.8 ± 11.0	42.5 ± 31.4
	Club	57.3 ± 17.1	61.4 ± 24.6	47.8 ± 31.0	41.2 ± 27.1
Front-foot defensive shots	Skilled	67.7 ± 29.5	71.2 ± 31.5	70.7 ± 19.2	67.6 ± 17.2
	Club	69.6 ± 22.1	72.8 ± 21.4	65.4 ± 20.8	59.0 ± 22.6
Timing and sequencing of key moments in the movement (ms)					
Initiation of bat-backswing	Skilled	68 ± 62	70 ± 49	75 ± 54	99 ± 51
	Club	25 ± 75	56 ± 60	48 ± 96	75 ± 33
Initiation of front-foot stride	Skilled	28 ± 18	65 ± 63	27 ± 27	92 ± 57
	Club	61 ± 48	58 ± 63	92 ± 56	91 ± 51
Peak bat-height	Skilled	322 ± 36	317 ± 35	320 ± 39	334 ± 33
	Club	320 ± 42	314 ± 37	325 ± 46	327 ± 28
Initiation of bat-downswing	Skilled	358 ± 33	344 ± 33	355 ± 35	361 ± 29
	Club	350 ± 35	341 ± 33	362 ± 23	356 ± 24
Completion of front-foot stride	Skilled	341 ± 17	331 ± 58	334 ± 33	342 ± 43
	Club	303 ± 79	348 ± 40	328 ± 69	374 ± 46
Bat-ball contact	Skilled	558 ± 6	539 ± 8	575 ± 27	543 ± 11
	Club	551 ± 8	546 ± 4	565 ± 13	553 ± 14
iFFS-iBS	Skilled	40 ± 67	6 ± 51	49 ± 49	7 ± 50
	Club	-37 ± 82	-8 ± 46	-44 ± 87	-23 ± 33
SD iFFS-iBS	Skilled	20 ± 13	23 ± 13	25 ± 12	17 ± 10
	Club	42 ± 34	25 ± 14	41 ± 24	34 ± 25
cFFS-iDS	Skilled	-45 ± 77	-21 ± 57	-24 ± 90	-6 ± 48
	Club	-99 ± 109	-28 ± 55	-116 ± 66	-46 ± 55
SD cFFS-iDS	Skilled	36 ± 31	18 ± 6	62 ± 37	32 ± 20
	Club	58 ± 40	31 ± 13	70 ± 47	46 ± 45
Duration of key movement phases (ms)					
Duration of backswing	Skilled	253 ± 42	247 ± 39	244 ± 27	235 ± 39
	Club	296 ± 49	259 ± 48	277 ± 57	252 ± 31
Duration of downswing	Skilled	200 ± 34	195 ± 31	220 ± 48	182 ± 20
	Club	201 ± 37	205 ± 31	203 ± 27	197 ± 27
Duration of front-foot stride	Skilled	312 ± 18	267 ± 32	307 ± 23	250 ± 35
	Club	241 ± 56	290 ± 53	235 ± 63	283 ± 39
Delay cFFS-BBC	Skilled	217 ± 18	207 ± 57	241 ± 40	200 ± 37
	Club	249 ± 82	198 ± 37	237 ± 80	180 ± 42
Spatial measures of displacement and velocity					
Percentage of time spent in bat-downswing (%)	Skilled	48.2 ± 8.8	49.2 ± 7.6	51.1 ± 4.8	51.5 ± 8.1
	Club	41.0 ± 9.4	46.9 ± 7.7	44.5 ± 13.7	49.0 ± 5.9
Peak bat-height (mm)	Skilled	1537 ± 242	1482 ± 110	1529 ± 260	1449 ± 162
	Club	1421 ± 211	1463 ± 180	1391 ± 223	1470 ± 197
Stride length (mm)	Skilled	302 ± 37	306 ± 82	308 ± 128	276 ± 100
	Club	257 ± 74	238 ± 125	247 ± 113	210 ± 93
Angular velocity of bat-swing (rad/sec^{-1})	Skilled	9.7 ± 0.9	11.2 ± 1.4	10.2 ± 1.4	11.8 ± 1.7
	Club	9.3 ± 1.8	9.6 ± 0.9	10.0 ± 1.4	10.8 ± 1.2
Stride velocity (m/s^{-1})	Skilled	0.9 ± 0.1	1.1 ± 0.3	0.9 ± 0.4	1.0 ± 0.4
	Club	0.8 ± 0.3	0.8 ± 0.3	0.7 ± 0.3	0.7 ± 0.3
Location of bat-ball contact relative to the stumps (mm)	Skilled	1522 ± 274	1712 ± 338	1607 ± 276	1794 ± 440
	Club	1595 ± 280	1534 ± 206	1645 ± 323	1551 ± 204
Head position relative to bat-ball contact (mm)	Skilled	37 ± 61	109 ± 96	129 ± 64	127 ± 106
	Club	34 ± 127	82 ± 77	123 ± 118	89 ± 120

2.4.2.1. Effects of Swing.

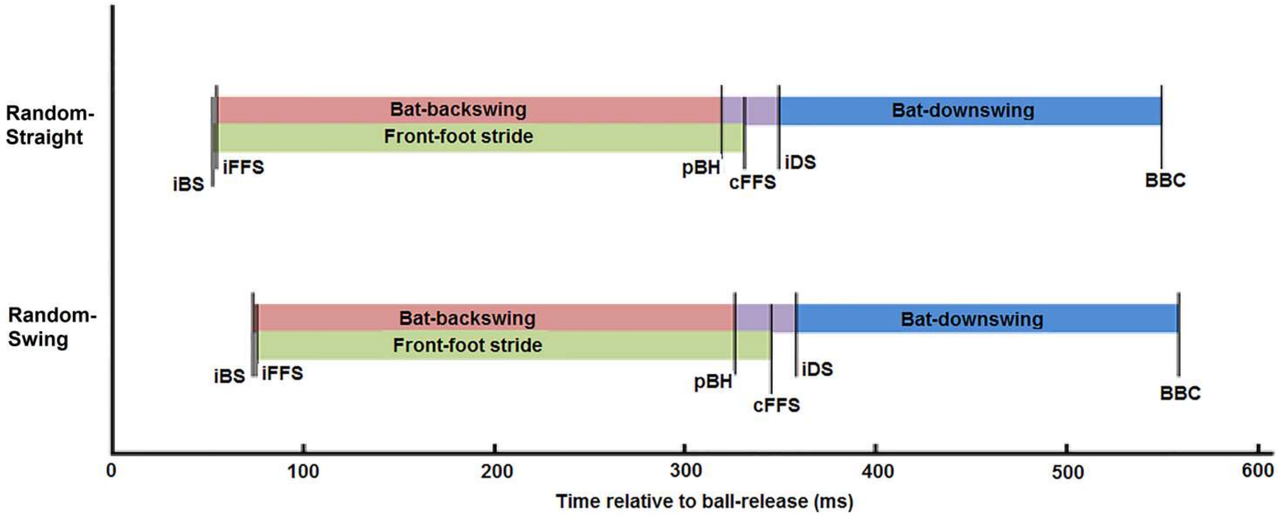

Figure 2.7. Timeline of the mean timing and duration of key phases of movement for Random-Straight and Random-Swing trials across skill and age. The solid vertical lines represent the initiation/completion of each key phase of movement: iBS, initiation of bat-backswing; *iFFS*, initiation of front-foot stride; *pBH*, peak bat-height; *cFFS*, completion of front-foot stride; *iDS*, initiation of bat-downswing; *BBC*, bat-ball contact.

2.4.2.1.1. Batting performance.

There was no difference in the percentage of front-foot defensive shots played for straight and swinging trials ($F(1, 36) = 1.55$, $p = .22$; $\eta_p^2 = .04$; random-straight $M = 70.3\%$, $SD = 26.5$; random-swing $M = 65.7\%$, $SD = 20.0$). However, swinging trials significantly decreased batting performance irrespective of the skill and/or age of the batter (% of good quality bat-ball contacts, $F(1, 34) = 22.67$, $p < .001$; $\eta_p^2 = .4$; random-straight $M = 70.5\%$, $SD = 22.3$; random-swing $M = 48.8\%$, $SD = 27.2$). This is consistent with previous studies that show performance decreases when intercepting targets that follow swinging flight-paths (e.g., Craig et al., 2011; 2006).

2.4.2.1.2. Movement kinematics.

Front-foot defensive shots played against swinging trials were different to those played against the random-straight trials. Figure 2.7 shows that there were significant delays in the timing of the initiation of bat-backswing ($F(1, 30) = 8.34$, $p = .007$; $\eta_p^2 = .22$), initiation of front-foot stride ($F(1, 30) = 23.71$, $p < .001$; $\eta_p^2 = .44$), completion of front-foot stride ($F(1, 30) = 6.45$, $p = .017$; $\eta_p^2 = .18$) and initiation of bat-downswing ($F(1, 30) = 9.4$, $p = .005$; $\eta_p^2 = .24$), leading to a delay in bat-ball contact ($F(1, 30) = 15.12$, $p = .001$;

η_p^2 = .34). The significant delays in the very early moments of the hitting action: the initiation of bat-backswing (random-straight *M* = 55 ms, *SD* = 63; random-swing *M* = 74 ms, *SD* = 67) and front-foot movement (random-straight *M* = 53 ms, *SD* = 53; random-swing *M* = 75 ms, *SD* = 52) show that the batters differentiated the straight and swinging deliveries at a very early point in the ball-flight (≈50 ms), highlighting the potential use of pre-release kinematic information to help guide the kinematic responses (as the movement time from ball-release is comfortably below that of human reaction time).

The interval between the completion of the front-foot stride and initiation of bat-downswing (a key marker of skill in batting; see Weissensteiner et al., 2011), was found to become more variable in the presence of ball-swing, irrespective of the skill and age of the batters (SD cFFS-iDS, *F*(1, 32) = 4.33, *p* = .046; η_p^2 = .12; random-straight *M* = 36 ms, *SD* = 27; random-swing *M* = 53 ms, *SD* = 40). This suggests that there was a breakdown in movement coupling when hitting a swinging ball.

Batters also made a number of changes to the way they swung their bat to intercept the swinging ball. The time spent in backswing when facing the swinging ball was marginally lower (*F*(1, 30) = 3.71, *p* = .064; η_p^2 = .11; random-straight *M* = 264 ms, *SD* = 46; random-swing *M* = 252 ms, *SD* = 43), leading to a reduction in the percentage of total bat-swing time spent in backswing when facing swinging trials (*F*(1, 30) = 5.41, *p* = .027; η_p^2 = .15; random-straight *M* = 54:46%, *SD* = 9; random-swing *M* = 51:49%, *SD* = 9). In addition, batters increased the angular velocity of their downswing when attempting to hit the swinging ball (*F*(1, 30) = 19.7, *p* < .001; η_p^2 = .4; random-straight *M* = 10.0 rad.s^{-1}, *SD* = 1.5; random-swing *M* = 10.7 rad.s^{-1}, *SD* = 1.6); but also increased the standard deviation (*F*(1, 32) = 9.35, *p* = .004; η_p^2 = .23; random-straight *M* = 1.0 rad.s^{-1}, *SD* = 0.6; random-swing *M* = 1.4 rad.s^{-1}, *SD* = 0.7). This finding is consistent with the idea that movements against the swinging ball were delayed as late as was permissible and compensated for by a faster downswing of the bat.

2.4.2.1.3. Effects of swing mediated by skill and/or age.

Some of the changes in behaviour when facing the swinging ball were mediated by the skill and/or age of the batters.

Skill x delivery interactions: The front-foot movements of the club batters were more influenced by the presence of ball-swing than were the movements of the skilled batters. The club batters were marginally more likely to delay the initiation (*F*(1, 30) = 4.13, *p* =

.051; $\eta_p^2 = .12$) and completion of their front-foot movement ($F(1, 30) = 4.59$, $p = .04$; $\eta_p^2 = .13$) when the ball swung.

Age x delivery interactions: The swinging ball influenced the bat-swing of the youth batters to a greater extent than it did the adult batters. When facing the swinging ball, the youth batters were more likely to delay the moment of their peak bat-height ($F(1, 30) = 5.07$, $p = .032$; $\eta_p^2 = .14$)[10] and were also more likely to decrease the duration of their bat-downswing ($F(1, 30) = 10.06$, $p = .003$; $\eta_p^2 = .25$), suggesting that they delayed their bat-swing in an attempt to gain as much ball flight information as possible before initiating the movement. The adult, but not youth batters on the other hand, altered *where* they made contact with the ball relative to the position of their head when the ball was swinging. When compared to the straight trials, the adult batters hit the ball further in front of their head when the ball was swinging ($F(1, 30) = 6.83$, $p = .014$; $\eta_p^2 = .19$). This may reflect a functional adaptation on the part of the adult batters to hit the ball as early as possible to minimise the amount of lateral deviation after ball-bounce.

2.4.2.1.4. Discriminant function for swinging trials.

A significant discriminant function equation was derived to differentiate straight and swinging deliveries (D = 0.45 * [*timing of the initiation of front-foot stride*] + 0.91 * [*timing of bat-ball contact*] + 0.48 * [*angular velocity of bat-downswing*] + 0.75 * [*head position relative to bat-ball contact*]; $F = 10.15$; *df* 4, 67; $p < .001$; group centroids: random-straight = -0.73; random-swing = 0.81). The predictors in the model for the swinging deliveries highlight the delayed timing in the initiation of front-foot stride and bat-ball contact, along with the compensatory increase in the velocity of bat-downswing and the closer head position relative to bat-ball contact. The model accurately predicted group membership for 77.8% of cases with 73.7% of random-straight and 82.4% of random-swing trials categorised correctly. Cross-validation revealed that successful classification of variables discriminating straight and swinging trails was maintained (73.6%), with 73.7% of random-straight and 73.5% of random-swing trials re-categorised correctly.

2.4.3. Outswing vs. Inswing

The mean results comparing each of the dependent variables when facing outswing and inswing trials are presented in Table 2.3. Here the main and interaction effects

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[10] A significant main effect for the timing of peak bat height was also observed for the type of delivery ($F(1, 30) = 7.59$, $p = .01$; $\eta_p^2 = .2$; random-straight M = 318 ms, SD = 36; random-swing M = 327, SD = 36).

associated with the *direction* of ball-swing are presented to determine how this influences the batting performance and kinematic behaviour of the batters.

For the sake of brevity, the main effects of skill and age are not presented in this section as they largely replicate those seen in the previous section.

Table 2.3.

Descriptive Statistics across Skill and Age When Facing Out-swinging and In-swinging Trials

		Outswing		**Inswing**	
		Adult	**Youth**	**Adult**	**Youth**
Batting performance (%)					
Good bat-ball contacts	Skilled	51.9 ± 25.6	39.2 ± 40.5	79.8 ± 18.8	45.8 ± 37.1
	Club	27.3 ± 25.4	33.5 ± 37.0	68.3 ± 43.4	77.1 ± 37.3
Front-foot defensive shots	Skilled	75.4 ± 20.6	77.0 ± 29.7	69.1 ± 39.0	62.5 ± 18.3
	Club	87.5 ± 17.5	65.2 ± 30.9	48.5 ± 27.8	48.9 ± 40.9
Timing and sequencing of key moments in the movement (ms)					
Initiation of bat-backswing	Skilled	96 ± 71	110 ± 58	70 ± 47	88 ± 55
	Club	57 ± 110	86 ± 55	39 ± 92	64 ± 30
Initiation of front-foot stride	Skilled	31 ± 46	103 ± 71	20 ± 34	81 ± 55
	Club	101 ± 59	105 ± 60	83 ± 68	77 ± 49
Peak bat-height	Skilled	317 ± 49	326 ± 37	338 ± 37	342 ± 33
	Club	300 ± 69	319 ± 29	351 ± 35	335 ± 32
Initiation of bat-downswing	Skilled	348 ± 46	351 ± 29	372 ± 28	371 ± 31
	Club	341 ± 34	346 ± 25	383 ± 31	366 ± 26
Completion of front-foot stride	Skilled	311 ± 60	328 ± 46	363 ± 29	357 ± 45
	Club	304 ± 83	344 ± 36	352 ± 65	403 ± 66
Bat-ball contact	Skilled	569 ± 11	541 ± 15	580 ± 49	545 ± 13
	Club	566 ± 11	557 ± 19	563 ± 19	550 ± 10
iFFS-iBS	Skilled	68 ± 48	7 ± 51	51 ± 56	7 ± 51
	Club	-44 ± 90	-20 ± 43	-43 ± 86	-13 ± 57
SD iFFS-iBS	Skilled	26 ± 13	22 ± 10	22 ± 15	14 ± 10
	Club	30 ± 17	24 ± 21	33 ± 31	25 ± 20
cFFS-iDS	Skilled	38 ± 38	23 ± 36	8 ± 35	14 ± 34
	Club	49 ± 83	2 ± 28	32 ± 79	-37 ± 53
SD cFFS-iDS	Skilled	37 ± 20	27 ± 19	57 ± 52	36 ± 35
	Club	77 ± 73	48 ± 32	84 ± 64	95 ± 66
Duration of key movement phases (ms)					
Duration of backswing	Skilled	221 ± 41	216 ± 40	268 ± 26	254 ± 47
	Club	243 ± 57	234 ± 42	312 ± 66	271 ± 39
Duration of downswing	Skilled	221 ± 47	190 ± 21	208 ± 64	174 ± 23
	Club	225 ± 37	211 ± 28	180 ± 28	184 ± 28
Duration of front-foot stride	Skilled	279 ± 35	225 ± 45	343 ± 43	276 ± 29
	Club	203 ± 50	239 ± 44	269 ± 85	326 ± 50
Delay cFFS-BBC	Skilled	259 ± 56	213 ± 40	217 ± 64	188 ± 40
	Club	263 ± 90	213 ± 32	211 ± 79	147 ± 63
Spatial measures of displacement and velocity					
Percentage of time spent in bat-downswing (%)	Skilled	55.6 ± 8.2	55.3 ± 8.9	47.5 ± 6.1	47.6 ± 9.8
	Club	50.0 ± 15.3	53.0 ± 8.6	39.0 ± 13.7	45.0 ± 6.5
Peak bat-height (mm)	Skilled	1461 ± 296	1370 ± 190	1558 ± 200	1529 ± 159
	Club	1301 ± 277	1433 ± 2126	1480 ± 182	1507 ± 190
Stride length (mm)	Skilled	255 ± 125	220 ± 99	387 ± 162	332 ± 108
	Club	200 ± 97	156 ± 629	293 ± 188	265 ± 131
Angular velocity of bat-swing (rad/sec^{-1})	Skilled	9.6 ± 1.7	11.2 ± 2.0	11.3 ± 1.6	12.5 ± 1.7
	Club	8.6 ± 2.2	9.3 ± 1.6	11.3 ± 1.3	12.2 ± 0.9
Stride velocity (m/s^{-1})	Skilled	0.9 ± 0.4	1.0 ± 0.4	1.1 ± 0.4	1.2 ± 0.4
	Club	0.9 ± 0.3	0.7 ± 0.3	1.0 ± 0.5	0.8 ± 0.4
Location of bat-ball contact relative to the stumps (mm)	Skilled	1628 ± 238	1831 ± 430	1623 ± 300	1757 ± 463
	Club	1689 ± 306	1585 ± 213	1602 ± 355	1567 ± 237
Head position relative to bat-ball contact (mm)	Skilled	133 ± 79	167 ± 92	132 ± 65	87 ± 151
	Club	155 ± 109	104 ± 108	92 ± 153	74 ± 150

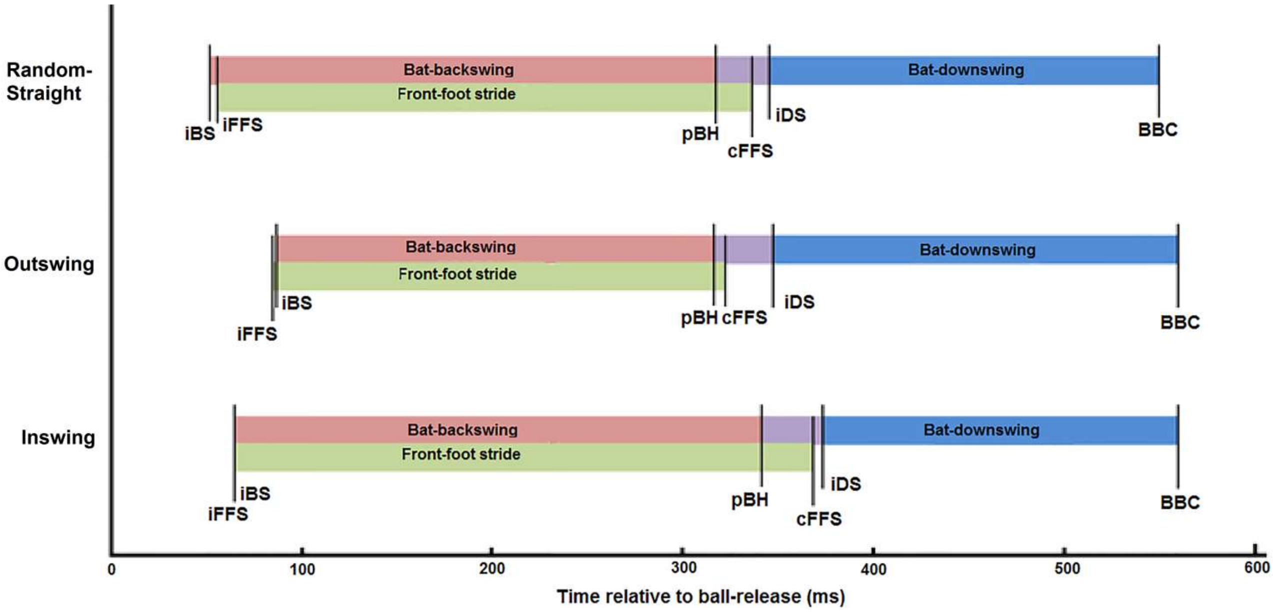

Figure 2.8. Timeline of the mean timing and duration of key phases of movement between Outswing and Inswing trials when compared to the random-straight trials (as a reference). The solid vertical lines represent the initiation/completion of each key phase of movement: iBS, initiation of bat-backswing; *iFFS*, initiation of front-foot stride; *pBH*, peak bat-height; *cFFS*, completion of front-foot stride; *iDS*, initiation of bat-downswing; *BBC*, bat-ball contact.

2.4.3.1.1. Batting performance.

The direction of ball-swing influenced both the likelihood of participants playing a front-foot defensive shot and the success of that shot. Batters were more likely to play a front-foot defensive shot against the outswing trials ($F(1, 35) = 7.71$, $p = .009$; $\eta_p^2 = .18$; outswing $M = 76.3\%$, $SD = 25.5$; inswing $M = 57.2\%$, $SD = 32.6$), but were also clearly less successful in intercepting those trials (% of good bat-ball contacts, $F(1, 31) = 14.30$, $p = .001$; $\eta_p^2 = .32$; outswing $M = 38.0\%$, $SD = 33.2$; inswing $M = 67.8$, $SD = 34.8$). This represents a remarkably strong effect on performance: the likelihood of a successful outcome is almost halved when hitting a ball that swings *away* from the body.

2.4.3.1.2. Movement kinematics.

There was no difference in the timing of bat-ball contact when attempting to hit the out- and in-swinging trials ($F(1, 31) = .05$, $p = .83$; $\eta_p^2 = .00$). However, as Figure 2.8 illustrates, the direction of ball-swing altered almost every other kinematic measure of timing and movement coordination. Further, these effects tended to occur irrespective of the batter’s skill and/or age (i.e., very few interactions with skill or age). When facing the out-swinging trials, in summary, batters relied on a more brief front-foot stride and a lower (and quicker) backswing, but a much slower bat-downswing, and the head was placed further behind the ball at the moment of bat-ball contact. More specifically, when facing outswing trials, batters significantly delayed the initiation of their bat-backswing ($F(1, 31) = 5.24$, $p = .029$; $\eta_p^2 = .15$; outswing $M = 87$ ms, $SD = 80$; inswing $M = 65$ ms, $SD = 64$), and lowered the peak bat height in the backswing ($F(1, 31) = 36.76$, $p < .001$; $\eta_p^2 = .54$; outswing $M = 1391$ mm, $SD = 250$; inswing $M = 1519$ mm, $SD = 184$). As a result, they completed the backswing earlier even though they had commenced their backswing later (time of peak bat-height, $F(1, 31) = 16.39$, $p < .001$; $\eta_p^2 = .35$; outswing $M = 316$ ms, $SD = 50$; inswing $M = 341$ ms, $SD = 35$; duration of backswing, $F(1, 31) = 37.83$, $p < .001$; $\eta_p^2 = .55$; outswing $M = 228$ ms, $SD = 47$; inswing $M = 276$ ms, $SD = 49$). For the front-foot stride, batters against the outswing trials used a shorter stride both in terms of duration ($F(1, 31) = 56.18$, $p < .001$; $\eta_p^2 = .64$; outswing $M = 237$ ms, $SD = 45$, inswing $M = 303$ ms, $SD = 58$) and length ($F(1, 31) = 22.98$, $p < .001$; $\eta_p^2 = .43$; outswing $M = 208$ mm, $SD = 100$; inswing $M = 319$ mm, $SD = 153$). As a result, the stride was completed much earlier against the outswing trials ($F(1, 31) = 27.04$, $p < .001$; $\eta_p^2 = .47$; outswing $M = 322$ ms, $SD = 62$; inswing $M = 369$ ms, $SD = 54$). The shorter stride also meant that the batters' head was placed further from the ball at the moment it was hit ($F(1, 31) = 4.79$, $p = .036$; $\eta_p^2 = .13$; outswing $M = 140$ mm, $SD = 99$; inswing $M = 96$ mm, $SD = 139$). Having completed their stride earlier, the batters then commenced their bat-downswing earlier against the outswing trials ($F(1, 31) = 28.98$, $p < .001$; $\eta_p^2 = .48$; outswing $M = 347$ ms, $SD = 34$; inswing $M = 373$ ms, $SD = 30$), and took longer to perform their bat-downswing ($F(1, 31) = 16.09$, $p < .001$; $\eta_p^2 = .34$; outswing $M = 212$ ms, $SD = 34$; inswing $M = 186$ ms, $SD = 39$), greatly increasing the percentage of downswing time relative to backswing ($F(1, 31) = 26.11$, $p < .001$; $\eta_p^2 = .46$; outswing $M = 47{:}53\%$, $SD = 11$; inswing $M = 55{:}45\%$, $SD = 10$). This lengthening of the downswing is particularly consistent with the idea that batters sought to regulate the position of the bat using online corrections when facing the out-swinging trials (see Bootsma & van Wieringen, 1990; Dewhurst, 1967; Johansson & Westling, 1984).

The direction of ball-swing influenced the relative timing of the movement coupling but not necessarily the strength of the coupling. When compared to the inswing trials, the time from the completion of the front-foot stride to the initiation of bat-downswing was longer in the outswing trials (main effect of delivery for time cFFS-iDS, $F(1, 31) = 6.4$, $p =$

.017; $\eta_p^2 = .17$; outswing $M = 28$ ms, $SD = 54$; inswing $M = 4$ ms, $SD = 55$). However, there was no difference in the strength of the coupling (SD of delivery for cFFS-iDS, $F(1, 19) = 1.88$, $p = .19$; $\eta_p^2 = .09$; outswing $M = 47$ ms, $SD = 55$; inswing $M = 68$ ms, $SD = 55$). These results suggest that the direction in which the ball swings alters the timing of movement but not necessarily the degree of underlying coordination.

2.4.3.1.3. Effects of the direction of swing mediated by skill and/or age.

Effects that were found as a result of the direction of ball-swing were generally not mediated by skill and/or age, suggesting that those effects were similar for all batters. There was however, one exception. The decrease in the velocity of the bat-downswing found against the outswing trials was greater for the club batters than it was for the skilled batters (skill x direction of swing interaction, $F(1, 31) = 4.81$, $p = .036$; $\eta_p^2 = .13$)[11].

2.4.3.1.4. Discriminant function for the direction of swing.

A significant discriminant function equation for prediction of the direction of ball-swing was derived (D = 0.58 * [*timing of the initiation of bat-downswing*] + 0.6 * [*duration of backswing*] + 0.65 * [*duration of front-foot stride*]; $F = 19.42$; *df* 3, 70; $p < .001$; group centroids: outswing = -0.9; inswing = 0.9). The predictors in the model show the earlier timing of the initiation of bat-downswing and the shorter duration of backswing and front-foot stride that batters were more likely to adopt when facing the out-swinging trials. The model accurately predicted group memberships for 84.0% of cases with 84.2% of outswing and 83.8% of inswing trials categorised correctly. Cross-validation revealed that successful classification of variables discriminating the outswing and inswing trails was maintained (82.7%), with 81.6% of the outswing and 83.8% of the inswing trials re-categorised correctly.

2.5. Discussion

The aim of this study was to examine the movement strategies used by skilled performers when intercepting a moving target in the presence of ball-swing. Four groups of cricket batters who systematically differed in their level of batting skill and/or age hit balls projected by a ProBatter ball-projection machine. The ball-flight characteristics were manipulated so that batters attempted to intercept balls that followed either a straight or a

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[11] A significant main effect of delivery was also observed for the angular velocity of bat-downswing ($F(1, 31) = 55.53$, $p < .001$; $\eta_p^2 = .64$; outswing $M = 9.7$ rad.s^{-1}, $SD = 1.9$; inswing $M = 11.8$ rad.s^{-1}, $SD = 1.5$).

swinging flight-path. Three separate analyses were performed. The first examined skill and age-related differences in interceptive performance and movement strategies. Hypothesis 1.1 expected skill-based difference in interceptive performance of the batters, with Hypothesis 1.2 expected a closer and more consistent synchronisation between the timing of the completion of their front-foot stride and the initiation of bat-downswing. Hypothesis 1.3 also expected these differences to be evident by late adolescence and would be sustained into adulthood. The second analysis examined the influence of the possibility of ball-swing on the kinematic behaviour of the batters. Hypothesis 2.1 expected the possibility of ball-swing to significantly alter the movement coordination of batters when hitting balls that followed a straight flight-path, with the lesser-skilled batters adopting a more predetermined movement strategy (Hypothesis 2.2). The third analysis examined the influence of ball-swing on the performance and kinematic behaviour of the batters. Hypothesis 3.1 predicted that ball-swing would significantly reduce the interceptive performance of all batters, with batters also compensating for the delay in the timing of the initiation of front-foot stride and bat-backswing with faster and shorter movements of the front-foot stride and bat-downswing (Hypothesis 3.2). Also, balls that swung away from the batter were expected to significantly decrease performance and alter the batter’s kinematic behaviour when compared to the balls that swung in (Hypothesis 3.3). Let’s now turn to a consideration of each of these hypotheses in light of the empirical results.

2.5.1. Performance and Kinematic Differences Mediated By Skill and Age

As expected, when hitting straight balls the skilled batters were better able to achieve successful bat-ball contact than the club batters were (Hypothesis 1.1). This was also the case when hitting random-straight trials that were co-presented with swinging trials. This latter finding is consistent with those from Gray (2002), suggesting that skilled batters are able to combine contextual and perceptual information to assess the predicted and actual ball-flight characteristics to successfully hit the ball. However, consistent with Hypothesis 3.1, batting performance when hitting swinging balls was significantly worse than it was for when hitting straight balls irrespective of the skill and/or age level of the batter. This finding is also consistent with previous studies (e.g., Craig et al., 2011; 2006) which show that observers make more errors when predicting the future arrival location of a swinging ball. Importantly, the results presented here show that this finding extends to a situation where an interceptive action is performed *in situ* rather than when simply making a perceptual judgement in a virtual environment.

The ability to couple the completion of the front-foot stride with the initiation of bat-downswing has previously shown to be a distinguishable quality of skilled batters (Weissensteiner et al., 2011), with the results from this study supporting the validity of this parameter as an important marker of batting expertise (Hypothesis 1.2). However, it was observed that the increased *consistency* of this coupling, rather than the *timing* per se, was more likely to differentiate skilled from club-level batters (*cf*. Weissensteiner et al., 2011). It is proposed that the consistency of timing (i.e., the SD) provides a better measure of coupling than the average time between the two events does. Take for instance a batter who, on average, co-aligns the moments of the completion of the front-foot stride and initiation of bat-downswing, but has high variability. This would indicate poor coupling because there is not a consistent time delay between the two events. In contrast, a batter whose delay between the two events has low variability will, irrespective of the average time between the two events, reliably couple one event to the other.

Apart from a few relatively minor exceptions (*viz*. faster angular velocity of bat-downswing, hitting the ball earlier, and increased SD cFFS-iDS), very few differences in batting performance or kinematic behaviour were mediated by age in the current study. Consistent with Hypothesis 1.3, this suggests that skill-based differences evident during adulthood may not change markedly from those that are evident by late adolescence (see Daum et al., 2007; Haywood et al., 1981). However, it is important to note that the differences in age between the groups of batters may not be large enough to adequately examine the effects of age on the kinematic behaviour of the batters. This may help explain why very few effects of age were found in this study. As a result, future studies examining younger batters may help determine whether kinematic markers of skill found here, and elsewhere (e.g., Weissensteiner et al., 2011), emerge earlier in development. This could potentially be useful for the purposes of talent identification and/or providing appropriate training goals to help developing batters improve their batting performance.

2.5.2. The *Possibility* of Ball-Swing Alters the Batter’s Movements When Hitting Straight Balls

When compared to straight balls that were blocked together, hitting straight balls that were co-presented with swinging trials resulted in clear differences in the batter’s spatial kinematics and ultimately when the ball was hit. This is a remarkable finding given that the ball-flight trajectories were identical for both the blocked and random-straight trials. The results show that the uncertainty created by ball-swing significantly alters the movement behaviour of the batters. Consistent with Hypothesis 2.1, the possibility of ball-swing caused batters to alter their movement coordination, with batters moving closer to the ball and hitting it earlier (to presumably account for the possibility of lateral deviations off the playing surface). In fact, the timing of bat-ball contact and the batter's head position relative to bat-ball contact were found to reliably discriminate random-straight from blocked-straight trials (accurately predicting group membership of 72.1% of cases).

As expected, the possibility of ball-swing was found to have a greater influence on the club batters than it did on the skilled batters (Hypothesis 2.2). Club batters were found to *improve* the strength of their movement coupling immediately following ball-release (SD iFFS-iBS) when facing the random-straight trials, compared to when straight trails were blocked together, to a level similar to that of the skilled batters. Furthermore, the idea that the club batters altered their movements when they were aware that the ball could swing is supported by the batters delaying the timing of the completion of front-foot stride in the random-straight trials compared to the blocked-straight trials. The propensity for adult club batters in particular to complete their front-foot stride very early in the blocked-straight trials was not found in the random-straight trials. As a result, delaying the completion of their front-foot stride resulted in a shorter delay between the completion of front-foot stride and bat-ball contact; but more importantly, a shorter timing between the completion of front-foot stride and the initiation of bat-downswing. By changing their movement coordination to account for the uncertainty in ball-flight, adult club batters also changed when they ultimately hit the ball. These results further support the idea that the contextual environment in which an action is performed can significantly influence how that action is accomplished (Todorović, 2010).

Collectively, these findings support the benefits of establishing task-specific training protocols that are conducted under high contextual variety, when compared to a blocked training approach. Although a blocked training paradigm might help beginners learn to coordinate movement effectively (see Schmidt & Wrisberg, 2008), prolonged exposure may lead to predetermined motor-programmes that are organised prior to the execution of the movement. By creating an environment where performers are uncertain of the ball's flight-path, such as those encountered during competition, performers are more likely to develop movement strategies that allow for changes in specific kinematic parameters with changes in ball-flight. Furthermore, this more random presentation approach has also shown to better facilitate the retention and transfer of learning (Wrisberg & Liu, 1991).

2.5.3. The *Presence* of Ball-Swing Alters the Interceptive Performance and Movement Kinematics of All Batters

The findings from this study, believed to be first of its kind, show that swinging deliveries significantly delayed each phase of the batter’s movement, irrespective of their skill and/or age. This delay is consistent with the need for batters to wait for updated visual information before initiating and completing their movement as late as was permissible in an attempt to increase their certainty of the future location of the ball (Bootsma & van Wieringen, 1990). What was surprising though was that even after only ≈50 ms of ball-flight there were significant delays in the initiation of bat-backswing and front-foot stride, suggesting that batters were able to differentiate straight from swinging trials at a very early point in ball-flight. This suggests the batters may have potentially used pre-release kinematic information from the bowler’s body (provided by the video projection of the ProBatter machine) to help guide their kinematic responses (see Müller et al., 2006). Consistent with Hypothesis 3.2, batters compensated for these delayed movements by predominantly modifying their bat-swing by increasing the angular velocity of bat-downswing, providing further support for the use of a more prospective control of movement when hitting swinging balls (see Diaz et al., 2009; Tresilian, 2005).

Based on both the asymmetrical positioning of the batter and the anecdotal observations of players and coaches, it was expected that the out-swinging balls would be more challenging to hit than the in-swinging balls. Indeed the direction of ball-swing was found to have a very strong effect on the behaviour of all batters, with the out-swinging ball markedly decreasing their performance and greatly changing their kinematics (Hypothesis 3.3). In fact, batting performance was almost halved when hitting the out-swinging trials compared to the in-swinging trials. Moreover, batting performance when hitting in-swinging deliveries was no different to that found when hitting the random-straight trials (random-straight M = 70.8%, SD = 23.6; inswing M = 64.1%, SD = 37.2; p = .367). This highlights that it may not be the presence of ball-swing that influences interceptive performance per se, but rather that the decrease in performance is related to a particular type of swinging target (in this case the out-swinging ball). The out-swinging ball also significantly influenced the timing of nearly all the key moments in the hitting action, with batters found to spend more time in the downswing phase of the bat-swing to presumably regulate the position of their bat to coincide with the ball at the moment of arrival (see Bootsma & van Wieringen, 1990; Dewhurst, 1967; Johansson & Westling, 1984). Three specific measures strongly discriminated movements made for out-swinging when compared to in-swinging deliveries: a quicker backswing, a shorter front-foot stride, and earlier downswing initiation (accurately predicting group membership of 84% of cases).

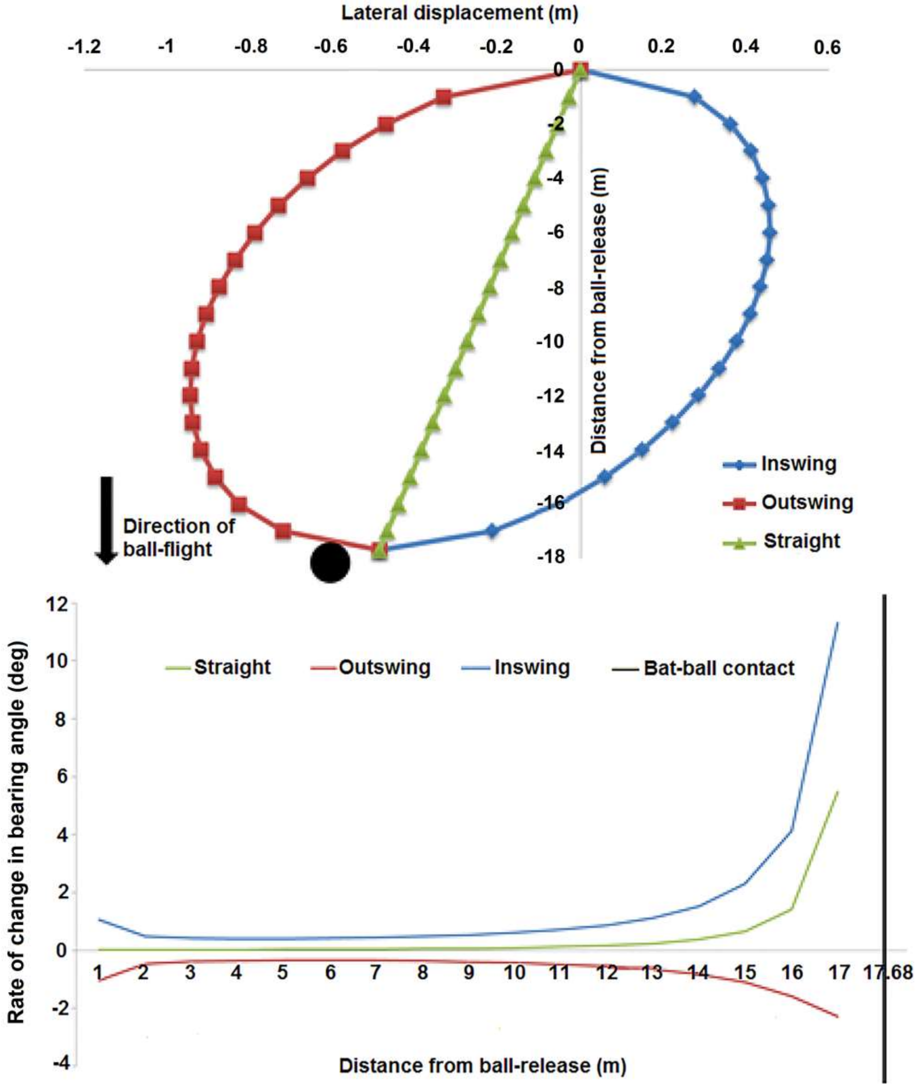

Figure 2.9. (*Top panel*): A schematic overhead view of the flight-path of a ball (not to scale) that swings away from the batter (outswing; red), in towards the batter (inswing; blue) and straight towards the batter (green). Note the asymmetry in the position of the batter's head (circle) and the location of ball-release. (*Bottom panel*): A calculation of the rate at which the bearing angle changes for the different flight-paths of the ball. The asymmetry between the position of the batter and the location of ball-release results in a difference in the rate of change in bearing angle.

It is not immediately clear how the direction of ball-swing influences performance and kinematics, with the current experimental design limiting the analysis of movement to only the sagittal plane. However, it is hypothesised that these differences in performance and kinematics between the out- and in-swinging deliveries could be best explained by the perceived differences in the rate of change in bearing angle and in the approach angle of the ball. Given the asymmetrical positioning of the batter and the location of ball-release in a task such as cricket batting, this also gives rise to an asymmetry in the bearing angle, and in the rate of change in bearing angle, for the outswing and inswing deliveries (see Figure 2.9). This is important because humans are thought to rely on an interceptive strategy that seeks to keep the rate of change in bearing angle constant to accurately predict the future arrival location of a target (Lenoir et al., 2005; Montagne et al., 1999; Peper et al., 1994). As a result, Diaz et al. (2009) proposed that the perceptual information from a more orthogonal trajectory (in this case the inswing trajectory) could be more easily detected by the performers as it is accompanied by noticeable differences in the rate at which the bearing angle changes. On the other hand, perceptual information from a more 'head-on' trajectory (in this case the outswing trajectory) may be more difficult to detect as it is accompanied by smaller perceived differences in the rate of change in bearing angle. Moreover, Welchman, Tuck, and Harris (2004) showed that performers tend to misperceive the approach angle of a ball when it travels along the mid-sagittal plane of the performer (which the outswing trajectory does for the majority of ball-flight compared to the inswing trajectory). As a result, it is possible that a similar strategy may restrict the batter's ability to predict the future arrival location of the out-swinging ball when performing a manual interceptive task *in situ*, and help explain the significant differences in performance and kinematics observed.

Collectively, the findings provide some empirical support for the long held anecdotal observations and coaching directions surrounding the ideals of hitting a swinging ball. For example, the coaching mantra of '*move late, move quickly*' is commonly advocated to encourage batters to delay the initiation of movement to obtain sufficient ball-flight information before moving (Cricket Australia, 2005; Woolmer et al., 2008). The results suggest that the batters indeed followed this adage: they delayed the timing of each phase of movement when facing the swinging deliveries, relying on an increase in the angular velocity of bat-downswing to compensate for this delay. This consequently resulted in batters hitting the ball significantly later. However, with the delayed initiation, and completion of the front-foot stride when hitting swinging balls, batters were less likely to effectively transfer their momentum into the shot and position their head closer to the ball at the point of bat-ball contact (Taliep et al., 2007).

2.6. Conclusion

Differences in the interceptive performance and kinematic behaviour of cricket batters of different skill and age levels were examined when attempting to hit balls in the presence of ball-swing. The results supported skill-based differences in batting performance and the coupling between the completion of the front-foot stride and the initiation of bat-downswing as key markers of batting expertise. Furthermore, the skilled batters were better than the club batters in differentiating straight from swinging balls, with the ability to do so found to be evident by late adolescence and sustained into adulthood. The *possibility* of ball-swing significantly altered the batter's performance and movement coordination when hitting straight balls. Club batters in particular were found to alter their movements to account for the uncertainty in ball-flight, ultimately influencing when the ball was hit. The *presence* of ball-swing significantly reduced the interceptive performance of the batters irrespective of their skill and/or age level. Batters delayed the timing of key kinematic moments in their hitting action when hitting swinging balls, with changes in movement coordination very early in ball-flight suggesting that batters were able to differentiate straight from swinging deliveries immediately following ball-release. The *direction* of ball-swing also influenced the batter's performance and kinematics, with these differences hypothesised to be the result of an increased difficulty to detect perceptual changes in the ball's flight-path when it swings away from the batter compared to those that swing in towards the batter.

CHAPTER 3

THE DEVELOPMENT OF VISUAL-MOTOR EXPERTISE WHEN HITTING A BALL

Following the kinematic findings from Chapter 2, Chapters 3 and 4 examine the influence of ball-swing on the batter's *gaze behaviour* to determine the perceptual variables that allow them to predict the future arrival location of straight and swinging balls. Although previous studies examining gaze behaviour reveal skill-based differences that underpin successful interception, they generally adopt a case-study design that may not provide an accurate representation of the wider population. This chapter therefore extends the current knowledge by examining the gaze behaviour of batters across skill and age when intercepting a block of straight balls, before exploring the influence of ball-swing on the batter's gaze in Chapter 4.

'*Just when you think you know all the answers, I change all the questions.*'

Rowdy Roddy Piper

3.1. Abstract

It is well established that batters in fast-ball sports do not align their gaze with the ball throughout ball-flight, but rather adopt a unique sequence of eye and head movements that contribute towards their interceptive skill. Although existing studies claim that skill-based differences exist in the ability to predict the future location of the ball, the support for these differences are based largely on studies that adopt case-study designs and/or simplified task environments that may not provide an accurate reflection of the findings they seek to represent. The aim of this study was to provide a comprehensive examination of the eye and head movement strategies that underpin the development of visual-motor expertise when intercepting a fast-moving target. It did so by examining the visual-motor behaviour of cricket batters using (i) a large number of participants, (ii) a broad range of skill and age groups, and (iii) an environment that closely replicates that experienced during competition (employing fast ball-speeds and numerous locations of ball-bounce). The results provided support for some existing markers of expertise (i.e., directing gaze ahead of the ball, predictive saccades towards bat-ball contact, and maintaining gaze at that location as they hit the ball), with the ability to do so found to be evident by late adolescence and sustained into adulthood. The previous assertions that skilled batters initiate earlier predictive saccades and/or direct their head closer to the location of the ball were not supported, highlighting the limitations of previous case-study designs. The location of ball-bounce significantly influenced the visual-motor behaviour of the batters, restricting their predictive ability for some bounce-points. The coordinated movement of the eyes *and* head appear to be an additional hallmark of visual-motor expertise that allows batters to account for the different locations of ball-bounce. Collectively, the findings shed new light on the development of visual-motor expertise when performing an interceptive action in an environment that closely replicates that experienced during competition.

3.2. Introduction

The successful interception of a moving target can demand an extraordinary degree of coordination between the neuromuscular and visual systems (Tresilian, 2005; Warren, 1988). Fast-ball sports are commonly used as an exemplar task to better understand the strategies that underpin efficacious interception, as they represent tasks that require the performer to overcome highly demanding spatio-temporal constraints that often test the limit of human achievement (Regan, 1992, 1997; Walsh, 2014). Recent examinations of the unique eye movements of skilled performers have revealed exciting insights that improve our understanding of how interceptive actions are controlled and performed (e.g., Land & McLeod, 2000; Mann et al., 2013). However, the conclusions made by these studies have generally been based on the examination of a very low number of participants and/or using relatively simplified task designs. As a result, there is a clear need for a more comprehensive examination of the visual-motor behaviour associated with skill in interception, ideally involving a larger number of participants, across a broader range of skill and age groups, and performing an interceptive action that closely replicates that experienced during competition (see Sarpeshkar & Mann, 2011). This study seeks to address these limitations by examining the visual-motor behaviour of cricket batters when performing a temporally constrained interceptive action in an effort to establish a comprehensive understanding of the strategies that underpin the development of visual-motor expertise.

When performing an interceptive task, performers do not abide by the common coaching adage to '*keep your eyes on the ball*' (e.g., Bahill & LaRitz, 1984; Land & McLeod, 2000; Mann et al., 2013). Instead, they are thought to use a combination of central (foveal) and peripheral vision to track the target throughout its flight-path (Bahill & LaRitz, 1984; Land & McLeod, 2000). Moreover, performers are known to rapidly shift their foveal vision ahead of the target to predict its future location. Land and McLeod (2000) reported that following ball-release, cricket batters track the ball for the initial portion of its flight before performing an *anticipatory saccade* towards the predicted location of ball-bounce[12]. Crucially, Land and McLeod reported that skilled batters perform *earlier* saccades towards ball-bounce than lesser-skilled batters do. The superior anticipatory ability of the skilled batters has been said to be consistent with the idea that batters use learnt internal models of ball-flight to predict where the ball will be in the near future and to

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[12] Similar to tennis players, cricket batters typically hit the ball after it has bounced on the ground.

position gaze in anticipation of a predicted event, such as ball-bounce (Land & Furneaux, 1997).

A recent study by Mann et al. (2013) that examined the gaze behaviour of two of the world's best cricket batters raised two additional points to those reported by Land and McLeod (2000) to foster a further understanding of the development of visual-motor expertise in batting. First, they found that the elite batters used their eyes to guide their head so that it is aligned with the position of the ball throughout the majority of its flight. In other words, the batters moved their head in a fashion that ensured the position of the ball was retained within a single egocentric direction relative to the head. They hypothesised that batters could use this strategy to help predict where the ball was likely to arrive, thereby simplifying the interceptive task to one where time-to-contact was needed to successfully hit the ball (see Lee et al., 1983; Oudejans et al., 1999). Second, the elite batters were found to produce anticipatory saccades not only towards the location of ball-bounce but also towards the likely location of bat-ball contact. Land and McLeod (2000) had reported that following ball-bounce, batters attempted to track the ball but generally were unable to do so in the final moments before bat-ball contact. In contrast, Mann et al. (2013) found that the elite batters they tested frequently performed a saccade to the anticipated location of bat-ball contact or tracked the ball up to the moment of contact. Essentially, the elite batters appeared to be doing whatever was necessary to direct their gaze towards the predicted location of bat-ball contact.

Although the very best batters may be able to co-locate their gaze with the ball at the moment they hit it, it is not yet clear whether doing so provides any sort of functional advantage in achieving successful bat-ball contact. The usefulness of perceptual information available immediately prior to bat-ball contact is likely to be limited. For example, cricket batters are thought to need at least 190 ms to modify their bat-swing to unexpected deviations in ball-flight, primarily because they must overcome the considerable inertia inherent when swinging a heavy bat (see McLeod, 1987). This finding has been interpreted to suggest that late ball-flight information may be redundant for successful interception, as it is very difficult for batters to alter their bat-swing once it has been initiated. However, Bootsma and van Wieringen (1990) have argued that this delay is excessive because it represents the time that is necessary to initiate a new action to an unexpected deviation in flight rather than that required to adapt an existing motor action to account for a more subtle deviation in ball-flight (Dewhurst, 1967; Johansson & Westling, 1984). It could be that the ability to direct gaze towards the anticipated position of bat-ball contact may allow batters to monitor the progress of the ball using their peripheral vision and make adjustments to their bat-swing as late as is permissible by the sensorimotor system (Bootsma & van Wieringen, 1990; Ripoll & Fleurance, 1988). By doing so, the truly elite performers may have developed a simple, yet elegant means by which to alter their actions as late as they possibly can (also see Lee et al., 1983; Ripoll & Fleurance, 1988).

Collectively, the findings from these previous studies have greatly progressed our understanding of the visual strategies that underpin successful interception. However as mentioned earlier, there remain three major concerns that limit the conclusions made from those studies. The first concern is that inferences about skill-based differences in gaze behaviour have typically been made on the basis of very low sample sizes. For instance, Land and McLeod (2000) examined just three batters, each of a different skill level (provincial, amateur or recreational), and Mann et al. (2013) tested four batters of two different skill levels (two international standard and two club-level). As a result of these low sample sizes, it is unclear whether the findings of those studies are truly representative of those expected across the wider population. There is a clear need for a more comprehensive study to determine whether the findings of those studies can be replicated using a larger sample of participants.

The second concern is that many of these existing studies examine performance in tasks that are typically simplified and therefore may not necessarily replicate the constraints experienced during competition. For instance, Land and McLeod (2000) examined the gaze behaviour of batters when facing balls that (i) were projected from a ball-projection machine rather than a bowler, and (ii) travelled at ball-speeds that were considerably slower than those experienced during competition (25 $m.s^{-1}$ or 90 $km.h^{-1}$ rather than the ≈42 $m.s^{-1}$ or 150 $km.h^{-1}$ commonly faced by international standard cricket batters). Croft et al. (2009) examined the gaze behaviour of cricket batters who faced balls that followed only one single ball trajectory, thereby making the trajectory very predictable to the batters. Gaze strategies and the magnitude of skill-based differences in gaze have been shown to vary according to where the ball bounces (Mann et al., 2013), and therefore studies which employ only one stereotypical trajectory could provide an inaccurate generalisation of interceptive behaviour. Lesser-skilled batters have been shown to exhibit more expert-like gaze behaviour (i.e., they direct gaze ahead of the ball) when the ball bounces far away from them (termed a *short-length* delivery), but are much less likely to do so when the ball bounces close to them (a *full-length* delivery). Crucially, they are least likely to show expert-like behaviour when the ball bounces in a position *in between* these two positions (a *good-length* delivery), helping to explain why this is most commonly considered to be the most challenging bounce position from which to hit a ball in cricket (see Bradman, 1958; Woolmer et al., 2008). As a result, it is important to examine manipulations in the location of ball-bounce as skill-based differences in visual-motor behaviour are expected to vary according to the bounce location.

The third limitation of existing studies is that very few have examined at what stage of development skill-based differences in gaze should be expected to be acquired. An examination of skill-based differences in both adult and youth batters would help to systematically evaluate whether the expert advantage apparent for elite adult batters is also apparent earlier in development. For example, Tenenbaum, Sar-El, and Bar-Eli (2000) reported, using temporal occlusion of a video display, that skill-based differences in the ability of tennis players to predict the future location of the ball prior to racquet-ball contact is evident as early as 8-11 years of age; whereas Weissensteiner et al. (2008) suggest that such differences in cricket batters may only be evident beyond 17 years of age. Furthermore, Dorfman (1977) examined the development of coincidence timing during a simulated interceptive task for performers between 6-19 years of age and found that accuracy improved and became more consistent at around 15 years of age (for a review, see Sanders, 2011). If skill-based differences in gaze are found to emerge from a young age, then this would suggest that expert-like visual-motor behaviour is a skill that can be acquired early in development and could therefore be a useful marker for the purposes of talent identification. Conversely, if skill-based differences emerge later then this would suggest that the accumulation of experience and/or maturation is necessary for the development of expert-like gaze behaviour (see Côté & Hay, 2002).

The aim of this study was to examine the eye and head movement strategies that underpin the development of visual-motor expertise when performing a fast-paced interceptive action. The gaze behaviour of four groups of cricket batters who systematically differed in their level of skill and/or age was examined when hitting a ball that was projected by a hybrid ball-machine designed to be more representative of facing a bowler as would be experienced during competition. Three broad hypotheses were made. Consistent with previous work, it was first expected that the skilled batters, when compared to the lesser-skilled batters, would demonstrate (i) better batting performance, (ii) earlier saccades towards ball-bounce (Land & McLeod, 2000), (iii) more saccades towards bat-ball contact (Mann et al., 2013), (iv) gaze co-located with the ball at the moment of bat-ball contact (Mann et al., 2013), and (v) better egocentric head tracking of the ball (Mann et al., 2013). Second, skill-based differences in the batters' ability to anticipate the future location of the ball were expected to emerge by late adolescence and that these differences would continue into adulthood (e.g., Dorfman, 1977). And third, skill-based differences in gaze behaviour were expected to differ according to the location of ball-bounce, with differences expected to be more evident when facing balls that bounced on a good-length compared to other ball-lengths.

3.3. Methods

3.3.1. Participants

A total of 43 male cricket batters were examined and were categorised into one of four groups according to their level of batting skill ('skilled' or 'club') and age ('adult' or 'youth'). The *adult skilled* group consisted of batters who had represented their state/province at the senior level (13 batters, $M_{age} = 25.1$ years, age range: 19-37), including four members of the Australian national squad at the time of testing. The *youth skilled* group consisted of batters who had represented their state/province at an under-19 and/or under-17 level (10 batters, $M_{age} = 17.7$ years, age range: 16-18), including four members of the Australian under-19s national squad at the time of testing. The club-level batters (i.e., *adult club* [10 batters, $M_{age} = 31.7$ years, age range: 26-39] and *youth club* [10 batters, $M_{age} = 21$ years, age range: 18-23]) consisted of competent but lesser-skilled recreational batters who played competitive club cricket in a local district competition and had not achieved any higher level representative selection. Informed consent was provided by all batters prior to the commencement of the experiment to a protocol that was approved by the University ethics committee.

3.3.2. Experimental Design

The experiment took place at an indoor facility that replicated the dimensions and ball rebound characteristics of a synthetic cricket surface. The hybrid ProBatter ball-projection machine (PX-2-PB2005-87; ProBatter Sports, Milford, CT) was used to project balls towards the batter (see Portus & Farrow, 2011; ProBatter Sports, 2015). The machine was located behind a large screen (2.6 m x 3.5 m) that had projected onto it (Hitachi CP-X809 LCD projector, Tokyo, Japan) a life-sized video footage of a cricket bowler in their full approach towards the batter, showing the bowler's full run-up, approach to the crease, ball-release, and follow-through (for more information on the benefits of the ProBatter machine compared to a live bowler and a bowling machine, see Mann et al., 2013). The ProBatter system was programmed to show a series of different video recordings of one particular bowler (that was recorded live during competition) so that the ball-flight characteristics seen for that delivery corresponded to that actually bowled, ensuring that any kinematic information in the bowler's action matched the actual outcome of the ball-flight. The distance of the machine from the batter (≈17.68 m), the height of ball-release from the ground (2.08 m [subtended angle of 6.66°]) and the approach angle of the ball (bearing angle of 1.94°) replicated those dimensions typically experienced during competition. At the moment of ball-release, a composite ball that is commonly used during training (Jugs Inc., Tualatin, Oregon) was projected through a hole in the screen at a release velocity of ≈33 $m.s^{-1}$ (119 $km.h^{-1}$). This ball-speed was chosen to represent a speed that was commonly experienced in competition but was also safe for all participants. Batters used their own cricket equipment (i.e., leg and thigh guards, gloves and cricket bat) and were instructed to bat as they would during competition; that is, to hit the ball in a manner that would allow them to successfully score runs whilst also minimising the likelihood of being dismissed.

Prior to data collection, three distinct areas on the playing surface were selected to represent the different locations of ball-bounce relative to the location of the stumps (i.e., *lengths*; *viz*. *full*, *good*, and *short* length trials), with the batter standing ≈1 m in front of the stumps. This not only reduces the batter's ability to predict the location of ball-bounce (*cf.* Croft et al., 2009), but also helps determine whether skill-based differences previously reported are still observed across the different locations of ball-bounce. In the *full-length* trials (or *deliveries*), the ball bounced close to the batter (3.5-4.5 m from the stumps) and would typically require them to step forward to hit the ball. In the *good-length* trials, the ball bounced 7.0-8.0 m from the stumps. This ball-length is commonly considered to be the most challenging position from which to hit the ball as it typically causes indecision as to whether to step forward or backward (e.g., Woolmer et al., 2008). In the *short-length* trials, the ball bounced furthest from the batter (9.0-9.5 m from the stumps) and would typically require them to step backward to hit the ball (Figure 3.1; also see Pinder et al., 2011a). To prevent the batter from anticipating the bounce point of the ball, the arrival location of the ball was also manipulated according to one of two different *lines*, which caused the ball to be directed either close to, or away from the batter's body. The line of the ball however, was of no particular experimental interest.

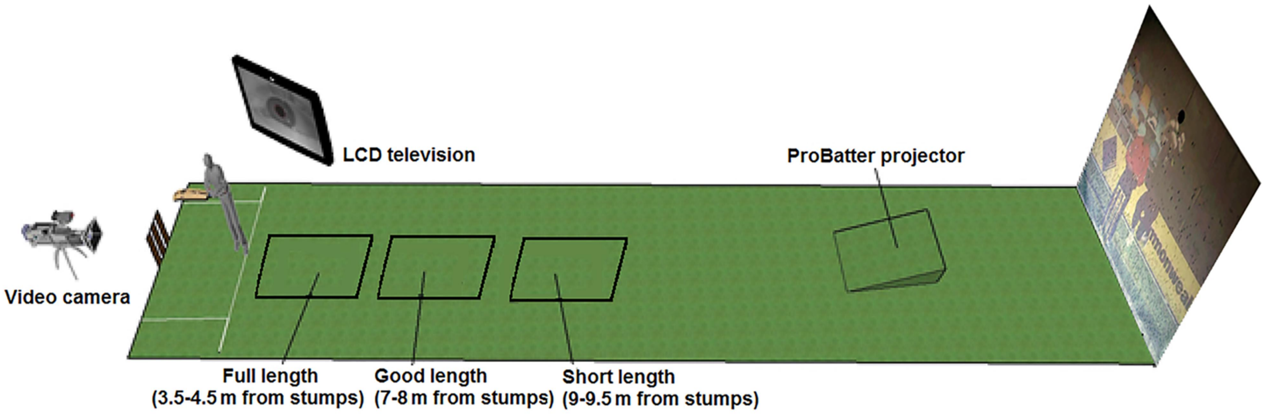

Figure 3.1. Schematic illustration of the experimental set-up. The LCD television was placed adjacent to the test area to monitor the eye tracking system, whilst a video camera located behind the batter helped to verify the moment of ball-release, ball-bounce and bat-ball contact when any of these events were not visible on the eye tracker footage. Bounce areas are shown on the pitch for schematic purposes only and were not present during the experiment proper.

3.3.3. Data Collection

Participants were fitted with a *Mobile Eye* monocular eye tracking system (25 Hz; Applied Science Laboratories, Bedford, MA) to record the direction of gaze while batting. Footage from the Mobile eye was recorded on a digital video recording unit (Sony GV-D 1000 Portable MiniDV Video Walkman, ≈1 kg) that was housed in a lightweight pouch worn around the batter's waist. To ensure that any disturbances to the camera were detected and corrected, a radio transmitter was also connected to the recording unit to wirelessly transmit the video footage to a LCD television screen located adjacent to the test area. Batters wore a customised helmet that had a portion of the brim removed to allow space for the eye tracker camera (see Figure 3.2). With the batter in their usual batting stance, calibration of the eye tracker was performed using predetermined locations in the batter's visual field.

Figure 3.2. A participant wearing the eye tracker and the modified helmet.

A video camera (Sony HDR-FX 1000, Tokyo, Japan; 25 Hz) was positioned behind the batter and was used for the synchronisation of the eye-movement footage with the moment of ball-release, ball-bounce, and/or bat-ball contact when any of these events were not clearly visible on the eye movement footage.

3.3.4. Procedure

Prior to the experiment proper, a short warm-up period (≈10-15 deliveries) was provided for the batters to familiarise themselves with the ProBatter system, the eye tracker and the range of trials they were to face in the experiment. Calibration checks were performed for the eye tracker prior to, and after the completion of each condition, or if the unit was deemed to have been disturbed. During the experiment proper, participants faced two separate counterbalanced blocks of trials: (i) *blocked-straight* trials and (ii) a *random* sequence of straight and swinging trials (this random mixture of straight and swinging trials forms the basis for a separate investigation [see CHAPTER 4] and will not be discussed here). For this study only the *blocked-straight* trials were analysed. Participants in the blocked-straight trials faced 18 trials that followed a straight flight-path and were equally distributed across the three different ball-lengths and two lines. The order of the trials within the block followed the same predetermined, but randomised sequence of deliveries that started at a random position for each batter. Testing took approximately one hour to complete for each batter.

3.3.5. Data Analysis

Footage from the *Mobile Eye* unit was manually digitised (Kinovea 8.15, 2011) to obtain the x-y coordinates of five specific locations within the visual field from the moment of ball-release to bat-ball contact: (i) location of gaze, (ii) location of ball-release, (iii) the ball, (iv) bottom left of the projection screen, and (v) bottom right of the projection screen. The first three reference points allowed for the calculation of the raw gaze, head, and ball angles subtended at the eye (in degrees). Because the scene camera in the gaze tracking system moves commensurate with the movements of the head, any movement of a fixed location in the visual field, such as the location of ball-release, provides a direct measure of head movement. The three singular angles were used for the calculation of three relative angles: (i) the *gaze-ball angle*, (ii) the *gaze-head angle*, and (iii) the *head-ball angle* (see Figure 3.3). The coordinates of the projection screen were used to correct for head rotation to ensure that the visual angles were reported relative to the global rather than local coordinate system. The x-y coordinates for the five spatial locations for a single participant showed high levels of intra- and inter-tester reliability (98% and 96% agreement respectively; with intra-tester coding performed four weeks apart).

In addition to the digitisation of the video footage, the eye movement footage was manually viewed frame-by-frame to detect the type and timing of saccades that took place between the moment of ball-release and bat-ball contact. A saccade was recorded when a distinctive shift in gaze occurred that was not commensurate with the flight-path of the ball. Two types of saccades were examined: (i) *saccade towards ball-bounce*, where a saccade was initiated *prior* to ball-bounce and brought gaze ahead of the ball to a stationary position towards the impending position of ball-bounce, and (ii) *saccade towards bat-ball contact*, where a saccade was initiated *after* ball-bounce and brought gaze ahead of the ball to a stationary position towards the impending position of bat-ball contact. The type and timing of the saccades of four batters (each from a different skill and/or age group) were assessed independently by two trained researchers. The manual coding of saccades showed a high degree of intra- and inter-tester reliability (at least 97% and 81% agreement respectively; with intra-tester coding performed four weeks apart). Pilot testing revealed other types of saccades that either caught up with, or took gaze ahead of the ball during flight. However, inter-tester reliability proved to be poor for these saccades and so they are not reported.

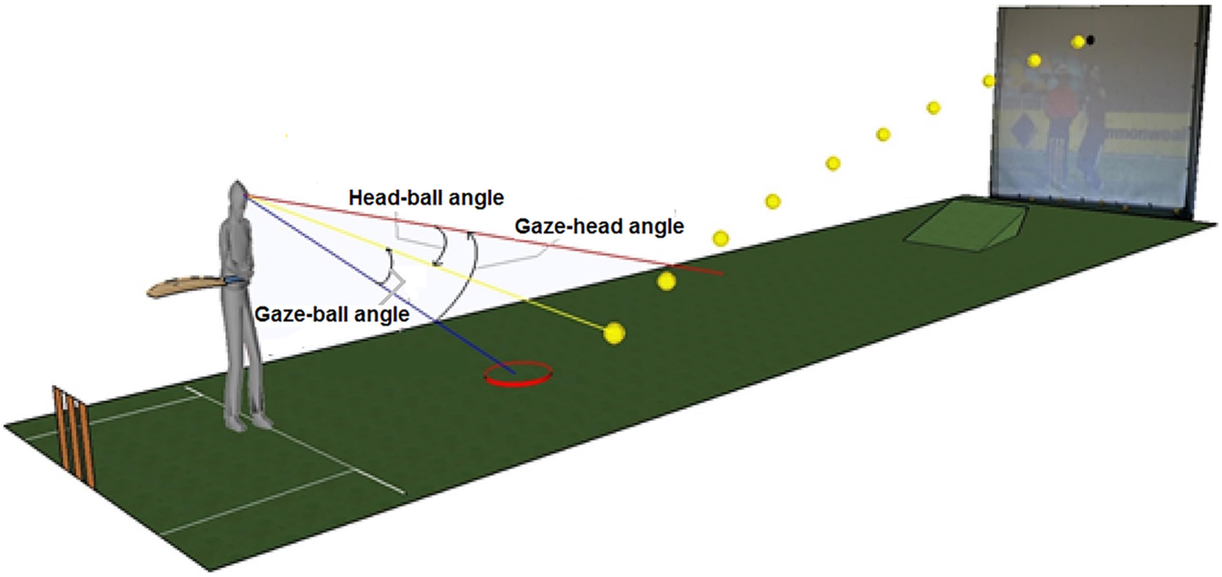

Figure 3.3. Measurement of the three relative angles. Individual angles are initially subtended by the direction of the head (red), ball (yellow) and gaze (blue) at the batter's eye (in degrees) relative to the direction of ball-flight. The relative angles in this case show a positive head-ball angle (head is directed behind the ball), a negative gaze-ball angle (gaze is directed ahead of the ball), and a negative gaze-head angle (gaze is directed ahead of the head direction).

A total of 543 out of 774 possible *blocked-straight* trials (70%) were analysed: 177 trials were excluded as the batter did not swing their bat to hit the ball (with the batter also generally making no further attempt to track the ball following ball-bounce; 23% of remaining trials) and 54 trials were excluded as technical difficulties with the eye tracker failed to obtain the gaze location and/or unreliably provided the location of gaze for more than two consecutive frames of ball-flight (7% of remaining trials).

3.3.6. Measures of Performance and Gaze Behaviour

A number of dependent variables were assessed to examine the (a) batting performance, (b) relative positions of gaze, head and ball throughout ball-flight, (c) type and timing of saccades, and (d) gaze position at the moment of bat-ball contact.

(a). Batting performance: two measures of interceptive performance were assessed in real-time by the primary investigator: (i) the *quality of bat-ball contact* (QoC; see Müller & Abernethy, 2008), and (ii) the *forcefulness of bat-swing* (FoBS; see Mann, Abernethy, & Farrow, 2010b). The QoC provides a simple and validated categorical means of determining whether the batter successfully made contact with the ball. A score of two,

one, or zero was given for each trial to represent ‘good’ (ball makes contact with the bat and travels in a direction consistent with the plane of bat motion), ‘poor’ (ball makes contact with the bat and travels in a direction inconsistent with the plane of bat motion) or ‘no contact’ (ball makes no contact with the bat) respectively (see Müller & Abernethy, 2008). This allowed for the calculation of the *% of trials with ‘good’ bat-ball contact* (for a similar type of analysis, see Chapter 2; Müller & Abernethy, 2006). The FoBS provides a categorical means of assessing how hard the ball was hit when bat-ball contact was achieved, reflecting the likelihood of runs being scored by the batter (see Mann et al., 2010b). Greater spatio-temporal precision is required for a faster, more aggressive bat-swing because there is a decrease in the time window in which the bat is optimally positioned to hit the ball. A score of two, one, or zero was also given for each trial to respectively reflect a complete follow-through of the bat, a partial follow-though, or no follow-though after bat-ball contact. This allowed for the calculation of the *% of trials with high FoBS* to determine the extent to which the nature of the shot performed by the batters changed across the different experimental conditions.

(b) Relative position of gaze, head and ball throughout ball-flight: The mean and standard deviation of the (i) *gaze-ball*; (ii) *gaze-head* and (iii) *head-ball* angles were calculated for each trial (all data expressed as the *mean* ± *standard deviation* in degrees). The percentage of ball-flight where batters directed their gaze ahead the ball ($\% \ Gaze_{ahead}$) was also calculated to provide an indication of the proportion of ball-flight time batters held their gaze in a position that anticipated the future location of the ball.

(c) Type and timing of saccades: The frequency and timing of saccades to (i) ball-bounce, and (ii) bat-ball contact were recorded between the moment of ball-release and bat-ball contact. The frequency of each type of saccade was reported as the percentage of trials in which that type of saccade was performed. The timing of each saccade was reported relative to the moment of ball-release (and reported as the *mean* ± *standard deviation* in milliseconds).

(d) Gaze at bat-ball contact: The location of gaze at the moment of bat-ball contact has previously been shown to discriminate skilled from lesser-skilled batters (see Mann et al., 2013). To determine whether gaze was directed towards the ball at contact, video footage of the moment closest to contact was manually viewed in conjunction with the frames prior to and after contact. Gaze was judged to have been directed towards the ball at contact if it was within one bat-width of ball at contact (approximating 4 deg of visual

angle). Although this may not conclusively establish whether foveal fixation was achieved on the ball at the moment of bat-ball contact, it allows for the differentiation between gaze being directed towards contact as opposed to when gaze was clearly directed elsewhere (usually lagging behind the ball or directed towards the post-contact direction; see Mann et al., 2013). This allowed for the calculation of the percentage of trials in which the gaze of the batters, at the moment of bat-ball contact, was either: (i) co-located with the ball ($\%\ BBC_{fixation}$), (ii) lagging behind the ball ($\%\ BBC_{lagging}$), or (iii) directed towards the post-contact direction of the ball ($\%\ BBC_{post\text{-}contact}$). The manual coding of the location of gaze at the moment of bat-ball contact for four batters revealed high levels of intra- and inter-tester reliability (98% and 90% respectively; with coding for intra-tester performed four weeks apart).

3.3.7. Statistical Analyses

A 2 (Skill: skilled, club) x 2 (Age: adult, youth) x 3 (Ball-length: full, good, short) ANOVA with repeated measures on the last factor was used to examine for differences in each of the dependent variables. A multivariate analysis of variance (MANOVA) was then performed incorporating each of the gaze variables. Variables found to be significant within the MANOVA were then subjected to a stepwise discriminant function analysis with the F value set between 0.05 and 0.15 (Tabachnick & Fidell, 2001). This allowed for the determination of the variable, or the combination of variables, that best predicted membership for the batter's skill level, age group, and ball-length (for a similar analysis, see Chapter 2 and Weissensteiner et al., 2011). Cross-validation of the models was also performed to assess the accuracy of predicting the same outcome variables for an independent dataset (Field, 2005).

Where the assumption of sphericity was violated, the Greenhouse-Geisser correction was used. Alpha was set at 0.05 for all comparisons. Partial eta squared (η_p^2) and Cohen's d values were calculated to indicate the effect size where appropriate.

3.4. Results

The mean group results for each of the dependent variables are presented in Table 3.1. For the sake of simplicity the three hypotheses are addressed in turn by typically reporting only the significant main or interaction effects.

Table 3.1.

Descriptive Statistics across Skill and Age when Facing Blocked-Straight Trials

		Across all ball-lengths		Full		Good		Short	
		Adult	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**
Batting performance									
%Good Bat-ball contacts	Skilled	90.4 ± 16.4	85.6 ± 16.9	86.5 ± 13.2	73.7 ± 23.6	91.7 ± 16.7	92.2 ± 12.5	93.1 ± 90.7	90.7 ± 14.7
	Club	64.7 ± 31.0	63.3 ± 31.0	63.3 ± 28.2	54.8 ± 32.9	72.5 ± 20.8	73.3 ± 22.5	58.3 ± 43.9	61.7 ± 37.5
%High FoBS	Skilled	47.8 ± 27.6	49.6 ± 28.8	66.0 ± 20.2	79.6 ± 16.7	18.6 ± 24.3	28.9 ± 38.2	58.8 ± 38.3	40.4 ± 32.6
	Club	35.4 ± 24.4	54.6 ± 30.1	65.2 ± 18.7	77.3 ± 24.0	12.5 ± 27.0	27.2 ± 32.4	28.7 ± 27.4	59.2 ± 33.8
Gaze and head tracking (deg)									
Gaze-Ball angle	Skilled	-0.1 ± 1.7	-1.2 ± 1.4	-0.5 ± 1.9	-0.8 ± 1.3	0.9 ± 1.9	-0.5 ± 1.1	-0.6 ± 1.5	-2.1 ± 1.8
	Club	0.6 ± 1.9	0.1 ± 1.9	1.0 ± 2.0	0.2 ± 1.9	0.7 ± 2.2	0.9 ± 1.8	0.2 ± 1.4	-0.7 ± 2
SD Gaze-Ball angle	Skilled	3.7 ± 2.5	3.7 ± 2.3	4.2 ± 3.4	2.6 ± 1.7	3.6 ± 2.6	3.1 ± 2.3	3.2 ± 1.4	5.4 ± 2.9
	Club	4.8 ± 2.6	3.5 ± 2.1	4.6 ± 2.2	3.2 ± 2.2	5.5 ± 2.7	3.3 ± 2.0	4.3 ± 3.0	3.9 ± 2.2
Gaze-Head angle	Skilled	-3.3 ± 2.1	-3.6 ± 2.4	-3.1 ± 2.4	-2.0 ± 3.1	-3.3 ± 1.6	-3.6 ± 1.6	-3.4 ± 2.3	-5.1 ± 2.5
	Club	-3.7 ± 2.3	-3.2 ± 1.4	-2.6 ± 2.9	-2.3 ± 1.8	-3.4 ± 2.0	-2.9 ± 1.0	-4.9 ± 1.9	-4.3 ± 1.3
SD Gaze-Head angle	Skilled	4.0 ± 1.9	5.4 ± 2.5	4.8 ± 2.7	4.6 ± 2.7	3.7 ± 1.8	5.0 ± 2.0	3.4 ± 1.2	6.5 ± 2.7
	Club	4.3 ± 2.6	4.4 ± 2.1	4.0 ± 2.8	4.2 ± 2.6	4.0 ± 2.9	3.3 ± 1.4	4.9 ± 2.0	5.7 ± 2.3
Head-Ball angle	Skilled	3.4 ± 2.3	2.8 ± 2.2	2.9 ± 2.7	1.8 ± 2.9	4.3 ± 2.3	3.4 ± 2.1	2.9 ± 2.1	3.0 ± 1.5
	Club	4.3 ± 2.6	3.2 ± 2.0	3.5 ± 2.8	2.4 ± 2.3	4.6 ± 2.9	3.7 ± 1.9	4.7 ± 2.5	3.4 ± 1.8
SD Head-Ball angle	Skilled	4.9 ± 3.2	3.6 ± 2.3	6.3 ± 3.8	4.1 ± 3.7	5.7 ± 3.8	4.3 ± 2.2	2.8 ± 2.0	2.4 ± 16.0
	Club	4.8 ± 2.9	3.8 ± 2.0	5.3 ± 2.9	4.5 ± 2.5	5.5 ± 3.7	4.3 ± 2.3	3.6 ± 2.1	2.7 ± 1.0
% Gaze$_{ahead}$	Skilled	53.0 ± 26.4	57.7 ± 24.5	61.5 ± 24.9	60.7 ± 28.7	47.8 ± 26.5	50.8 ± 20.9	49.7 ± 27.7	61.6 ± 24.0
	Club	45.3 ± 22.2	47.6 ± 30.1	44.5 ± 24.4	59.2 ± 31.1	41.2 ± 20.6	40.5 ± 33.6	50.1 ± 21.8	43.0 ± 25.6

Table 3.1 continued.

		Across all ball-lengths		Full		Good		Short	
		Adult	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**
Gaze at bat-ball contact									
%BBC$_{\text{fixation}}$	Skilled	41.3 ± 32.3	51.0 ± 30.1	34.1 ± 33.8	41.9 ± 35.9	26.1 ± 24.3	24.1 ± 34.5	63.6 ± 38.8	87.0 ± 20.0
	Club	26.0 ± 39.5	26.2 ± 25.8	25.6 ± 32.7	21.1 ± 26.6	25.9 ± 43.4	8.2 ± 16.3	26.7 ± 42.4	49.4 ± 34.6
%BBC$_{\text{lagging}}$	Skilled	26.3 ± 24.5	30.9 ± 29.5	29.6 ± 25.1	33.3 ± 31.2	40.3 ± 26.8	53.7 ± 40.6	9.1 ± 21.6	5.6 ± 16.7
	Club	49.9 ± 45.6	50.0 ± 32.7	48.5 ± 40.9	44.4 ± 34.6	52.4 ± 45.8	73.9 ± 28.3	48.9 ± 50.1	31.7 ± 35.1
%BBC$_{\text{Post-contact}}$	Skilled	31.4 ± 30.6	18.1 ± 27.9	36.4 ± 31.5	24.8 ± 31.6	33.6 ± 25.5	22.2 ± 37.3	24.2 ± 34.7	7.4 ± 14.7
	Club	24.0 ± 40.2	23.8 ± 30.5	25.9 ± 42.6	34.4 ± 33.2	21.7 ± 38.4	18.0 ± 25.8	24.4 ± 39.7	18.9 ± 32.5
Type of saccades (%)									
Saccade towards ball-bounce	Skilled	46.2 ± 33.0	49.2 ± 37.7	65.6 ± 29.6	63.0 ± 32.9	36.9 ± 36.2	38.3 ± 39.3	36.2 ± 33.3	46.3 ± 40.9
	Club	56.2 ± 45.4	34.2 ± 33.6	61.7 ± 44.5	46.3 ± 40.0	52.0 ± 46.7	26.8 ± 23.9	54.8 ± 45.1	29.5 ± 37.8
Saccade towards bat-ball contact	Skilled	20.9 ± 21.4	28.8 ± 25.3	0 ± 0	1.7 ± 5.3	19.0 ± 28.0	23.3 ± 33.5	43.9 ± 36.3	61.3 ± 37.3
	Club	13.3 ± 24.2	9.3 ± 14.9	0 ± 0	0 ± 0	22.5 ± 35.2	6.5 ± 14.2	17.5 ± 37.4	19.3 ± 25.0
Timing of saccade (following ball-release; ms)									
Saccade towards ball-bounce	Skilled	329 ± 42	325 ± 37	414 ± 34	399 ± 29	343 ± 67	343 ± 40	229 ± 25	234 ± 43
	Club	315 ± 52	316 ± 54	394 ± 42	416 ± 27	274 ± 49	319 ± 96	275 ± 65	212 ± 39
Saccade towards bat-ball contact	Skilled	407 ± 38	378 ± 36			500 ± 47	438 ± 28	492 ± 41	461 ± 37
	Club	436 ± 22	473 ± 12			445 ± 25	470 ± 14	427 ± 19	476 ± 9

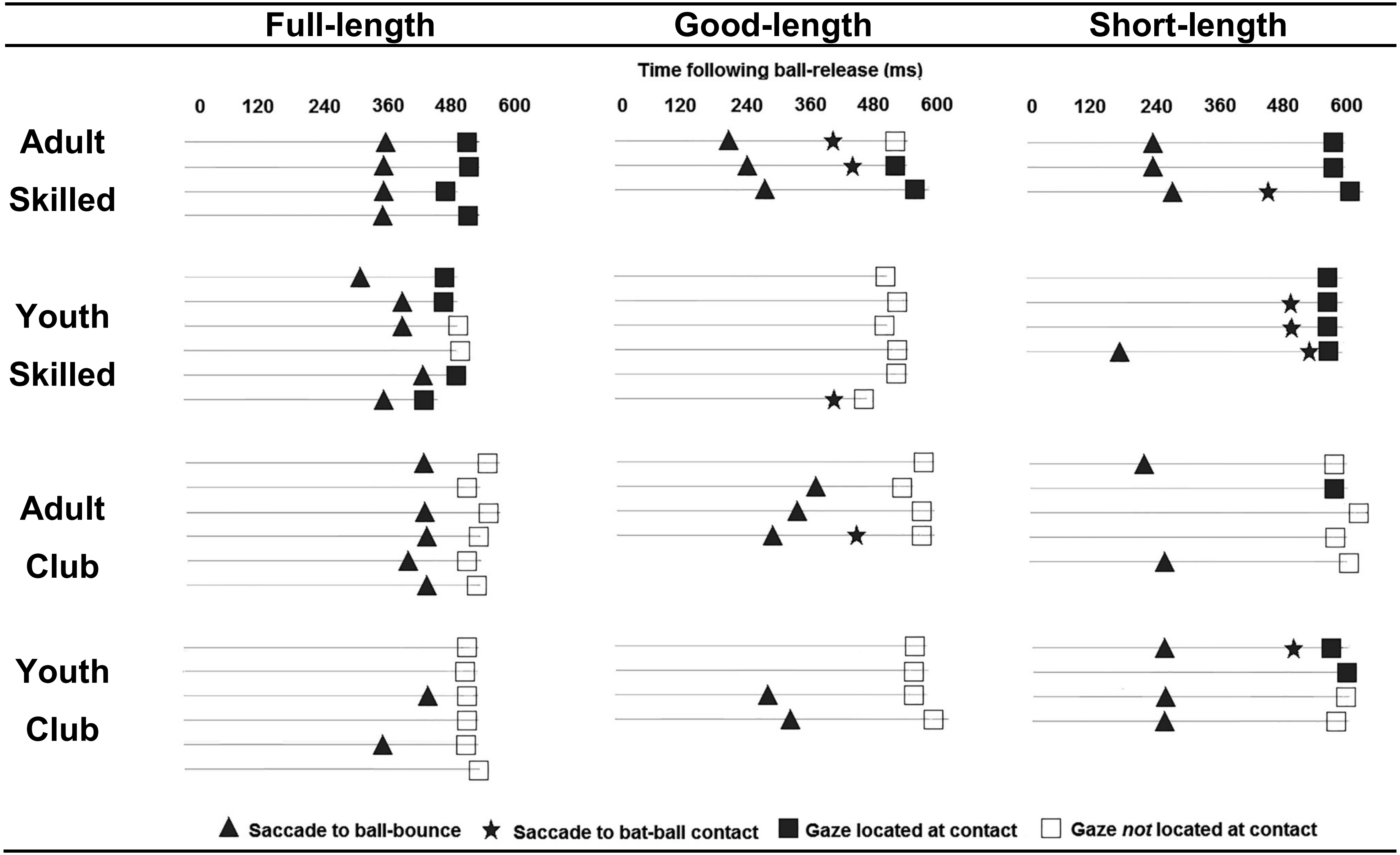

Figure 3.4. The saccadic behaviour on all of the trials for an exemplar batter from each of the four groups of batters. Each horizontal line represents a single trial. The timing of each gaze event is indicated relative to the moment of ball-release (ms).

3.4.1. Skill and Age Based Differences in Visual-Motor Behaviour

Here, the differences in batting performance and visual-motor behaviour between the batters of different skill and age levels across the three different ball-lengths are first established. A summary of the saccadic behaviour of an exemplar batter from each of the four groups of batters are presented in Figure 3.4. Note the differences in the timing and type of saccades initiated, and the location of gaze at the moment of bat-ball contact for each of the different ball-lengths.

3.4.1.1. Skill-related differences.

The skilled batters performed better than the club batters did. The skilled batters achieved a greater percentage of good bat-ball contacts than the club batters ($F(1, 37) = 24.51$, $p < .001$, $\eta_p^2 = .4$; skilled $M = 88.0\%$, $SD = 21.8$; club $M = 64.0\%$, $SD = 22.1$), while there was no difference in the forcefulness of bat-swing, with skilled and club batters showing no difference in the percentage of trials with a high FoBS score ($F(1, 37) = 0.35$, $p = .56$, $\eta_p^2 = .01$; skilled $M = 48.7\%$, $SD = 28.2$; club $M = 45.0\%$, $SD = 28.6$).

The findings from this study only supported a few of the key findings reported in previous studies of visual-motor control. Land and McLeod (2000) reported that skilled batters initiate their saccade towards ball-bounce earlier than less-skilled batters do. This was not the case in this study, with no difference in the timing of the saccades towards ball-bounce ($F(1, 18) = 1.96$, $p = .179$, $\eta_p^2 = .10$; skilled $M = 325$ ms, $SD = 28$; club $M = 310$ ms, $SD = 42$), or in the frequency of those saccades ($F(1, 39) = 0.09$, $p = .768$, $\eta_p^2 = .01$; skilled $M = 47.7\%$, $SD = 38.3$; club $M = 45.2\%$, $SD = 40.7$). An interaction was found between skill and ball-length for the timing of the saccades towards ball-bounce ($F(2, 36) = 3.95$, $p = .028$, $\eta_p^2 = .18$); however, the interaction appeared to be a result of the skilled batters initiating their saccade to ball-bounce *later* than the club batters did when facing the good-length trials (skilled $M = 343$ ms, $SD = 54$; club $M = 298$ ms, $SD = 78$; $p = .068$; $d = 0.66$), but not when facing the full-length (skilled $M = 408$ ms, $SD = 33$; club $M = 405$ ms, $SD = 36$; $p = .821$; $d = 0.08$) or short-length trials (skilled $M = 232$ ms, $SD = 34$; club $M = 249$ ms, $SD = 63$; $p = .355$; $d = 0.34$).

When examining gaze at the moment of bat-ball contact, Mann et al. (2013) reported that skilled batters were more likely to initiate a saccade towards bat-ball contact and to ensure gaze was directed towards the ball at contact. These results were supported in this study, with the skilled batters initiating more saccades towards bat-ball contact than the club batters (*F*(1, 39) = 5.06, *p* = .03, η_p^2 = .12; skilled *M* = 24.9%, *SD* = 19.8; club *M* = 11.3%, *SD* = 19.6), and the skilled batters were more likely to direct gaze towards the ball at the moment of bat-ball contact (*F*(1, 34) = 5.61, *p* = .024, η_p^2 = .14; skilled *M* = 46.1%, *SD* = 26.0; club *M* = 26.1%, *SD* = 25.9). When compared across all ball-lengths, the gaze of the club batters was more likely to lag behind the ball at the moment of bat-ball contact than the skilled batters' (i.e., % BBC$_{\text{lagging}}$, *F*(1, 34) = 5.73, *p* = .022, η_p^2 = .14; skilled *M* = 28.6%, *SD* = 40.8; club *M* = 50.0%, *SD* = 39.8). These differences were however superseded by interactions with ball-length (i.e., skill x ball-length interaction for percentage of saccades towards bat-ball contact, *F*(2, 78) = 7.51, *p* = .001, η_p^2 = .16 and for % BBC$_{\text{fixation}}$, *F*(2, 68) = 3.565, *p* = .034, η_p^2 = .1; Figure 3.5). The skilled batters initiated more saccades to bat-ball contact than the club batters when facing the short-length trials (*p* = .003; *d* = 1.0), but not when facing the good-length (*p* = .552; *d* = 0.18) or full-length trials (*p* = .357; *d* = 0.29). Similarly, the skilled batters directed their gaze towards the ball at contact more frequently than the club batters did when facing the short-length trials (*p* = .009; *d* = 0.88), but not when facing the good-length (*p* = .238; *d* = 0.37) or full-length trials (*p* = .309; *d* = 0.32).

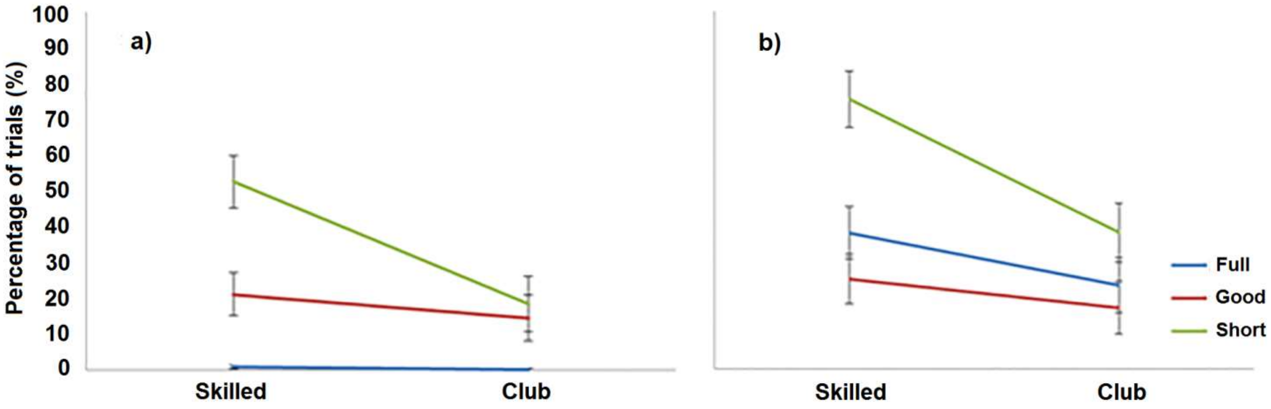

Figure 3.5. Mean group-based differences for a) percentage of saccades towards bat-ball contact and b) % BBC$_{\text{fixation}}$ as a function of ball-length across the batter's skill level. Data are displayed with standard error bars.

Mann et al. (2013) reported that skilled batters were more likely to egocentrically track the ball than lesser-skilled batsmen were, however this was not supported in this study (i.e., head-ball angle, *F*(1, 37) = 0.99, *p* = .327, η_p^2 = .03; skilled *M* = 3.1 deg, *SD* = 2.9; club *M* = 3.7 deg, *SD* = 3.0).

On average, the skilled batters directed their gaze further ahead of the ball than the club batters (i.e., gaze-ball angle, *F*(1, 37) = 5.15, *p* = .029, η_p^2 = .12; skilled *M* = -0.6 deg

SD = 2.0; club *M* = 0.4 deg, *SD* = 2.0). Furthermore, the adult skilled batters were found to coordinate their eyes and head in a manner that was unique to that of the other group of batters. A three-way skill x age x length interaction for gaze-head angle ($F(2, 74) = 3.64$, $p = .031$, $\eta_p^2 = .09$; Figure 3.6) revealed that only the adult skilled batters maintained a similar gaze-head angle across all ball-lengths ($p = .89$, $\eta_p^2 = .01$). In contrast, the other groups moved their gaze progressively further ahead of their head direction as the ball bounced further away from them ($ps < .012$, $\eta_p^2s > .57$). The findings suggest that the adult skilled batters account for the different ball-lengths by the coordinated movement of both their eyes *and* head; whereas the remaining batters may do so by the more independent rotation of either the eyes *or* head.

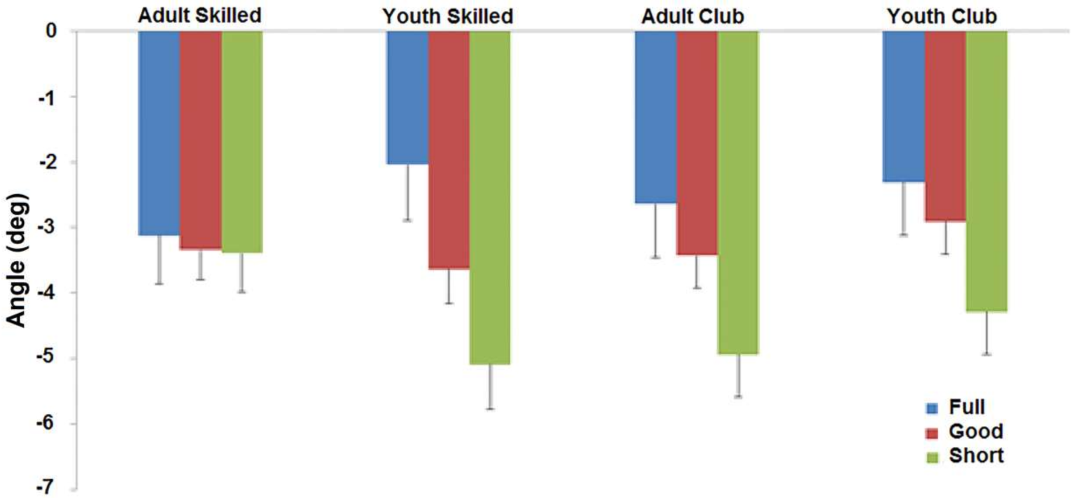

Figure 3.6. Mean differences for gaze-head angle as a function of ball-length across the batter’s skill and age group. Data are presented with standard error bars.

3.4.1.1.1. Discriminant function for skill.

A stepwise discriminant function analysis was performed, following a MANOVA, to determine which variable(s) most strongly discriminated between skill levels and how accurately group membership could be predicted. When collapsed across all ball-lengths, a significant discriminant function equation was derived for the prediction of skill ($D = -1.5 + 0.04 * [\% BBC_{lagging}]$; $F = 5.57$; $df\,(1, 38)$; $p = .024$; group centroids: skilled = -0.36, club = 0.39). The sole predictor in the model was the ability to align gaze with the ball at the moment of bat-ball contact (see Mann et al., 2013). The model accurately predicted 71.4% of cases with 86.4% of skilled and 55.0% of club batters categorised correctly. Cross validation revealed successful classification of skill levels did not change.

3.4.1.2. Age-related differences.

The age of the batters did not influence their batting performance as measured by either the percentage of good bat-ball contacts (*F*(1, 37) = 0.42, *p* = .519, η_p^2 = .01; adult *M* = 77.6%, *SD* = 21.1; youth *M* = 74.4%, *SD* = 22.7) or the percentage of trials with high FoBS (*F*(1, 37) = 2.80, *p* = .103, η_p^2 = .07; adult *M* = 41.6%, *SD* = 27.4; youth *M* = 50.1%, *SD* = 29.4). With age, the batter's ability to direct their gaze towards the ball at bat-ball contact did appear to change for certain ball-lengths (age x ball-length interaction for % $BBC_{fixation}$, *F*(2, 68) = 4.24, *p* = .018, η_p^2 = .11). Although the follow-up tests failed to reach significance, the interaction appeared to be a result of the adult batters tending to *decrease* the proportion of trials where gaze was directed towards the ball at contact when facing short-length trials (*p* = .141, *d* = 0.48), but not for good-length (*p* = .555, *d* = 0.18) or full-length trials (*p* = .824, *d* = 0.07). However, there were no other differences in the visual-motor behaviour of batters across age, consistent with the hypothesis that skill-based differences in gaze behaviour would be evident by late adolescence and not change with age.

3.4.1.2.1. Discriminant function for age.

A significant discriminant function equation was not derived for the discrimination of age as the MANOVA analysis failed to find any variables that significantly differed across the age groups.

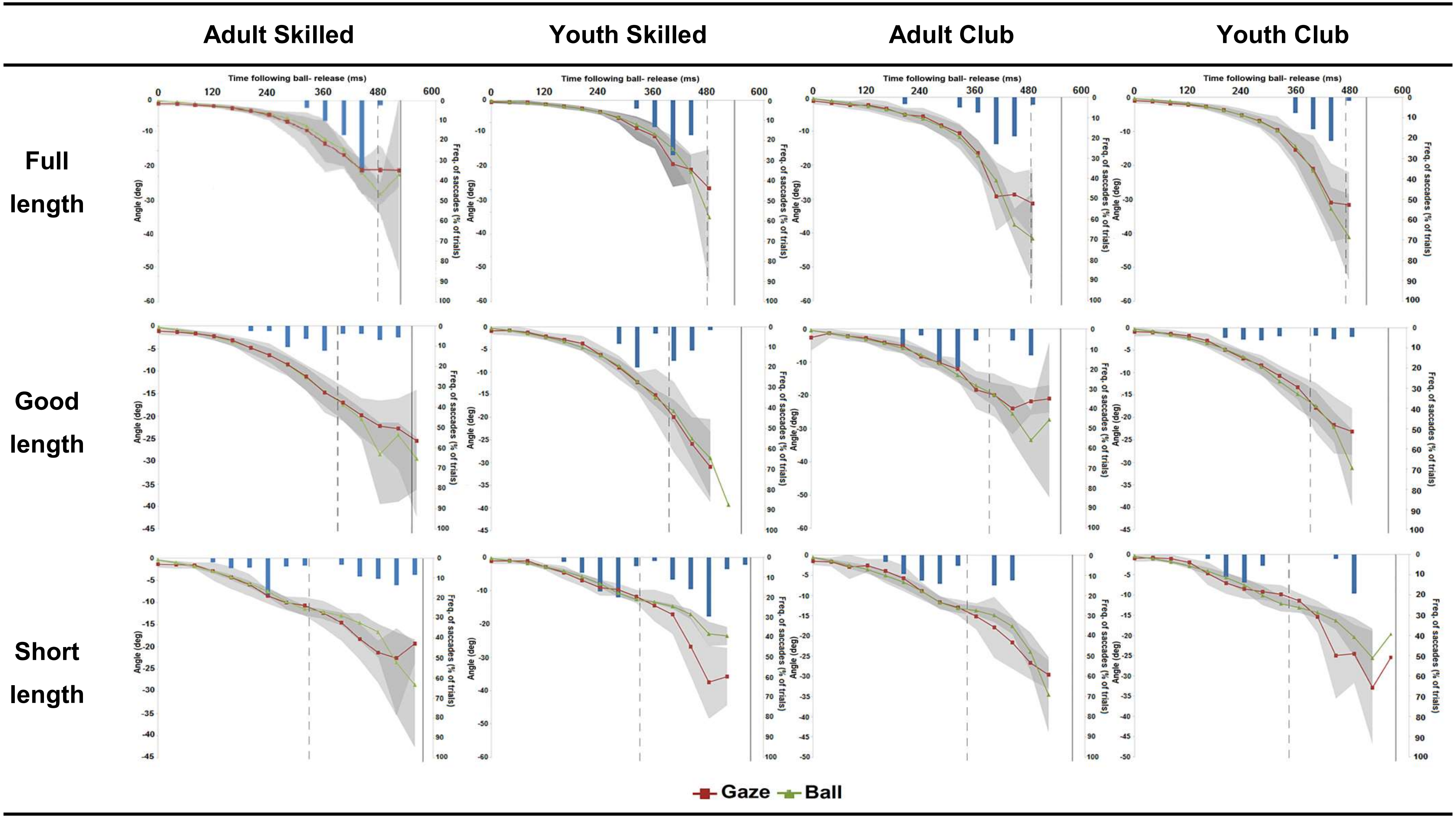

Figure 3.7. Mean direction of gaze relative to the ball across all batters. Each graph illustrates (i) the mean vertical gaze and ball angles (red and green lines respectively), and (ii) for each moment in time, the percentage of trials where a saccade to ball-bounce and/or saccade to bat-ball contact was performed. The shaded area represents the standard deviation across trials, the broken black line indicates the mean time of ball-bounce, and the solid black line indicates the mean time of bat-ball contact.

3.4.2. Effects of Ball-Length

In this section, the main effects for ball-length are reported along with any remaining interaction effects to determine whether changes in the location of ball-bounce significantly influenced the batting performance and the eye and head movements of the batters.

The length of the trials influenced the forcefulness with which the batters swung their bat ($F(2, 74) = 40.77$, $p < .001$, $\eta_p^2 = .52$)[13]. Batters were most aggressive when facing the full-length trials ($M = 72.0\%$, SD = 20.1; *p*s < .001 when compared to good-length and short-length trials), followed by the short-length ($M = 46.7\%$, $SD = 33.7$; $p < .001$ when compared to good-length trials), and then the good-length trials ($M = 21.8\%$, $SD = 30.6$). Nonetheless, there were no significant differences in the percentage of good bat-ball contacts across the three ball-lengths, though the effect did approach significance ($F(2, 74) = 2.72$, $p = .073$, $\eta_p^2 = .07$; full $M = 69.6\%$, $SD = 25.2$; good $M = 82.4\%$, $SD = 18.7$; short $M = 75.9\%$, $SD = 31.3$).

The ball-length significantly altered the saccades performed while batting. Not surprisingly, there was a significant difference in the *timing* of the saccades to ball-bounce for the different ball-lengths ($F(2, 36) = 47.67$, $p < .001$, $\eta_p^2 = .73$), with batters initiating their saccades earliest when facing short-length trials ($M = 244$ ms, $SD = 47$), then on good-length trials ($M = 311$ ms, $SD = 61$), and latest on full-length trials ($M = 398$ ms, $SD = 38$; all *p*s < .01 for follow-up tests). There were no differences in the timing of the saccades towards bat-ball contact across the different lengths ($p = .993$). The *type* of saccades produced by the batters was also significantly influenced by ball-length. The ball-length altered the percentage of saccades towards ball-bounce ($F(2, 78) = 5.42$, $p = .006$, $\eta_p^2 = .12$), with batters producing more saccades when facing full-length trials ($M = 59.2\%$, $SD = 36.7$) compared to the good-length ($M = 38.5\%$, $SD = 37.6$; $p = .017$) and short-length trials ($M = 41.7\%$, $SD = 39.3$; $p = .04$). There was no difference in the percentage of saccades to good-length and short-length trials ($p = 1.0$). As Figure 3.7 shows, this led to

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[13] An additional analysis was performed to determine whether the differences in the eye and head movements of batters were the result of different ball-lengths or because of the forcefulness of bat-swing. Analysis of high and low FoBS scores (i.e., 2 vs. 1 & 0) was performed, instead of individual scores (i.e., 2 vs 1 vs 0), to ensure a good representation of all lengths were assessed. The results showed that very few length-based differences were influenced by variations in the batter's forcefulness of bat-swing, suggesting that the differences in the eye and head movements of batters were a result of the ball-length rather than the variations in the FoBS associated with those ball-lengths.

the batters directing their gaze ahead of the ball for a larger proportion of ball-flight when facing full-length trials (% $\text{Gaze}_{\text{ahead}}$, $F(2, 74) = 6.13$, $p = .003$, $\eta_p^2 = .14$; $M = 56.5\%$, $SD = 27.4$) compared to good-length trials ($M = 45.1\%$, $SD = 26.2$; $p = .006$). There were no differences when facing short-length ($M = 51.1\%$, $SD = 25.2$) compared to full-length ($p = .372$) and good-length trials ($p = .133$). There was also a three-way skill x age x length interaction for the percentage of time with gaze ahead of the ball ($F(2, 74) = 3.51$, $p = .035$, $\eta_p^2 = .09$). Although none of the between-group ANOVAs for each of the three ball-lengths approached significance (*p*s > .35), the source of the interaction appeared to be the lower percentage of time that the adult club batters spent with their gaze ahead of the ball when facing the full-length trials (adult skilled vs adult club, $p = .075$; when performing follow-up *t*-tests to compare groups for each length, *p*s > .12).

The ability to perform predictive saccades towards the location of bat-ball contact changed commensurate with the ball-length ($F(2, 78) = 28.47$, $p < .001$, $\eta_p^2 = .42$). Saccades towards bat-ball contact were mostly performed when facing short-length trials ($M = 35.5\%$, $SD = 34.8$), then good-length trials ($M = 18.3\%$, $SD = 29.8$; $p = .001$), with almost none performed when facing full-length trials ($M = 0.4\%$, $SD = 2.6$; all *p*s < .01 for follow-up *t*-tests; see Figure 3.5 for the interaction with skill). Not surprisingly then, batters were better able to co-locate their gaze with the ball at the moment of bat-ball contact when facing short-length trials ($F(2, 68) = 20.61$, $p < .001$, $\eta_p^2 = .38$; $M = 56.7\%$, $SD = 35.4$) compared to good-length ($M = 21.1\%$, $SD = 31.1$; $p < .001$) and full-length trials ($M = 30.7\%$, $SD = 32.7$; $p = .001$). However, there was no difference between full-length and good-length trials ($p = .195$), with batters being better able to track the ball up to the moment of bat-ball contact when facing full-length trials. The gaze of the batters was more likely to lag behind the ball at contact when facing the good-length trials ($F(2, 68) = 15.41$, $p < .001$, $\eta_p^2 = .31$; $M = 55.1\%$, $SD = 35.9$) when compared to both the full-length ($M = 39.0\%$, $SD = 33.1$; $p = .031$) and short-length trials ($M = 23.8\%$, $SD = 33.0$; $p < .001$). Batters were also more likely to lag behind the ball when facing full-length compared to short-length trials ($p = .046$).

The length of the trials also significantly influenced the relative movements of the eyes, head, and ball (Figure 3.8). On average, the degree to which gaze was located ahead of the ball (i.e., gaze-ball angle, $F(2, 74) = 9.70$, $p < .001$, $\eta_p^2 = .21$) was greatest when facing the short-length trials ($M = -0.8$ deg, $SD = 1.7$), was aligned with the ball in the full-length trials ($M = 0.0$ deg, $SD = 1.8$; $p = .033$) and behind the ball in the good-length trials ($M = 0.5$ deg, $SD = 1.8$; $p < .001$). No differences in gaze-ball angle were found between the good-length and full-length trials (p = .348). Ball-length also linearly altered the location of the batter's gaze relative to their head direction (i.e., gaze-head angle, (F(2, 74) = 22.03, p < .001, η_p^2 = .37), with gaze furthest ahead of the head direction when facing the short-length trials (M = -4.4 deg, SD = 2.0), followed by the good-length trials (M = -3.3 deg, SD = 1.6; p = .029), and finally the full-length trials (M = -2.5 deg, SD = 2.6; all ps < .05 for follow-up t-tests). The ability to egocentrically track the ball with the head was better when facing the full-length trials (i.e., head-ball angle, F(2, 74) = 11.84, p < .001, η_p^2 = .24; M = 2.6 deg, SD = 2.7) than it was when hitting the good-length (M = 4.0 deg, SD = 2.3; p < .001) and short-length trials (M = 3.6 deg, SD = 1.9; p = .012). No difference was found between the good-length and short-length trials (p = .289)[14].

3.4.2.1. Discriminant function for different ball-lengths.

A significant discriminant function equation for the prediction of ball-length was derived (D = -5.13 - 0.08 * [*gaze-ball angle*] - 0.02 * [*percentage of saccades towards bat-ball contact*] + 16.74 * [*timing of saccade towards ball-bounce*] + 0.01 * [*% $BBC_{lagging}$*]; F = 8.0; *df* 8, 140; p < .001; group centroids: full = 1.81; good = -0.17; short = -1.75). The predictors in the model most likely to discriminate between the different deliveries were the ability to direct gaze ahead of the ball, initiate an earlier saccade to ball-bounce, produce more saccades towards bat-ball contact and align gaze with the ball; with batters most likely to achieve this behaviour when facing short-length trials compared to the other ball-lengths. The model accurately categorised 76.1% of trials, predicting 91.2% of full-length, 59.4% of good-length and 76.9% of short-length trials. Cross-validation revealed that successful classification of variables discriminating different length trails was maintained (71.7%), with 88.2% of full-length, 50.0% of good-length and 76.9% of short-length trials re-categorised correctly.

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[14] Seemingly minor main effects across ball-lengths were observed for the consistency in the batter's gaze-head angle (F(2, 74) = 3.94, p = .024, η_p^2 = .1; full M = 4.4 deg, SD = 2.7; good M = 4.0 deg, SD = 2.1; short M = 5.1 deg, SD = 2.1) and head-ball angle (F(2, 74) = 11.67, p < .001, η_p^2 = .24; full M = 5.0 deg, SD = 3.3; good M = 4.9 deg, SD = 3.2; short M = 2.9 deg, SD = 1.7). Furthermore, somewhat inconsequential age x length interactions for SD gaze-ball angle (F(2, 74) = 3.64, p = .031, η_p^2 = .09) and SD gaze-head angle, (F(2, 74) = 3.34, p = .041, η_p^2 = .08) suggest that although none of the between-group comparisons for the different ball-lengths approached significance for the SD gaze-ball angle (ps > .119, ds < .49), the consistency in the batter's gaze-head angle improved with age when facing short-length trials (p = .004, d = .94), but not full-length (p = .793, d = .08) or good-length trials (p = .807, d = .08).

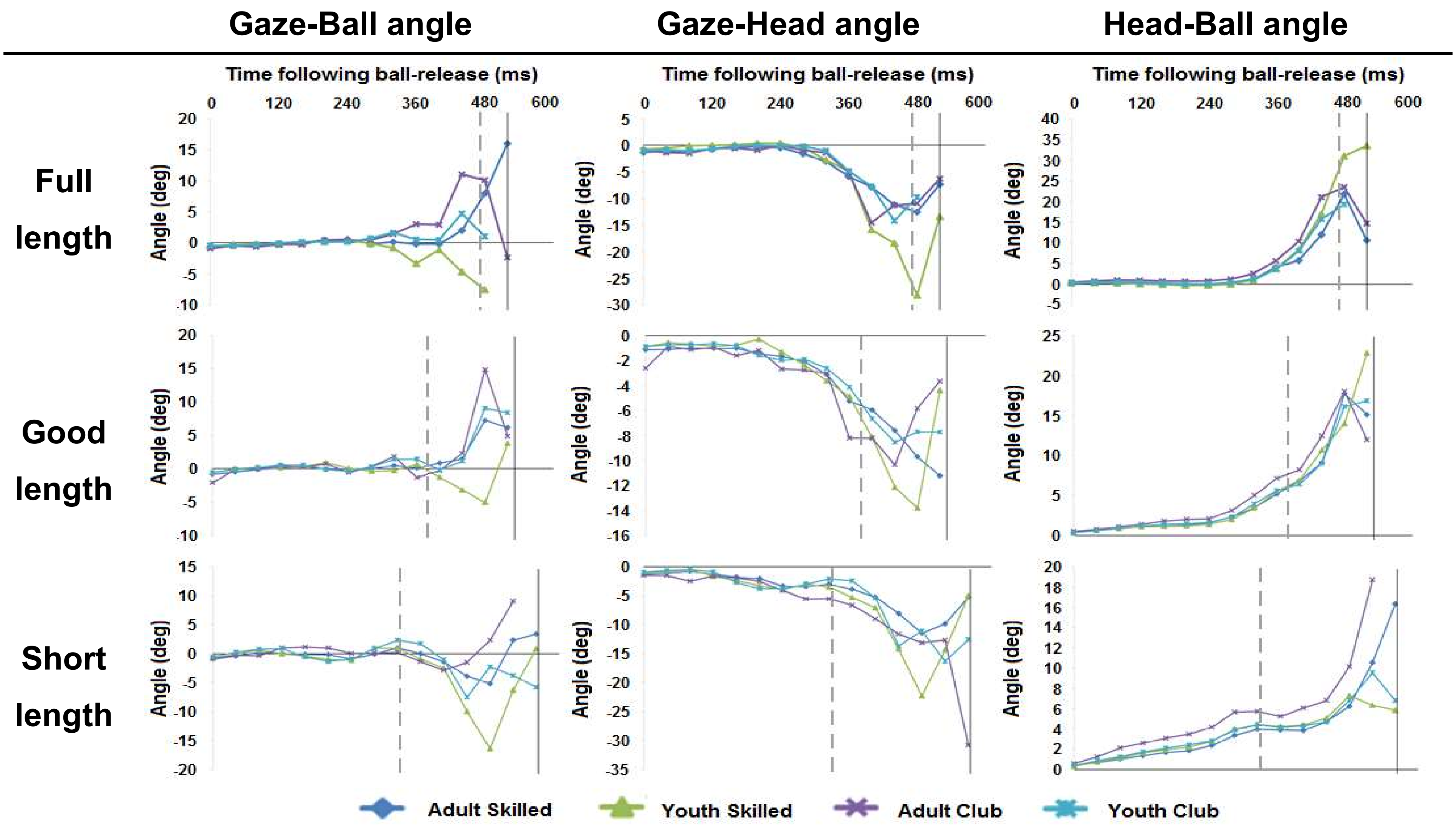

Figure 3.8. Comparisons of the mean (i) gaze-ball, (ii) gaze-head, and (iii) head-ball angles of the batters from the four groups across the different ball-lengths. The broken lines represent the mean time for ball-bounce and the solid line represents the mean time for bat-ball contact.

3.5. Discussion

The purpose of this study was to examine the eye and head movement strategies that underpin the development of visual-motor expertise when performing a fast-paced interceptive action. The eye and head movements of four groups of cricket batters, who systematically differed in their level of batting skill and/or age, were examined when hitting balls that followed a straight flight-path. Three broad hypotheses were made. First, skill-based differences in the eye and head movements of the batters were expected to be consistent with previous work, with skilled batters to demonstrate: (i) better batting performance, (ii) earlier saccades towards ball-bounce (Land & McLeod, 2000), (iii) more saccades towards bat-ball contact, (iv) gaze co-located with the ball at the moment of bat-ball contact, and (v) better egocentric head tracking of the ball (see Mann et al., 2013). Second, these skill-based differences in the visual-motor behaviour of the batters were expected to emerge by late adolescence and continue into adulthood. And third, skill-based differences were expected to be related to the location of ball-bounce, with differences in the batter's predictive ability and interceptive performance to be more evident when facing good-length deliveries compared to the other ball-lengths.

3.5.1. Visual-Motor Strategies as a Function of Skill

The overall findings from this study provide support for only some of those widely held beliefs about skill-based differences in gaze when intercepting a fast-moving target. This highlights the limitations of previous studies that have adopted case-study designs, as they may be too sensitive to individual differences in visual-motor control (e.g., Land & McLeod, 2000) and therefore may not accurately represent the visual-motor behaviour that exists across the wider population.

As expected, the batting performance of the skilled batters was clearly better than it was for the club batters. The quality of bat-ball contact, as a measure of the percentage of trials with good bat-ball contact, was clearly better for the skilled batters ($p < .001$), despite finding no difference in the forcefulness with which the batters attempted to hit the ball ($p = .56$). This supports the idea that the interceptive accuracy of the batters could sufficiently discriminate between groups of different skill levels (e.g., Chapter 2; Weissensteiner et al., 2011).

Contrary to the hypothesis, this study was not able to replicate the widely cited finding that skilled batters initiate earlier saccades towards ball-bounce than club batters (see Land & McLeod, 2000). In fact while there were no differences across skill for the full and short-length deliveries, the skilled batters tended to initiate their saccades *later* than the club batters when facing good-length deliveries. This is consistent with the idea that the skilled batters, when faced with the more challenging ball-length, waited for updated ball-flight information to more accurately predict the future location of the ball (Bootsma & van Wieringen, 1990). The difference in findings across the two studies cannot be explained by differences in the skill level of the batters, because the most skilled batter in the study by Land and McLeod was of state/provincial level (equivalent to the adult skilled group) and the lesser skilled betters were amateur/club level batters (equivalent to the adult club group). Rather, the results are probably best explained by either the simplified task design employed by Land and McLeod (i.e., facing a slower ball-speed with predictable ball trajectories), and/or by the failure of case-study designs to truly capture the behaviour seen across the wider population (see Sarpeshkar & Mann, 2011). These findings challenge the widely held assumption that skilled batters perform earlier predictive saccades when intercepting fast-moving targets (also see Mann et al., 2013).

The ability of batters to initiate a second anticipatory saccade towards bat-ball contact following ball-bounce (and to maintain gaze there when hitting the ball) have previously been shown to distinguish skilled from lesser-skilled performers (see Mann et al., 2013). The results from this study support the validity of these measures as key markers of batting expertise. The skilled batters performed more anticipatory saccades to bat-ball contact and were more likely to co-locate gaze with the ball at the moment of bat-ball contact, though both findings held primarily when facing the short-length deliveries. This supports the idea that skilled batters do whatever is necessary to direct their gaze towards the predicted location of bat-ball contact (Mann et al., 2013). By directing their gaze ahead of the ball prior to bat-ball contact, skilled batters could compare the predicted and actual ball-flight information to facilitate a more accurate estimation of the moment of bat-ball contact when compared to what is possible when simply tracking the ball (see Ripoll & Fleurance, 1988). This in turn may also promote successful interception through the continuous regulation of bat-swing as late as is permissible by the sensorimotor system (see Bootsma & van Wieringen, 1990). With the gaze of the club batters generally lagging behind the ball at the moment of bat-ball contact, it appears that the skilled batters have a better capacity to '*watch the ball onto the bat*' (accurately discriminating the skilled from the lesser-skilled batters in 71.4% of cases; see Mann et al., 2013).

Another key marker of batting expertise proposed by Mann et al. (2013) was that skilled batters were able to rotate their head in a fashion that allows them to maintain a constant alignment between the ball and their head (i.e., they reducing the position of the ball to a single egocentric direction). The results from this study however *do not* support this, with no difference in the head-ball angle found across the skilled and club-level batters. This difference could be explained by a difference in the skill level of the batters across the two studies. The two elite batters in the Mann et al. study were reported to be two of the world's best international-level batters, whereas there was much more variability in the skill level of the most highly skilled batters tested in this study (ranging from state/provincial to elite international-level batters). It may be that the low head-ball angle reported for the exceptional batters in the Mann et al. study is a behaviour seen in only the very best batters. This is not to say though that the batter's head direction does not play an important role in the tracking strategies of the batters. In fact, the results from this study suggest that only the adult skilled batters were able to coordinate the movements of their eyes *and* head direction when tracking the ball to maintain a similar gaze-head angle across all ball-lengths. This leads us to question what functional advantage this may provide. Previous studies suggest that this synergistic movement of the eye and head may reflect the performer's ability to predict how the target's flight-path is likely to unfold (e.g., Brown, 1990). This is consistent with the idea that with an accumulation of experience facing the different ball-flight trajectories, performers can better orchestrate the coordination of their head and eyes, allowing them to be better able to predict the future location of the target (also see Aivar, Hayhoe, Chizk, & Mruczek, 2005; Collins & Barnes, 1999). In other words, the development of learnt internal models of ball-flight characteristics may allow performers to adopt a flexible, yet specific coordination of the eye and head movement to prepare for the different ball-lengths (Diaz, Cooper, & Hayhoe, 2013; Hayhoe, McKinney, Chajka, & Pelz, 2012). As a result when tracking the ball, maintaining a similar gaze-head angle across all ball-lengths may provide batters with a consistent reference frame from which to better predict where the ball is likely to bounce, and also more accurately predict where it is likely to arrive (e.g., Oudejans et al., 1999; Zaal & Michaels, 2003). In contrast, the other batters who tended to independently rotate the eyes and head, may be less certain of, and must otherwise predict, the future location of the ball when it bounces on different ball-lengths. With the coordinated movements of the eyes and head appearing to be a key characteristic to skilled performance, future studies examining the behaviour of the world's best batters can start to point to an important differentiation between the highly skilled and the truly exceptional batters. This can also help establish a foundation from which to examine whether training paradigms aimed to accumulate experience facing different ball-flight trajectories, and promote an effective coordination of the eyes and head, can improve batting performance.

3.5.2. Visual-Motor Strategies as a Function of Age

Consistent with the hypothesis of this study, there were very few differences in the visual-motor behaviour of the batters across the youth and adult age groups. If there were to be age-related differences in the batter's gaze behaviour, then this would suggest that a greater accumulation of experience and/or maturation was necessary for the development of expert-like gaze behaviour. However, the results show that almost all skill-based differences present in adulthood were evident by late adolescence, suggesting that these are skills that may be acquired early in development. Interestingly, no age-based differences were found in the interceptive performance of the batters (adult vs youth, *M* = 77.6% vs 74.4% respectively; *p* = .519). This suggests that the simplified measures of batting performance used here (and elsewhere) may be capable of discriminating gross differences in skill, but not in the more refined skills likely to be necessary for an elite youth batter to develop into an elite batter at the senior level of competition. While batters may have successfully hit the ball, little is known whether they were successful in scoring runs or decreasing the likelihood of dismissal; both factors which are critical when examining performance during cricket batting (see Mann et al., 2010b). Moreover, the adult batters may have developed higher-level cognitive strategies that are not measurable using the current experimental design. For example, one would expect the adult batters to have accumulated greater experience and developed learnt internal models of the different ball-flight trajectories to allow them to better predict where the ball will be in the future and ensure their bat coincides with the ball at the moment of arrival (e.g., Diaz, Cooper, & Hayhoe, 2013; Land & Furneaux, 1997). However, this expectation is an effect on average and one that may not hold true for all participants. Future studies may seek to develop a more comprehensive examination of interceptive proficiency that takes into consideration these objective performance-based measures to better determine whether expert-like interception is attainable early in development.

Collectively, the findings from this study suggest that key markers of expertise in gaze may potentially be useful for the purposes of talent identification. Although the differences in age between the groups of batters in this study may not be large enough to adequately examine the effects of age on the gaze behaviour of the batters, there is reason to believe that these findings can still have practical implications. Previous studies suggest that the most crucial time in the talent development pathway may be for batters of 16-20 years of age (e.g., Weissensteiner, 2008), and this represents the typical age group at which talent identification and development takes place (e.g., Côté, Ericsson, & Law, 2005). Considering that the youth batters in this study are representative of this age group, this suggests that the same markers used to discriminate skilled from lesser-skilled adult batters could prove to be a useful means of helping to discriminate skilled and lesser-skilled youth batters. This provides a fruitful opportunity for further studies to validate this approach as a potentially effective means of identifying talented young performers. This can be achieved by determining whether batters identified in this manner go on to achieve the same degree of batting success as the elite batters in this study.

3.5.3. The Influence of Ball-Length on Visual-Motor Strategies

Competitors in fast-ball sports (e.g., bowlers) often seek to vary the location of ball-bounce to gain an advantage over their opponents. The results from this study show that batters modulate the forcefulness with which they swing their bat in order to maintain consistency in their quality of bat-ball contact. The study placed no restrictions on the batter in terms of the type of shot they could play and so it was possible for a batter to swing their bat aggressively or defensively to the same trajectory of ball-flight; ultimately influencing the amount of time the bat was optimally positioned to achieve good bat-ball contact. Batters swung their bat more forcefully when facing full-length deliveries compared to the other ball-lengths. As the ball would bounce later in flight (and also closer to their position compared to the other ball-lengths), the batters could hit the ball immediately following ball-bounce, thus (i) minimising the likelihood of missing the ball as a result of unexpected deviations off the playing surface, and (ii) using a larger lever arm they could still hit the ball in the most advantageous part of the bat (see Sarpeshkar & Mann, 2011; Weissensteiner et al., 2011). In contrast, when facing deliveries that bounced further away from them, batters decreased their aggressiveness and thereby decreased the spatio-temporal precision required to hit the ball. This allowed them to maintain their quality of bat-ball contact when facing the more challenging ball-lengths.

The findings from this study help to explain why good-length trials represent the most challenging type of delivery to face when batting in cricket (see Bradman, 1958; Woolmer et al., 2008). The forcefulness of bat-swing was lowest for all batters when facing this ball-length, presumably to ensure that batters could maintain a reasonable level of bat-ball contact. Batters performed the least number of saccades to ball-bounce when hitting the good-length trials and the skilled batters tended to initiate their saccade to ball-bounce *later* than the club batters did when facing the good-length deliveries. As mentioned earlier, they may have done so in an attempt to sample more of ball-flight in these deliveries in order to overcome the challenges experienced when facing those deliveries. Gaze was also found to lag behind the ball most when facing the good-length trials (mean gaze-ball angle was positive; Figure 3.8), and ultimately at the moment of bat-ball contact, gaze was more likely to lag behind the ball when facing those deliveries.

It was expected that good-length deliveries would be the ones most likely to discriminate the gaze of the batters of different skill levels. Based on the idea that those deliveries were the hardest to face, it was hypothesised that most skill-based differences in gaze would be found when batters faced the good-length trials. The results failed to support this hypothesis, with most skill-based differences found when facing the *short-length* trials. Overall, the batters of all skill levels did tend to exhibit more ‘expert-like’ gaze behaviour when facing short-length deliveries (lowest gaze-ball angle, most saccades to bat-ball contact, most trials where gaze was directed towards the ball at contact; e.g., Mann et al., 2013). However it was also on these trials that the gaze of the skilled batters could be best discriminated from that of the club batters. The skilled batters performed significantly more saccades to bat-ball contact and ultimately were more likely than the club batters to ensure gaze was directed towards the ball at contact. Considering the longer duration of time between ball-bounce and bat-ball contact when facing short-length deliveries (compared to the other ball-lengths), locating gaze ahead of the ball may provide batters with a functional advantage that allows them to better detect, and correct for, unexpected deviations in the ball’s flight-path (see Hayhoe et al., 2005; Mann et al., 2013). Evidently, it is the short-length deliveries that best discriminate batters of different skill levels.

Although the skilled batters were not found to use more accurate head-ball coupling than the club batters in this study (*cf*. Mann et al., 2013), the location of ball-bounce was found to significantly influence this coupling. Both the skilled and club-level batters were better able to couple the direction of their head to the ball when facing the full-length deliveries. It may be that batters find it easier to head-track the ball in those trials because of the lower rate at which the vertical height of the ball changes during its flight (see Brouwer, López-Moliner, Brenner, & Smeets, 2006). Coaches commonly advocate that batters should rotate their head downwards along the flight-path of the ball and follow the adage to '*hit the ball under your eyes*' to promote successful interception (e.g., Bradman, 1958; Cricket Australia, 2005; Woolmer et al., 2008). Head tracking was best when facing the full-length deliveries, meaning that gaze too would have been most closely aligned with the ball if batters only moved their head and kept their eyes still relative to their head. However, batters were found to initiate the *most* anticipatory saccades to ball-bounce when facing those deliveries. It appears that this strategy allowed them to best ensure they could watch the ball at contact. It was seen that almost no saccades to bat-ball contact were performed when facing the full-length trials, yet they were still able to align gaze with the ball at contact by tracking the ball for the short period of time from ball-bounce to bat-ball contact.

Future studies may seek to extend on these findings by exploring how robust the visual-motor strategies of skilled performers are to other strategies used by opponents to gain an advantage. One example would be to examine the influence of curved (or swinging) flight-paths on the visual-motor behaviour of the performers to determine whether the same strategies that underpin the successful interception of a target that follows a straight flight-path would also promote successful interception when the target follows a swinging flight-path. A more comprehensive understanding of visual-motor expertise in interception could be established by determining how skilled batters account for the continuous deviations of the target in its flight as it curves through the air.

3.6. Conclusion

The eye and head movements of cricket batters of different skill and age levels were examined to determine the strategies that underpin the development of visual-motor expertise when performing a fast-paced interceptive action. The overall findings of this study supported only some of the existing markers of visual-motor expertise that have been found largely on the basis of case-study designs (*viz*. directing gaze ahead of the ball, predictive saccades towards bat-ball contact, and maintaining gaze at that location when hitting the ball). However, the results from this study failed to support the claim that skilled batters perform earlier saccades or that they are better able to egocentrically track the location of the ball, highlighting the limitation of previous case-study examinations in accurately representing the visual-motor behaviour of the wider population. Those differences that were found as a result of skill were present by late adolescence and continued into adulthood, demonstrating that these skills may be acquired early in development. The location of ball-bounce significantly influenced the visual-motor behaviour of the batters, with skill-based differences most evident when facing short-length deliveries at the final moments leading up to bat-ball contact. Moreover, the batter’s ability to account for the different ball-lengths by the coordinated movement of their eyes *and* head appears to be a key hallmark of visual-motor expertise.

CHAPTER 4

VISUAL-MOTOR ADAPTATIONS IN THE PRESENCE OF BALL-SWING WHEN PERFORMING A DYNAMIC INTERCEPTIVE ACTION

Further to the findings from Chapter 3, the second paper in the examination of the batter’s gaze behaviour seeks to explore whether the visual-motor strategies that underpin successful interception when hitting a straight ball also promotes successful interception in the presence of ball-swing. As a result, this chapter seeks to explore the eye and head movements of batters across skill and age when intercepting blocks of straight and swinging balls to determine the extent to which the *possibility*, *presence* and *direction* of ball-swing may influence the visual-motor behaviour of batters.

‘I have noticed even people who claim everything is predestined, and that we can do nothing to change it, look before they cross the road.’

Stephen Hawking

4.1. Abstract

To successfully intercept a fast-moving target in sport, performers need to obtain perceptual information from ball-flight that allows them to be positioned at the right place at the right time. Although existing studies reveal skill-based differences in the visual-motor behaviour of performers when intercepting a target that follows a *straight* flight-path, it is unclear whether the same strategies help performers to account for the increased spatio-temporal demands of intercepting a target that follows a *curved* (or *swinging*) flight-path. The aim of this study was to examine the development of visual-motor expertise when hitting a ball in the presence of ball-swing. The eye and head movements of 43 cricket batters who systematically differed in their level of batting skill and/or age were examined when hitting both straight and swinging balls. The results showed that (i) the *possibility* of ball-swing significantly reduced the interceptive performance and predictive ability of the batters when hitting the straight balls, (ii) batters adapted their eye and head movements when the ball did swing but that these were insufficient to avoid a significant reduction in interceptive proficiency, and (iii) the direction of ball-swing significantly influenced both the interceptive performance and visual-motor behaviour of batters. Ball-swing elicited new markers of batting expertise, whilst also supporting others found when hitting straight balls. These differences were generally found to be present by late adolescence and sustained into adulthood. These findings shed new light on the strategies that underpin successful interception in the presence of ball-swing, and help to foster a more comprehensive understanding of the development of visual-motor expertise in interception.

4.2. Introduction

Successful interception demands the coordination of visually guided movements that position the end effector so that it coincides with the future arrival location of a target, often doing so with remarkable spatio-temporal precision (Tresilian, 2005). Examining these behaviours in an environment where the spatio-temporal constraints of the task often push the boundaries of human achievement, such as in fast-ball sports, presents an ideal opportunity to examine the visual-motor strategies that underpin successful interception (Regan, 1997; Walsh, 2014; Warren, 1988). Although previous studies report skill-based differences in the visual-motor behaviour of performers during interception, these differences are generally observed when the target follows a straight trajectory towards the performer. However, very little is known about the ability of performers to adapt their behaviour when faced with more complex ball-flight trajectories. For instance, it is not uncommon for opponents in fast-ball sports to seek to gain an advantage by manipulating the ball's flight-path so that it follows a curved (or *swinging*) trajectory (see Chapter 2). The increased spatial and temporal demands imposed by swinging ball-flights can drive the performer to misperceive the future location and/or time of arrival of a target, for instance when a baseball pitcher throws a curveball or when a soccer free-kick is bent through the air (Chapter 2; Craig et al., 2011; Craig et al., 2009; Port et al., 1997). As a result, examining how performers might account for the increased spatio-temporal demands of hitting a swinging target can shed new light on the development of visual-motor expertise and the strategies that underpin successful interception (see Sarpeshkar & Mann, 2011).

Previous studies of the gaze strategies relied on by skilled performers during an interceptive action reveal a unique sequence of eye movements that direct gaze ahead of the ball to predict its future location in flight. Particularly, performers are known to rapidly shift their gaze ahead of the target, using what is termed an *anticipatory saccade* (see Bahill & LaRitz, 1984; Chapter 3; Land & McLeod, 2000; Mann et al., 2013). For example, the landmark study by Land and McLeod (2000) revealed that cricket batters initially track the ball following ball-release before rapidly shifting their gaze ahead of the ball towards the predicted location of ball-bounce, and then attempt to loosely track the ball for the remainder of ball-flight prior to bat-ball contact. Mann et al. (2013) recently added that truly elite performers (in that instance, two of the world's best cricket batters) not only produced an anticipatory saccade towards ball-bounce, but also produced a second anticipatory saccade towards the likely location of bat-ball contact, maintaining gaze at that location until they hit the ball. It may be that by directing their gaze ahead of the ball prior to bat-ball contact, batters could gain a better estimation of the moment of contact as they can monitor the ball’s flight-path using their peripheral vision and make fine adjustments to their bat-swing as late as is permissible by the sensorimotor system (Bootsma & van Wieringen, 1990; Ripoll & Fleurance, 1988). The elite batters in the study by Mann et al. (2013) were also found to use their eyes to guide their head to effectively track the ball. By reducing the position of the ball to a single egocentric direction (i.e., maintaining a constant alignment between the ball and their head), it was proposed that the batters could better predict where the ball was likely to arrive (see Lee et al., 1983; Oudejans et al., 1999; however for a contrary argument, see Chapter 3). Collectively, these elite batters may have developed a simple, yet elegant means by which to account for the severe spatio-temporal constraints imposed by the interceptive task inherent in many fast-ball sports.

Knowledge of the skill-based differences in the eye and head movements of performers has progressed our understanding of the visual-motor strategies that underpin successful interception. However, this behaviour is primarily observed when intercepting a target that follows a *straight* flight-path and it is not clear whether the same strategies underpin the successful interception of a target that follows a *swinging* flight-path. Swinging flight-paths arise as a result of pressure differentials created by an imbalance in the airflow around an in-flight object that is either spinning (as is the case for a curving soccer ball) or has contrasting surface textures (such as the shiny and rough sides of a swinging cricket ball; for a comprehensive overview, see Mehta, 2009). This pressure differential generates an additional force perpendicular to the object’s flight-path, causing it to deviate laterally in the direction of lower pressure (i.e., Magnus forces; for more information, see section 1.3.1; Mehta, 1985; 2009; Walker, 1999). As a result, a critical distinction required when intercepting swinging targets, compared to a straight target, is that performers need to account for the continuous lateral deviation in flight-path when predicting the future location of the target. In other words, performers need to obtain perceptual information from ball-flight that allows them to prospectively guide the position of the end effector (e.g., hands or bat) on the basis of the changing heading direction of the target to ensure that their position coincides with the future arrival location of the target (also see Casanova et al., 2015; Montagne et al., 1999; Peper et al., 1994). This is clearly a challenging task. Craig et al. (2011) recently showed that the interceptive proficiency of recreational soccer goalkeepers in an immersive virtual-reality environment was poorer when attempting to stop a curving ball when compared to a ball that followed a straight flight-path (15% vs. 57% respectively). Similarly, Chapter 2 showed that cricket batters found it more difficult to hit swinging balls *in situ* when compared to straight balls (49% vs. 71% respectively). This suggests that the informational variables (*viz*. changes in target size and bearing angle) that allow performers to accurately predict the future arrival location of a target that follows a straight flight-path may be less reliable when the target is swinging (Craig et al., 2009; Port et al., 1997). This has collectively led to the hypothesis that fundamental limitations within the visual system may restrict the performer's ability to account for the continually changing trajectory of a swinging target, helping to explain the poorer interceptive performance against swinging deliveries (Craig et al., 2006; Craig et al., 2009; Port et al., 1997).

Given the proposal of a fundamental limitation in the ability of the visual system to predict the future location of targets that follow a swinging trajectory, it is surprising that very few studies have examined the strategies adopted when attempting to intercept those trajectories. Chapter 2 showed significant differences in the *kinematic* behaviour of cricket batters when intercepting targets that followed a mixture of straight and swinging flight-paths. Particularly, swinging balls were associated with batters significantly delaying the timing of key kinematic moments (and ultimately hitting the ball later) to presumably sample more of the ball-flight to assist interceptive performance. It was also found that the *direction* of ball-swing significantly influenced not only performance, but also the timing and coordination of movement irrespective of the skill and/or age of the batters. Specifically, targets that swung *away* from the batter were more difficult to hit compared to targets that swung *in* towards the batter, with performance against these in-swinging targets found to be no different to when hitting the targets that followed a straight flight-path. It was hypothesised that as the ball was more likely to be aligned with the batter's eyes and head (as it travelled along the mid-sagittal plane of the batter) for the majority of the ball-flight, batters would find it more difficult when the ball swung away to detect both the approach angle of the ball (Welchman et al., 2004) and the rate at which the ball was deviating laterally (Diaz et al., 2009). Collectively, performers may find it more difficult to predict the future location of a target that follows a swinging flight-path and that this too may alter gaze, resulting in a reduced likelihood of gaze being directed ahead of the target prior to bat-ball contact.

Another remarkable observation from Chapter 2 was that the *possibility* of ball-swing had a profound impact on the kinematic behaviour of batters when hitting targets that did not swing. When compared to the straight balls that were presented in a blocked fashion, the simple knowledge that the ball *could* swing significantly changed the batters' coordination of movement, resulting in batters moving further forward to hit the ball soon after it bounced (to minimise the likelihood of missing the ball as a result of lateral deviations after ball-bounce). This suggests that the range of possible outcomes (i.e., straight or swinging trajectories) can influence the way the action is performed (see Gray, 2002; Tijtgat et al., 2010; Todorović, 2010). It may be that the presence of ball-swing would also significantly influence the gaze of performers when attempting to hit not only a swinging flight-path, but also a *straight* one. As a result, differences in gaze when facing balls that follow a straight trajectory may also be expected if there is the possibility that the ball could follow a swinging trajectory.

In relation to the gaze of the performers when hitting a swinging target, there is reason to believe that adaptations in gaze behaviour may allow performers to account for a lateral deviation in ball-flight. Viviani et al. (1977) revealed that performers were able to incorporate a lateral component to their saccades when shifting their gaze between two distinctive locations in a virtual environment (i.e., '*oblique saccades*'; also see Smit, Van Opstal, & Van Gisbergen, 1990). Mrotek and Soechting (2007) also observed that when a section of a target's swinging trajectory was briefly occluded in a virtual environment, performers accounted for the target's curvature and produced a saccade towards the predicted location from where the target was likely to re-emerge. Although this behaviour has not yet been reported when intercepting a target *in situ*, it is consistent with the idea that performers may be able to utilise existing memory representations to shift their eyes to the anticipated location of the target through the shortest possible route (see Becker & Jürgens, 1990; Diaz, Cooper, & Hayhoe, 2013). As a result, the superior anticipatory ability of the skilled performers may allow them to better account for the horizontal deviation in ball-flight through the use of oblique predictive saccades. If oblique saccades do help facilitate interceptive performance when hitting a swinging ball, then an increased prevalence of oblique saccades would be expected commensurate with increased skill when hitting a swinging ball. On the other hand, a visual strategy that does not account for the horizontal deviation in ball-flight would result in straight saccades that incorrectly anticipate where the ball is directed, and/or tracking eye movements (rather than saccades) that move gaze downwards in a straight direction. These behaviours could significantly influence the perception of the future arrival location of a target (famously the anecdotal reports by baseball batters of the 'sudden' break of a curveball; for more information, see Bahill & Baldwin, 2004; Shapiro et al., 2010; Sivak & MacKenzie, 1992).

As a result, performers would be expected to be less likely to direct their gaze ahead of the ball prior to bat-ball contact; behaviours that would ultimately be associated with poorer interceptive performance.

The aim of this study was to examine the development of visual-motor expertise when intercepting a fast-moving target in the presence of ball-swing. The eye and head movement strategies of four groups of cricket batters, who systematically differed in their level of batting skill and/or age, were examined *in situ* when hitting balls that were presented in (i) a block of straight flight-paths only, and (ii) a combination of straight and swinging flight-paths. Three broad hypotheses were made. First, the *possibility* of ball-swing (i.e., when facing the straight trials that were mixed with swinging trials) was expected to significantly alter the visual-motor behaviour of batters when hitting straight balls. Consistent with previous work (e.g., Gray, 2002), it was expected that the uncertainty in ball-flight would have a greater influence on the batting performance of the lesser-skilled batters, compared to the skilled batters, and also on their ability to direct their gaze ahead of the ball. Second, the increased spatio-temporal demands necessary to intercept targets that follow a swinging trajectory were expected to reduce the ability of all batters to predict the future location of the ball irrespective of their skill or age. Specifically, a reduction in the frequency of predictive saccades that direct gaze ahead of the ball towards ball-bounce and towards bat-ball contact were expected, leading to a decrease in the likelihood of gaze being directed towards contact when the ball was hit and ultimately resulting in more novice-like batting performance (Chapter 2; Craig et al., 2011). If oblique saccades provide a functional mechanism to facilitate the interception of swinging targets then an increased prevalence of oblique saccades was expected commensurate with increased skill. Third, the *direction* of ball-swing was expected to significantly influence the visual-motor behaviour and performance of all batters, with balls that swing *away* from the batter expected to decrease batting performance and result in more novice-like gaze behaviour when compared to balls that swing *in towards* the batter (Chapter 2).

4.3. Methods

4.3.1. Participants

A total of 43 male cricket batters took part in the study. Batters were categorised into one of four groups that differed according to their level of batting skill (‘skilled’ or ‘club’) and age (‘adult’ or ‘youth’). The *adult skilled* group (13 batters, $M_{\text{age}} = 25.1$ years, age range: 19-37) consisted of batters who had represented their state/province at a senior level (including four members of the Australian national squad at the time of testing). The *youth skilled* group (10 batters, $M_{\text{age}} = 17.7$ years, age range: 16-18) consisted of batters who had all represented their state/province at an under-19 and/or under-17 level (including four members of the Australian under-19s national squad at the time of testing). The *adult club* (10 batters, $M_{\text{age}} = 31.7$ years, age range: 26-39) and *youth club* groups (10 batters, $M_{\text{age}} = 21$ years, age range: 18-23) consisted of lesser-skilled recreational batters who played competitive club cricket in a local district competition. Prior to the commencement of the experiment, all batters provided informed consent to a protocol that was approved by the University ethics committee.

4.3.2. Experimental Design

The experiment took place at an indoor batting facility which replicated the dimensions and ball rebound characteristics of a synthetic cricket surface. A ProBatter ball-projection machine (PX-2-PB2005-87; ProBatter Sports, Milford, CT) was used to project balls towards the batters. It incorporates a life-sized video projection (Hitachi CP-X809 LCD projector, Tokyo, Japan) of a bowler shown on a screen (2.6 m x 3.5 m) that is synchronised with a ball machine so that a ball is projected through the screen at the moment the ball would be released by the bowler seen in the video footage (for more information on the ProBatter system, see Portus & Farrow, 2011; ProBatter Sports, 2015). A series of different video recordings of a particular bowler (recorded live during competition) was programmed into the ProBatter system so that the ball-flight seen for that delivery was similar to that actually bowled in the video footage, ensuring that any kinematic information in the bowler’s action matched the actual outcome of the ball flight (see Mann et al., 2013 for more information on the benefits of the ProBatter machine compared to a 'live' bowler and/or bowling machine). The distance of the machine from the batter (≈17.68 m), the height of ball-release from the ground (2.08 m [subtended angle of 6.66°]) and the approach angle of the ball (bearing angle of 1.94°) replicated those dimensions typically experienced during competition. At the moment of ball-release, a composite ball commonly used during training (Jugs Inc., Tualatin, Oregon) was projected through a hole in the screen at a velocity of ≈ 33 m.s^{-1} (119 km.h^{-1}). This ball-speed was chosen to be representative of a speed that would be encountered in competition but would also be safe for all participants. Batters used their own cricket equipment (i.e., leg and thigh guards, gloves and cricket bat) and were instructed to bat as they would during competition. That is, in a manner that would allow them to successfully score runs whilst also minimising the likelihood of being dismissed.

Prior to data collection, three distinct areas on the playing surface were selected (i.e., *lengths*) to represent common locations of ball-bounce relative to the stumps (*viz.* *full*, *good*, and *short* length trials), with the batters standing ≈1 m in front of the stumps. In the full-length trials (or *deliveries*), the ball bounced 3.5-4.5 m from the stumps, a bounce position that would typically require the batter to step *forward* to hit the ball. Good-length trials bounced 7.0-8.0 m from the stumps. This ball-length is commonly considered to be the most challenging position from which to hit the ball, as it typically causes indecision as to whether to step forward or backward to hit the ball (e.g., Bradman, 1958; Woolmer et al., 2008). In the short-length trials, the ball bounced 9.0-9.5 m from the stumps, typically requiring the batter to step *backward* to hit the ball (see Chapters 2 and 3; Pinder et al., 2011a). The arrival location of the ball was also manipulated according to one of two different *lines*, resulting in the ball arriving either close to, or away from the batter’s body. These variations in line only served to prevent the batter from anticipating the future location of the ball and were of no particular experimental interest.

Batters attempted to hit balls that did or did not swing in the air when the ball was in flight (from now on referred to as *swing* and *straight* trials respectively). To achieve ball-swing, sideward spin was imparted on the ball (for a similar technique, see Craig et. al 2011; 2006) to ensure that the ball swung either in towards (*inswing*), or away from (*outswing*) the batter’s body (see Figure 4.1).

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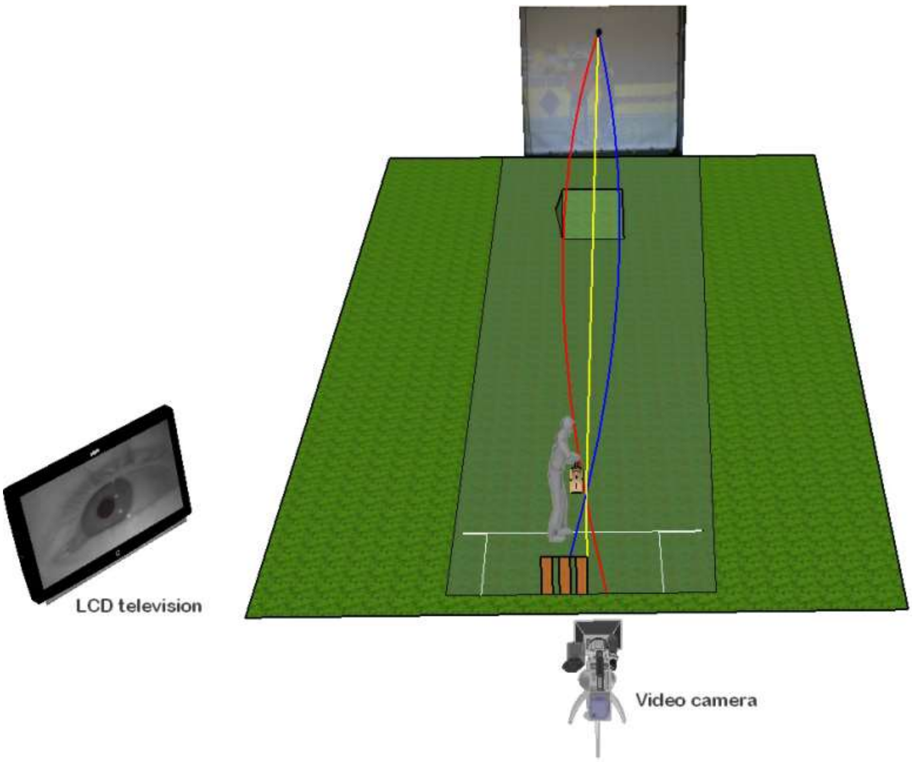

Figure 4.1. A schematic illustration of the direction of ball-swing during ball-flight. The red, yellow and blue lines respectively represent the out-swinging, straight, and in-swinging flight-paths experienced during the experiment. An LCD television was placed adjacent to the test area to monitor the eye tracking system, whilst a video camera located behind the batter helped to verify the moment of ball-release, ball-bounce and bat-ball contact when any of these events were not visible on the eye tracker footage.

4.3.3. Data Collection

A *Mobile Eye* monocular eye tracking system (25 Hz; Applied Science Laboratories, Bedford, MA) was fitted to the batters to record the direction of gaze while batting. The Mobile Eye footage was recorded on a portable video recording unit (Sony GV-D 1000 Portable MiniDV Video Walkman, ≈1 kg) that was housed in a lightweight pouch worn around the batter’s waist. To ensure that any disturbances to the camera were detected and corrected, a radio transmitter was also connected to the recording unit to wirelessly transmit the video footage to an LCD television screen located adjacent to the test area. Batters wore a customised helmet that had a portion of the brim removed to allow sufficient space for the eye tracker camera. Calibration of the eye tracker was performed using predetermined locations in the visual field with the batter adopting their usual batting stance. Recalibration of the eye tracker was performed prior to, and after the completion of each condition, or if the unit was deemed to have been disturbed.

An event-synchronised MiniDV video camera (Sony HDR-FX1000, Tokyo, Japan; 25 Hz) was also positioned behind the batter and was used for the synchronisation of the eye-movement footage with the moment of ball-release, ball-bounce, and/or bat-ball contact when any of these events were not clearly visible on the eye tracker footage.

4.3.4. Procedure

Prior to data collection, a short warm-up period (≈10-15 deliveries) was provided for the batters to familiarise themselves with the ProBatter machine, the eye tracker and the range of trials they were to face in the experiment. During the experiment proper, participants faced two separate blocks of trials that were counterbalanced across participants: (i) straight trials only and (ii) a combination of straight and swinging trials. In the straight only (*blocked-straight*) trials, the participants faced 18 trials that followed a straight flight-path and were equally distributed across the three different ball-lengths and two lines. In the other block of trials, participants faced a mixture of straight (*random-straight*) and swinging deliveries (*random-swing*). Specifically, the random block consisted of 48 trials: 16 straight trials, 16 outswing trials, and 16 inswing trials. In this block, the trials were evenly distributed across the two lines but only two different ball-lengths (full and good-lengths) because the ProBatter machine was not able to project short-length deliveries while imparting swing on the ball. The order of trials within each block followed a predetermined but randomised sequence of deliveries that started at a random position for each batter. Each batter took approximately one hour to complete the experiment.

4.3.5. Data Analysis

The Mobile Eye footage was manually digitised (Kinovea 8.15, 2011) to obtain, from the moment of ball release to bat-ball contact, the x-y coordinates of five specific points in the visual field: (i) location of gaze; (ii) location of ball-release; (iii) the ball; (iv) bottom left of the projection screen; and (v) bottom right of the projection screen. The first three reference points allowed for the calculation of the raw gaze, head, and ball angles subtended at the eye respectively (in degrees). The scene camera of the Mobile Eye moves commensurate with the batter’s head movement, ensuring that any movement of a fixed location, such as the location of ball-release, provided a direct measure of head movement. The three raw angles were used for the calculation of three relative angles: (i) the *gaze-ball angle*, (ii) the *gaze-head angle*, and (iii) the *head-ball angle* (see Figure 4.2). To correct for head rotation, the coordinates of the projection screen were used to ensure that the visual angles were reported in the global rather than local coordinate system. The x-y coordinates for the five spatial locations for a single participant showed high levels of intra- and inter-tester reliability (98% and 96% agreement respectively; with intra-tester coding performed four weeks apart).

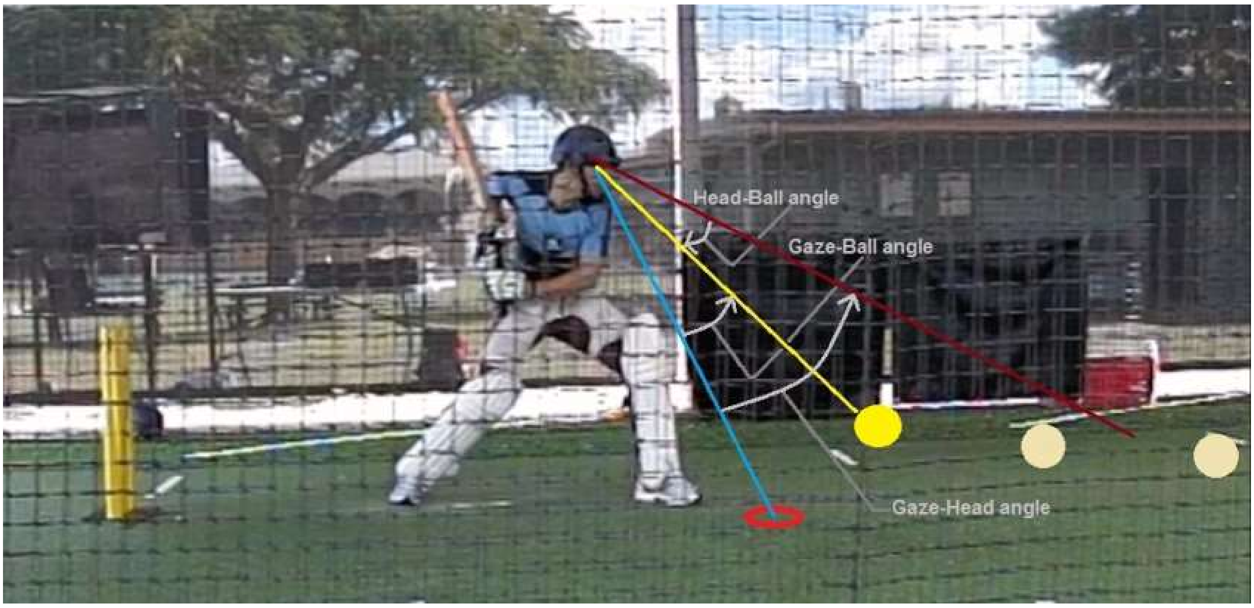

Figure 4.2. Measurement of the three relative angles. Individual angles are initially subtended by the direction of the head (red), ball (yellow) and gaze (blue) at the batter's eye (in degrees) relative to the direction of ball-flight. The relative angles in this case show a positive head-ball angle (head is directed behind the ball), a negative gaze-ball angle (gaze is directed ahead of the ball), and a negative gaze-head angle (gaze is directed ahead of the head direction).

Additionally, the eye movement footage was manually viewed frame-by-frame to detect the type and timing of any saccades that may have taken place between the moment of ball-release and bat-ball contact. A saccade was recorded when a distinctive shift in gaze occurred that was not commensurate with the flight-path of the ball. Two types of saccades were recorded: (i) *saccades towards ball-bounce*, and (ii) *saccades towards bat-ball contact*, (see Table 4.1 for operational definitions; Bahill & LaRitz, 1984; Chapter 3; Land & McLeod, 2000; Mann et al., 2013). Furthermore, the saccades towards ball-bounce were subdivided into saccades that moved purely in the vertical direction or *oblique saccades* that incorporated a lateral component (see Becker & Jürgens, 1990; Smit et al., 1990; Viviani et al., 1977). Pilot testing revealed that it was only possible to identify oblique saccades towards bat-ball contact because the ball-speed (≈33 $m.s^{-1}$) and frame rate of the Mobile Eye camera (capturing video frames at 40 ms intervals) made it difficult to accurately measure lateral gaze position when the ball was close to the batter (also see Mann et al., 2013). The type and timing of saccades of four batters (of different skill and age groups) were assessed independently by two trained researchers. The manual coding of saccades revealed a high degree of intra- and inter-tester reliability (minimum 97% and 81% agreement respectively; with intra-tester coding performed four weeks apart). Batters were also found to produce other types of saccades (e.g., saccades that realigned gaze with the ball after falling behind); however, inter-tester reliability revealed those saccades to be difficult to reliably detect and so were not included in this study.

For this study, only the trials where the ball bounced on either a full-length or good-length were analysed (2580 out of 2838 possible trials, 91%). A total of 709 trials were excluded as the batter did not swing their bat to hit the ball (with the batter also generally making no further attempt to track the ball following ball-bounce; 27% of remaining trials) and 98 trials were excluded because of technical difficulties with the eye tracker failing to obtain the gaze location for more than two consecutive frames of ball-flight (4% of remaining trials). In the end a total of 1773 out of 2580 possible trials (69%) were included for analysis.

4.3.6. Dependent Variables

A number of key variables were assessed to examine the (a) batting performance, (b) relative positions of gaze, head and ball throughout ball-flight, (c) type and timing of saccadic behaviours, and (d) gaze position at the moment of bat-ball contact.

(a). Batting performance: The interceptive performance of batters was analysed across all attempted shots when the ball bounced on either a full or good-length (unlike in Chapter 2 where only one particular shot was analysed when the ball bounced on a good-length). As a result, two measures of interceptive performance were assessed in real-time by the primary investigator: (i) the *quality of bat-ball contact* (QoC; see Müller & Abernethy, 2008), and (ii) the *forcefulness of bat-swing* (FoBS; see Mann et al., 2010b). The QoC provides a simple and validated categorical measure to determine whether the batter successfully made contact with the ball. A score of two, one, or zero was given for each trial to represent ‘good’ (ball makes contact with the bat and travels in a direction consistent with the plane of bat motion), ‘poor’ (ball makes contact with the bat and travels in a direction inconsistent with the plane of bat motion) or ‘no contact’ (ball makes no contact with the bat) respectively. This allowed for the calculation of the *% of trials with ‘good’ bat-ball contact* (for a similar type of analysis, see Chapter 3; Müller & Abernethy,

2006). The FoBS provides a categorical measure to assess how hard the ball was likely to have been hit when bat-ball contact was achieved, reflecting the likelihood of the batter scoring runs. Achieving spatio-temporal precision for successful interception when adopting a faster, more aggressive bat-swing is difficult as the amount of time the bat is optimally positioned to hit the oncoming ball is decreased. A score of two, one, or zero was also given for each trial to reflect a complete follow-through of the bat, a partial follow-though of the bat, or no follow-though of the bat after bat-ball contact. As a result, this allowed for the calculation of the *% of trials with high FoBS* (for a similar type of analysis, see Chapter 3; Mann et al., 2010b).

(b) Relative positions of gaze, head and ball throughout ball-flight: The mean and the standard deviation of the (i) *gaze-ball*, (ii) *gaze-head*, and (iii) *head-ball* angles were calculated in both the vertical and horizontal directions for each trial (all data expressed as the *mean* ± *standard deviation* in degrees). Additionally, the percentage of ball-flight where batters directed their gaze ahead the ball ($\%\ Gaze_{ahead}$) was calculated to provide an indication of the proportion of time batters held their gaze in anticipation of the future location of the ball.

(c) Saccadic behaviours: The frequency of each type of saccade (saccades to ball-bounce, oblique saccades to ball-bounce, saccades to bat-ball contact) was reported as the percentage of trials in which that type of saccade was performed, with the timing of each saccade reported relative to the moment of ball-release (as the *mean* ± *standard deviation* in milliseconds).

(d) Gaze at bat-ball contact: The location of gaze at the moment of bat-ball contact has previously shown to be a key marker of expertise in batting (see Chapter 3; Mann et al., 2013). After manually examining the frames prior to, and after bat-ball contact, gaze was judged to be co-located with the ball if gaze was seen to be within one bat-width of the location of the ball at the moment of contact (approximating 4 deg of visual angle). Although it is difficult to conclusively establish whether the ball was successfully foveated at the moment of bat-ball contact, this approach allows for the differentiation of gaze being directed towards bat-ball contact or towards another location (usually lagging behind the ball or directed towards the post-contact direction; see Chatper 3; Mann et al., 2013). This allowed for the calculation of the percentage of trials where, at the moment of bat-ball contact, the gaze of batters was either: (i) co-located with the ball ($\%\ BBC_{fixation}$), (ii) lagging behind the ball ($\%\ BBC_{lagging}$), or (iii) directed towards the post-contact direction

of the ball (% $BBC_{post\text{-}contact}$). The manual coding of the location of gaze at the moment of bat-ball contact also revealed high levels of intra- and inter-tester reliability (98% and 90% respectively; with coding for intra-tester performed four weeks apart).

4.3.7. Statistical Analyses

Three specific analyses were performed. First, a 2 (Skill: skilled, club) x 2 (Age: adult, youth) x 2 (Randomisation: blocked-straight, random-straight) x 2 (Length: full, good) ANOVA with repeated measures on the last two factors was performed to compare the tracking strategies used when hitting straight balls that were blocked together and those that were co-presented with swinging balls. Second, to determine whether batters adapted their tracking strategies when hitting a ball that *did* or *did not* swing, a 2 (Skill) x 2 (Age) x 2 (Type of delivery: straight, swing) x 2 (Length) ANOVA was performed with repeated measures on the last two factors. Third, to determine whether there were differences in tracking strategies for the two different directions of swing, a 2(Skill) x 2 (Age) x 2 (Direction of swing: outswing, inswing) x 2 (Length) ANOVA was performed with repeated measures on the final two factors. Where the assumption of sphericity was violated, the Greenhouse-Geisser correction was used. Alpha was set at 0.05 for all comparisons. Partial eta squared (η_p^2) and Cohen's *d* values were calculated to indicate the effect size where appropriate.

A multivariate analysis of variance (MANOVA) was also performed for each of the above analyses listed above incorporating each of the gaze variables. Variables found to be significant within the MANOVA were then subjected to a stepwise discriminant function analysis with the *F* value set between 0.05 and 0.15 (Tabachnick & Fidell, 2001). This allowed for the determination of the variable(s) that best predicted the batter's skill level, age group and ball-flight condition (for a similar analysis, see Chapters 2 and 3; Weissensteiner et al., 2011). Cross-validation of the models was also performed to indicate the accuracy of the model in predicting the same outcome variables to an independent dataset (Field, 2005).

Table 4.1.

Operational definitions for the different types of saccades.

Type of saccade	Operational definitions
Anticipatory saccade towards ball-bounce	A change in the rate of movement of gaze that is quicker than the flight-path of the ball, is initiated *prior* to ball-bounce, and brings gaze ahead of the ball to a stationary position at the impending position of ball-bounce.
Oblique saccade towards ball-bounce	A change in the horizontal *and* vertical rate of gaze movement that is quicker than the flight-path of the ball, is initiated *prior* to ball-bounce, and brings gaze ahead of the ball to a stationary position at the impending position of ball-bounce.
Anticipatory saccade towards bat-ball contact	A change in the rate of movement of gaze that is quicker than the flight-path of the ball, is initiated *after* ball-bounce, and brings gaze ahead of the ball to a stationary position towards the impending position of bat-ball contact.

4.4. Results

4.4.1. Blocked-Straight vs Random-Straight Trials

The mean results comparing each of the dependent variables when facing blocked-straight and random-straight trials are presented in Table 4.2. In this section, the main and interaction effects of randomisation are reported to determine whether the *possibility* of ball-swing influenced the gaze behaviour of batters. See Chapter 3 for more information on the skill and age-based differences in the eye and head movements of batters when hitting straight balls.

Table 4.2.

Descriptive Statistics across Skill and Age When Facing Blocked-Straight and Random-Straight Trials across the Different Ball-Lengths

		Full				**Good**			
		Blocked-Straight		**Random-Straight**		**Blocked-Straight**		**Random-Straight**	
		Adult	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**
Batting performance									
%Good bat-ball contacts	Skilled	85.1 ± 12.5	74.7 ± 22.5	68.3 ± 18.2	66.6 ± 30.6	91.7 ± 16.7	93.0 ± 12.0	80.2 ± 18.6	72.5 ± 10.6
	Club	63.3 ± 28.2	54.8 ± 32.9	62.8 ± 26.1	59.7 ± 34.0	72.5 ± 20.8	73.3 ± 22.5	80.5 ± 18.4	71.6 ± 23.1
%High FoBS	Skilled	69.3 ± 22.3	80.0 ± 14.8	71.5 ± 27.0	73.0 ± 19.3	19.7 ± 24.7	26.0 ± 37.1	24.5 ± 30.0	13.7 ± 21.8
	Club	65.2 ± 18.7	77.3 ± 24.0	58.5 ± 31.9	64.0 ± 31.8	12.5 ± 27.0	27.2 ± 32.4	9.5 ± 17.1	13.7 ± 18.8
Gaze and Head tracking (deg)									
Gaze-Ball angle	Skilled	-0.5 ± 1.9	-0.7 ± 1.3	0.9 ± 1.5	-0.7 ± 1.1	0.6 ± 2.0	-0.3 ± 1.2	0.9 ± 1.9	0.3 ± 1.6
	Club	1.0 ± 2.0	0.2 ± 1.9	1.2 ± 1.6	0.5 ± 1.6	0.7 ± 2.2	0.9 ± 1.8	1.9 ± 1.6	0.6 ± 1.5
SD Gaze-Ball angle	Skilled	4.3 ± 3.2	2.9 ± 1.9	3.4 ± 2.3	2.8 ± 1.8	3.5 ± 2.4	3.2 ± 2.2	3.0 ± 2.0	3.2 ± 2.5
	Club	4.6 ± 2.2	3.2 ± 2.2	3.7 ± 2.1	3.2 ± 2.0	5.5 ± 2.7	3.3 ± 2.0	3.9 ± 1.6	2.5 ± 1.8
Gaze-Head angle	Skilled	-3.3 ± 2.3	-2.4 ± 3.1	-2.5 ± 2.3	-3.2 ± 2.9	-3.5 ± 1.6	-3.5 ± 1.6	-2.7 ± 2.3	-3.1 ± 2.3
	Club	-2.6 ± 2.9	-2.3 ± 1.8	-2.7 ± 2.7	-2.3 ± 2.2	-3.4 ± 1.9	-2.9 ± 1.0	-2.4 ± 2.3	-2.9 ± 1.8
SD Gaze-Head angle	Skilled	5.0 ± 2.5	5.0 ± 2.8	4.1 ± 2.5	5.0 ± 2.4	3.9 ± 1.9	4.9 ± 1.9	3.4 ± 2.0	4.5 ± 2.4
	Club	4.0 ± 2.8	4.2 ± 2.6	3.4 ± 2.4	4.1 ± 2.5	4.0 ± 2.9	3.3 ± 1.4	2.7 ± 1.5	3.6 ± 2.1
Head-Ball angle	Skilled	3.0 ± 2.6	2.2 ± 3.0	3.5 ± 1.6	3.0 ± 3.2	4.2 ± 2.3	3.7 ± 2.2	3.7 ± 1.5	2.9 ± 2.1
	Club	3.5 ± 2.8	2.3 ± 2.3	4.0 ± 3.4	2.9 ± 2.5	4.6 ± 2.9	3.7 ± 2.2	4.4 ± 3.1	3.6 ± 2.3
SD Head-Ball angle	Skilled	6.2 ± 3.9	4.6 ± 3.9	6.1 ± 2.7	5.2 ± 4.2	5.3 ± 3.9	4.7 ± 2.5	4.7 ± 2.3	3.6 ± 2.2
	Club	5.3 ± 2.9	4.5 ± 2.5	5.5 ± 3.6	4.8 ± 3.1	5.5 ± 3.7	4.3 ± 2.3	4.7 ± 2.9	4.6 ± 2.6
% Gaze$_{ahead}$	Skilled	61.5 ± 24.9	61.1 ± 27.1	43.1 ± 24.7	59.3 ± 29.8	45.3 ± 24.8	49.9 ± 19.9	35.5 ± 26.1	46.9 ± 21.2
	Club	44.5 ± 24.4	59.2 ± 31.1	47.4 ± 23.8	50.4 ± 28.7	41.2 ± 20.6	40.5 ± 33.6	34.5 ± 17.5	49.7 ± 30.8
Lateral Gaze-Ball angle	Skilled	1.0 ± 1.6	0.3 ± 0.5	0.5 ± 1.1	0.2 ± 0.7	0.5 ± 0.9	0.0 ± 0.5	0.5 ± 0.8	0.4 ± 0.9
	Club	0.7 ± 1.3	0.5 ± 1.3	0.9 ± 1.0	0.2 ± 0.8	0.7 ± 1.7	0.6 ± 0.4	0.9 ± 1.4	0.2 ± 1.0
SD lateral Gaze-Ball angle	Skilled	2.0 ± 2.2	1.0 ± 0.4	1.3 ± 1.2	0.9 ± 0.7	1.1 ± 0.7	1.0 ± 0.6	1.0 ± 0.7	1.1 ± 0.9
	Club	1.7 ± 2.0	1.7 ± 2.2	1.7 ± 1.7	1.4 ± 1.1	2.8 ± 2.7	1.2 ± 0.8	1.2 ± 1.1	1.3 ± 1.4
Lateral Gaze-Head angle	Skilled	0.0 ± 1.8	0.0 ± 1.3	0.0 ± 2.1	0.1 ± 1.4	-0.3 ± 2.3	0.0 ± 1.8	-0.1 ± 2.2	0.0 ± 1.5
	Club	-0.2 ± 2.0	0.0 ± 1.5	0.3 ± 2.1	0.1 ± 1.3	-0.2 ± 2.5	0.4 ± 0.9	0.2 ± 2.1	-0.1 ± 1.3
SD lateral Gaze-Head angle	Skilled	2.8 ± 2.8	1.3 ± 0.6	1.6 ± 0.9	1.5 ± 0.8	2.6 ± 2.3	2.3 ± 1.4	1.7 ± 1.0	1.8 ± 1.3
	Club	2.2 ± 1.8	2.1 ± 2.3	2.4 ± 1.9	2.1 ± 1.5	2.6 ± 2.0	1.9 ± 0.9	1.6 ± 1.1	1.3 ± 1.5
Lateral Head-Ball angle	Skilled	1.4 ± 2.4	0.3 ± 1.4	0.7 ± 1.8	0.0 ± 1.3	0.8 ± 2.2	0.1 ± 1.4	0.7 ± 1.8	0.4 ± 1.2
	Club	0.8 ± 1.1	0.5 ± 0.7	0.5 ± 1.0	0.5 ± 0.9	0.8 ± 1.6	0.2 ± 0.6	0.5 ± 0.9	0.3 ± 0.8
SD lateral Head-Ball angle	Skilled	2.1 ± 2.4	1.3 ± 1.0	1.9 ± 1.5	1.4 ± 0.8	2.2 ± 1.8	1.5 ± 0.7	1.7 ± 1.1	1.2 ± 0.5
	Club	1.6 ± 0.9	1.0 ± 0.4	1.3 ± 0.7	1.0 ± 0.8	2.3 ± 2.3	1.1 ± 0.4	1.2 ± 0.6	0.7 ± 0.6

Table 4.2 continued.

Gaze at bat-ball contact									
%BBC$_{fixation}$	Skilled	38.6 ± 34.6	39.7 ± 34.6	10.9 ± 11.9	32.0 ± 26.3	29.1 ± 22.8	29.2 ± 36.3	21.0 ± 30.3	14.6 ± 16.5
	Club	25.6 ± 32.7	26.7 ± 36.7	14.4 ± 26.1	20.4 ± 28.5	25.9 ± 43.4	10.9 ± 16.8	14.8 ± 27.2	5.0 ± 10.0
%BBC$_{lagging}$	Skilled	25.0 ± 25.6	32.0 ± 29.7	59.1 ± 21.8	45.2 ± 29.1	41.8 ± 25.8	50.8 ± 39.4	58.1 ± 27.6	73.7 ± 22.7
	Club	48.5 ± 40.9	44.4 ± 34.6	61.7 ± 38.6	53.5 ± 26.3	52.4 ± 45.8	74.8 ± 28.2	69.6 ± 30.5	91.8 ± 12.4
%BBC$_{Post\text{-}Contact}$	Skilled	36.4 ± 31.5	28.3 ± 31.8	30.0 ± 24.9	22.7 ± 22.2	29.1 ± 19.6	20.0 ± 35.8	20.9 ± 22.9	11.7 ± 24.9
	Club	25.9 ± 42.6	28.9 ± 34.4	23.9 ± 35.0	26.1 ± 18.9	21.7 ± 38.4	14.3 ± 25.8	15.6 ± 24.7	3.2 ± 9.5
Type of saccades (%)									
Saccade towards ball-bounce	Skilled	60.3 ± 31.6	52.7 ± 36.5	59.8 ± 30.2	65.9 ± 24.2	36.9 ± 36.2	38.3 ± 39.3	28.2 ± 33.2	32.8 ± 18.4
	Club	48.3 ± 46.1	34.7 ± 35.6	34.2 ± 36.9	33.9 ± 25.6	49.5 ± 46.0	24.8 ± 25.3	31.3 ± 37.6	15.4 ± 26.2
Saccade towards bat-ball contact	Skilled	0 ± 0	1.7 ± 5.3	0 ± 0	1.4 ± 4.5	19.0 ± 28.0	23.3 ± 33.5	10.9 ± 22.4	17.2 ± 18.2
	Club	0 ± 0	0 ± 0	0 ± 0	0 ± 0	22.5 ± 35.1	6.5 ± 14.2	0 ± 0	0 ± 0
Oblique saccade towards ball-bounce	Skilled	5.4 ± 8.4	10.3 ± 26.4	3.2 ± 6.0	8.3 ± 21.2	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	Club	13.3 ± 24.6	11.7 ± 25.2	7.9 ± 21.0	6.3 ± 10.7	2.5 ± 7.9	4.0 ± 8.4	5.0 ± 15.8	3.9 ± 8.7
Timing of saccade (following ball-release; ms)									
Saccade towards ball-bounce	Skilled	414 ± 34	399 ± 29	415 ± 29	398 ± 25	343 ± 67	343 ± 40	362 ± 41	383 ± 43
	Club	394 ± 42	416 ± 27	413 ± 19	420 ± 23	274 ± 49	319 ± 96	369 ± 57	387 ± 27
Saccade towards bat-ball contact	Skilled					500 ± 47	438 ± 28	467 ± 31	437 ± 27
	Club					445 ± 25	470 ± 14		
Oblique saccade towards ball-bounce	Skilled			453 ± 23	415 ± 35				
	Club			450 ± 42	360 ± 106				340 ± 85

4.4.1.1. Batting performance.

Strikingly, the awareness that the ball *could* swing (i.e., comparing the random-straight to blocked-straight trials) resulted in a significant decrease in the percentage of good bat-ball contacts achieved (*F*(1, 38) = 4.67, *p* = .037, η_p^2 = .11; blocked-straight *M* = 76.1%, *SD* = 13.8; random-straight *M* = 70.3%, *SD* = 16.1). There was no change in the forcefulness of bat-swing across the two conditions (*F*(1, 38) = 2.01, *p* = .164, η_p^2 = .05; blocked-straight *M* = 47.1%, *SD* = 19.3; random-straight *M* = 41.0%, *SD* = 21.0). Surprisingly though, the skilled batters were more influenced by the possibility of ball-swing than the club batters were (i.e., skill x randomisation interaction for percentage of good bat-ball contacts, *F*(1, 38) = 10.01, *p* = .003, η_p^2 = .21; Figure 4.3). The co-presentation of straight and swinging trials reduced the batting performance of the skilled batters (blocked-straight *M* = 86.3%, *SD* = 9.5; random-straight *M* = 72.1%, *SD* = 13.6; *p* < .001; *d* = 1.21), but not the club batters (blocked-straight *M* = 66.0%, *SD* = 17.1; random-straight *M* = 68.7%, *SD* = 18.1; *p* = .538; *d* = 0.15). In fact, the performance of the skilled batters was indistinguishable from that of the club batters when straight and swinging trials were interleaved (*p* = .484; *d* = 0.22).

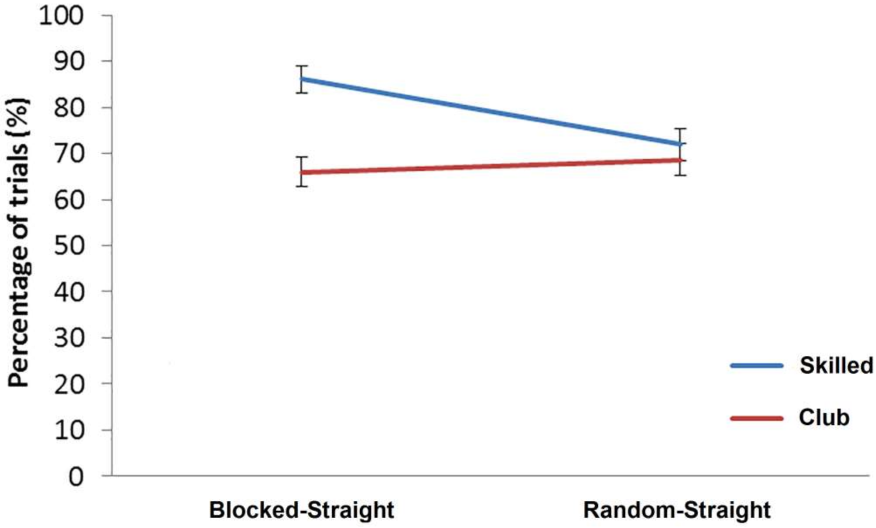

Figure 4.3. The effects of randomisation on the percentage of good bat-ball contacts as a function of the batter’s skill. Data are presented with standard error bars

4.4.1.2. Gaze and head position relative to the ball.

The possibility of ball-swing resulted in significant changes in gaze. When compared to batting against the blocked-straight deliveries, batters directed their gaze further behind the ball when facing the random-straight deliveries[15] (i.e., gaze-ball angle, $F(1, 38) = 5.91$, $p = .02$, $\eta_p^2 = .14$; blocked-straight $M = 0.2$ deg, $SD = 1.6$; random-straight $M = 0.7$ deg, $SD = 1.5$) and were more consistent in the position of gaze relative to the ball (i.e., SD for gaze-ball angle, $F(1, 38) = 5.03$, $p = .031$, $\eta_p^2 = .12$; blocked-straight $M = 3.8$ deg, $SD = 1.9$; random-straight $M = 3.2$ deg, $SD = 1.8$). Moreover, batters when facing the random-straight trials were more consistent in their ability to laterally co-align their gaze and head with the ball (SD for lateral gaze-ball angle, $F(1, 38) = 4.35$, $p = .044$, $\eta_p^2 = .1$; blocked-straight $M = 1.6$ deg, $SD = 1.3$; random-straight $M = 1.2$ deg, $SD = 0.9$; SD for lateral gaze-head angle, $F(1, 38) = 11.0$, $p = .002$, $\eta_p^2 = .23$; blocked-straight $M = 2.2$ deg, $SD = 1.7$; random-straight $M = 1.8$ deg, $SD = 11.6$; SD for lateral head-ball angle, $F(1, 38) = 4.57$, $p = .039$, $\eta_p^2 = .11$; blocked-straight $M = 1.6$ deg, $SD = 1.2$; random-straight $M = 1.3$ deg, $SD = 0.8$).

It has previously been proposed that a key marker of expertise in batting may be the batter's ability to align the direction of their head with the ball (Mann et al., 2013; though see Chapter 3). In the present study, the possibility of ball-swing resulted in poorer head tracking against the full but not good-length deliveries (i.e., randomisation x length interactions for head-ball angle, $F(1, 38) = 10.37$, $p = .003$, $\eta_p^2 = .21$; and lateral head-ball angle, $F(1, 38) = 5.27$, $p = .027$, $\eta_p^2 = .12$; blocked vs. random straight for full-length trials, $p = .05$; $d = 0.22$, and for good-length trials, $p = .144$; $d = 0.18$; Figure 4.4a). Head tracking of the ball is typically better when facing full-length trials than it is against good-length trials (see Chapter 3), but the effects of randomisation decreased the batter's head tracking against the full-length deliveries to a level that was no longer distinguishable from the good-length deliveries. There was though a marginal improvement in the *lateral* head-tracking against full-length ($p = .058$; $d = 0.24$) but not good-length trials ($p = .882$; $d = 0.02$) as a result of randomisation (Figure 4.4b).

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[15] A four-way interaction was found for gaze-ball angle ($F(1, 38) = 5.48$, $p = .025$, $\eta_p^2 = .13$), reflecting a tendency for only the adult club batters to direct their gaze further behind the ball as a result of randomisation when facing the good-length trials ($p = .095$, $d = 0.59$), with no differences found across groups when facing full-length trials (*p*s > .1, *d*s < 0.61). A four-way interaction was also observed for % $\text{Gaze}_{\text{ahead}}$ ($F(1, 38) = 6.39$, $p = .016$, $\eta_p^2 = .14$), in which the effects of randomisation significantly reduced the proportion of ball-flight that the adult skilled batters had directed their gaze ahead of the ball when facing full-length ($p = .007$, $d = .62$) and good-length trials ($p = .086$, $d = 0.38$). This effect was not found across the other groups of batters (*p*s > .214, *d*s < 0.35).

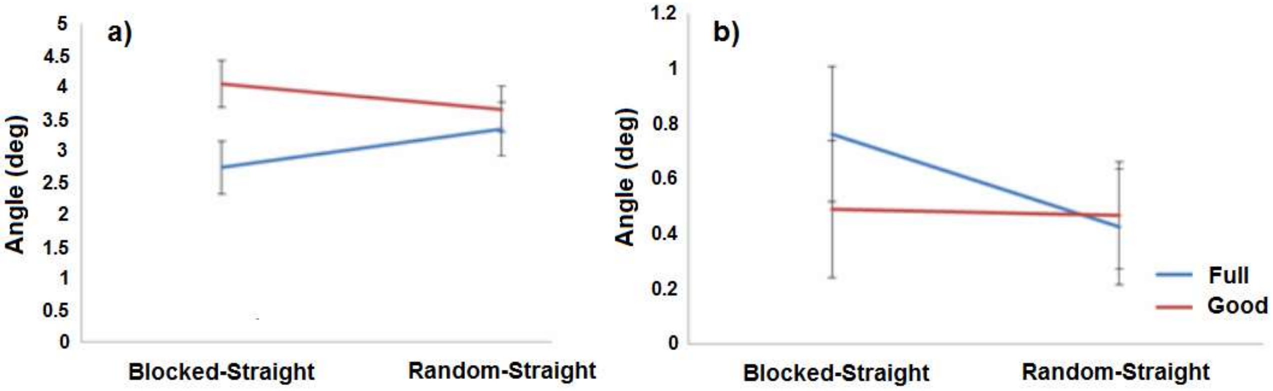

Figure 4.4. The effects of randomisation as a function of ball-length for a) head-ball angle; and b) lateral head-ball angle. All data are presented with standard error bars.

4.4.1.3. Predictive saccades.

The knowledge that the ball could swing also influenced the predictive behaviour of the batters. Batters delayed the timing of their saccade towards ball-bounce when facing the random-straight trials (*F*(1, 18) = 24.32, *p* < .001, η_p^2 = .58; blocked-straight *M* = 358 ms, *SD* = 33; random-straight *M* = 389 ms, *SD* = 28), and initiated fewer saccades towards both ball-bounce (*F*(1, 39) = 5.22, *p* = .028, η_p^2 = .12; blocked-straight *M* = 48.8%, *SD* = 29.1; random-straight *M* = 42.0%, *SD* = 28.9) and towards bat-ball contact (*F*(1, 39) = 6.88, *p* = .012, η_p^2 = .15; blocked-straight *M* = 9.1%, *SD* = 15.1; random-straight *M* = 3.7%, *SD* = 8.2; Chapter 3). However, the possibility of ball-swing altered the behaviour of the club batters more than it did the skilled batters. Specifically, Figure 4.5 shows an interaction between skill and randomisation (*F*(1, 18) = 5.27, *p* = .034, η_p^2 = .23), revealing that the timing of the saccades of the club batters to ball-bounce were delayed more than they were for the skilled batters. There was a significant delay in the timing of the saccade to ball-bounce as a result of randomisation for the skilled batters (blocked-straight *M* = 367 ms, *SD* = 28; random-straight *M* = 384 ms, *SD* = 31; *p* = .035; *d* = 0.56), though the increase in delay was greater for the club-level batters (blocked-straight *M* = 350 ms, *SD* = 36; random-straight *M* = 395 ms, *SD* = 22; *p* = .002; *d* = 1.52).

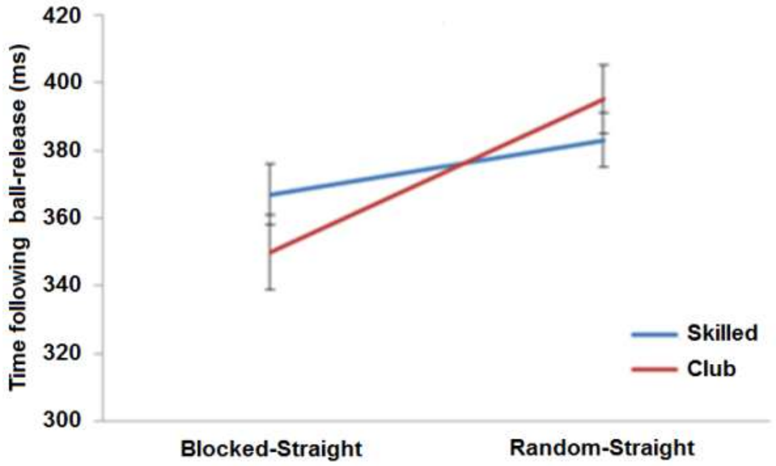

Figure 4.5. The effects of randomisation as a function of the batter's skill for the timing of saccade towards ball-bounce. All data are presented with standard error bars

The impact of randomisation on anticipatory behaviour also differed for the two different ball-lengths (i.e., randomisation x length interactions for timing of saccade to ball-bounce, *F*(1, 18) = 29.65, $p < .001$, $\eta_p^2 = .62$; and percentage of saccades towards bat-ball contact, *F*(1, 39) = 4.37, $p = .043$, $\eta_p^2 = .1$; Figure 4.6). When facing good-length deliveries, batters accounted for the uncertainty in ball-flight by delaying the timing of the saccade to ball-bounce ($p < .001$; $d = 1.2$) and initiating fewer saccades towards bat-ball contact ($p = .008$; $d = 0.47$). When facing full-length trials however, the effect of randomisation *did not* change the batter's timing of the saccade to ball-bounce ($p = .781$; $d = 0.06$; Figure 4.6a) or the percentage of saccades towards bat-ball contact ($p = .915$; $d = 0.02$; Figure 4.6b). This suggests that the good-length trials (that were already the most challenging ball-length to face; Chapter 3) became even more challenging for the batters in the random-straight condition (Figure 4.7).

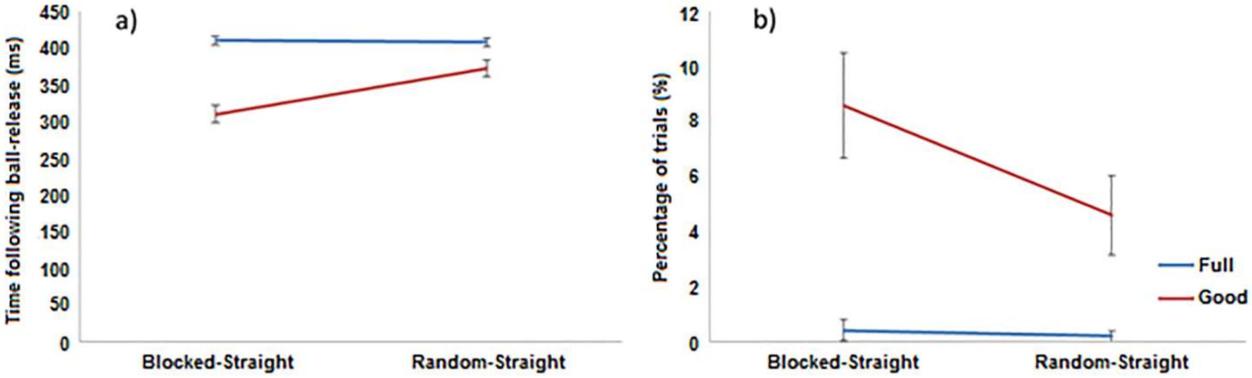

Figure 4.6. The effects of randomisation as a function of ball-length for a) timing of saccade towards ball-bounce; and b) percentage of saccades towards bat-ball contact. All data are presented with standard error bars.

4.4.1.4. Gaze at bat-ball contact.

In the end, the possibility of ball-swing meant that batters were less likely to co-locate their gaze with the ball at the moment of bat-ball contact ($F(1, 35) = 15.37$, $p < .001$, $\eta_p^2 = .31$; blocked-straight $M = 28.2\%$, $SD = 28.5$; random-straight $M = 16.6\%$, $SD = 19.2$), with gaze more likely to lag behind the ball when it was hit ($F(1, 35) = 29.35$, $p < .001$, $\eta_p^2 = .46$; blocked-straight $M = 46.2\%$, $SD = 29.1$; random-straight $M = 64.1\%$, $SD = 22.3$; Figure 4.7). Given that the ability to watch the ball at the moment of bat-ball contact is one of the key predictors of skill in batting (Chapter 3; Mann et al., 2013), it is not surprising that batting performance decreased significantly in the random-straight condition.

4.4.1.5. Discriminant function for randomisation.

A stepwise discriminant function analysis accurately discriminated between blocked-straight and random-straight trials with the following prediction equation ($D = -7.85 + 0.03 * [\% \ BBC_{fixation}] + 0.03 * [\% \ BBC_{lagging}] - 0.05 *$ [*percentage of trials with saccades towards bat-ball contact*] + 16.85 * [*timing of saccade to ball-bounce*], $F = 8.05$; *df* 4, 60; $p < .001$; group centroids: blocked-straight = -0.61; random-straight = 0.86). The predictors of the random-straight trials were the delayed initiation of saccades towards ball-bounce, fewer saccades towards bat-ball contact, a reduced likelihood of co-locating gaze with the ball at the moment of bat-ball contact, and an increased likelihood of gaze lagging behind the ball at contact. The model accurately predicted group membership for 72.3% of cases with 73.7% of blocked-straight and 70.4% of random-straight trials categorised correctly. Cross-validation correctly re-categorised 70.8% of cases with 73.7% of blocked-straight and 66.7% of random-straight trials

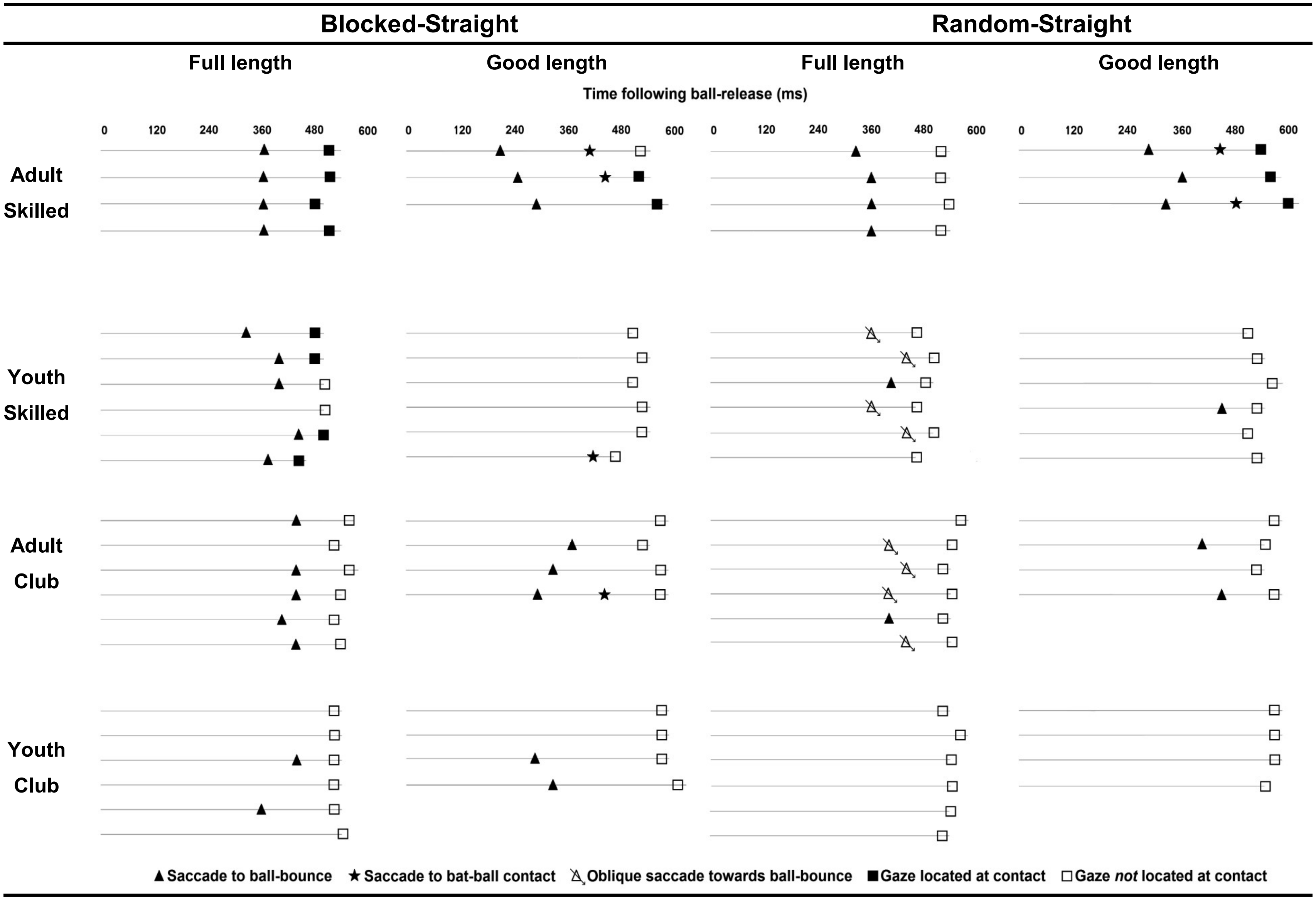

Figure 4.7. The saccadic behaviour of an exemplar batter representative of each of the four groups of batters. Each horizontal line represents a single trial. The timing of each gaze event is indicated relative to the moment of ball-release (ms).

4.4.2. Random-Straight vs. Random-Swing Trials

The results comparing each of the dependent variables when facing random-straight and random-swing trials are presented in Table 4.3. In this section, the main and interaction effects of swing are reported to determine whether the *presence* of ball-swing influences visual gaze behaviour when compared to facing straight deliveries. For the sake of brevity, the main effects of skill and age are not presented in this section as they are mostly superseded by higher-order interactions. Length-based main and interaction effects (with the batter's skill and/or age) are also not presented as they are consistent with the findings reported in Chapter 3. However, interactions that involve the type of delivery (straight vs. swing) are discussed.

Table 4.3.

Descriptive Statistics across Skill and Age When Facing Random-Straight and Random-Swing Trials across the Different Ball-Lengths.

		Full				**Good**			
		Random-Straight		**Random-Swing**		**Random-Straight**		**Random-Swing**	
		Adult	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**
Batting performance									
%Good bat-ball contact	Skilled	68.4 ± 18.2	66.6 ± 30.6	57.7 ± 11.8	51.1 ± 15.3	80.2 ± 18.6	72.6 ± 10.6	62.2 ± 14.0	56.8 ± 30.0
	Club	62.8 ± 26.1	59.7 ± 34.0	27.4 ± 11.9	33.1 ± 15.3	80.5 ± 18.4	71.6 ± 23.1	59.6 ± 30.6	55.9 ± 31.1
%High FoBS	Skilled	71.5 ± 27.0	73.1 ± 19.3	64.5 ± 22.6	58.5 ± 33.0	24.5 ± 30.0	13.7 ± 21.8	20.2 ± 21.6	19.3 ± 17.5
	Club	58.5 ± 31.9	64.0 ± 31.8	50.5 ± 34.8	40.1 ± 32.8	9.5 ± 17.1	13.7 ± 21.8	18.3 ± 17.9	30.9 ± 18.4
Gaze and Head tracking (deg)									
Gaze-Ball angle	Skilled	1.1 ± 1.4	-0.7 ± 1.1	0.4 ± 0.9	-0.5 ± 1.1	1.2 ± 1.5	0.3 ± 1.6	0.7 ± 1.0	0.0 ± 1.0
	Club	1.2 ± 1.6	0.5 ± 1.6	1.3 ± 2.4	1.3 ± 2.9	1.9 ± 1.6	0.6 ± 1.5	2.0 ± 1.9	0.7 ± 1.3
SD Gaze-Ball angle	Skilled	3.4 ± 2.4	2.8 ± 1.9	2.8 ± 0.9	2.8 ± 1.4	2.8 ± 2.1	3.2 ± 2.5	2.2 ± 0.9	3.8 ± 2.5
	Club	4.0 ± 1.8	3.2 ± 2.0	5.1 ± 2.2	4.0 ± 3.5	4.2 ± 1.5	2.5 ± 1.8	4.6 ± 1.5	2.5 ± 1.4
Gaze-Head angle	Skilled	-2.3 ± 2.4	-3.2 ± 2.9	-1.8 ± 1.9	-2.4 ± 2.6	-2.2 ± 1.8	-3.1 ± 2.3	-1.8 ± 1.7	-2.9 ± 2.3
	Club	-3.0 ± 2.7	-2.3 ± 2.2	-2.9 ± 2.7	-2.1 ± 1.7	-2.8 ± 2.1	-2.9 ± 1.8	-2.5 ± 2.2	-2.5 ± 1.3
SD Gaze-Head angle	Skilled	4.1 ± 2.6	5.0 ± 2.4	3.7 ± 1.4	4.0 ± 2.0	3.0 ± 1.6	4.5 ± 2.4	3.0 ± 0.9	4.4 ± 2.5
	Club	3.7 ± 2.4	4.1 ± 2.5	3.9 ± 2.3	3.4 ± 1.7	2.8 ± 1.6	3.6 ± 2.1	2.8 ± 1.3	3.0 ± 1.5
Head-Ball angle	Skilled	3.5 ± 1.7	3.0 ± 3.2	2.4 ± 1.8	2.1 ± 2.5	3.6 ± 1.6	2.9 ± 2.1	2.5 ± 1.1	3.2 ± 2.4
	Club	4.5 ± 3.4	2.9 ± 2.8	4.3 ± 3.1	3.4 ± 2.7	4.9 ± 2.9	3.6 ± 2.3	4.6 ± 2.6	3.3 ± 1.7
SD Head-Ball angle	Skilled	6.4 ± 2.7	5.2 ± 4.2	4.6 ± 2.3	3.5 ± 2.4	4.8 ± 2.4	3.6 ± 2.2	3.4 ± 1.5	3.8 ± 2.5
	Club	6.1 ± 3.5	4.8 ± 3.1	5.4 ± 2.7	5.0 ± 3.5	5.2 ± 2.6	4.6 ± 2.6	4.4 ± 2.1	4.0 ± 2.1
% Gaze$_{ahead}$	Skilled	42.9 ± 25.9	59.3 ± 29.8	48.5 ± 24.8	63.3 ± 25.3	31.9 ± 24.1	46.9 ± 21.2	33.1 ± 23.5	49.4 ± 16.9
	Club	49.0 ± 24.7	50.4 ± 28.7	46.8 ± 23.1	53.2 ± 24.1	35.8 ± 18.0	49.7 ± 30.8	35.6 ± 18.9	50.9 ± 23.4
Lateral Gaze-Ball angle	Skilled	0.5 ± 1.2	0.2 ± 0.7	0.4 ± 0.9	0.4 ± 0.7	0.4 ± 0.9	0.4 ± 0.9	0.5 ± 0.8	0.3 ± 0.8
	Club	0.9 ± 1.0	0.2 ± 0.8	0.9 ± 1.5	0.1 ± 0.9	0.9 ± 1.5	0.2 ± 1.0	0.4 ± 1.7	0.3 ± 1.0
SD lateral Gaze-Ball angle	Skilled	1.4 ± 1.3	0.9 ± 0.7	1.5 ± 0.9	1.2 ± 0.7	0.9 ± 0.7	1.1 ± 0.9	0.9 ± 0.4	0.9 ± 0.4
	Club	1.8 ± 1.8	1.4 ± 1.1	2.3 ± 1.3	1.5 ± 1.2	1.3 ± 1.1	1.3 ± 1.4	2.1 ± 1.4	1.1 ± 0.6
Lateral Gaze-Head angle	Skilled	0.2 ± 2.1	0.1 ± 1.4	-0.3 ± 2.2	0.2 ± 0.3	-0.1 ± 2.3	0.0 ± 1.5	-0.2 ± 2.3	0.5 ± 1.8
	Club	0.3 ± 2.3	0.1 ± 1.3	0.2 ± 1.9	-0.1 ± 1.2	0.2 ± 2.3	-0.1 ± 1.4	0.0 ± 2.1	0.0 ± 1.5
SD lateral Gaze-Head angle	Skilled	1.7 ± 0.9	1.5 ± 0.8	2.3 ± 1.0	1.5 ± 0.7	1.7 ± 1.1	1.8 ± 1.3	2.0 ± 1.3	1.9 ± 0.9
	Club	2.6 ± 1.9	2.1 ± 1.5	2.2 ± 1.1	1.7 ± 1.0	1.8 ± 1.1	1.3 ± 1.5	1.9 ± 0.9	1.5 ± 1.0
Lateral Head-Ball angle	Skilled	0.6 ± 1.9	0.0 ± 1.3	0.8 ± 2.0	0.3 ± 1.1	0.7 ± 1.9	0.4 ± 1.2	0.7 ± 1.8	0.0 ± 1.2
	Club	0.5 ± 1.1	0.6 ± 0.9	0.7 ± 1.0	0.3 ± 1.0	0.5 ± 0.9	0.3 ± 0.8	0.4 ± 1.0	0.3 ± 1.0
SD lateral Head-Ball angle	Skilled	2.0 ± 1.5	1.4 ± 0.8	2.3 ± 1.1	1.6 ± 0.5	1.7 ± 1.1	1.2 ± 0.5	1.6 ± 1.0	1.6 ± 0.5
	Club	1.4 ± 0.7	1.0 ± 0.8	2.0 ± 0.6	1.7 ± 1.1	1.3 ± 0.5	0.7 ± 0.6	2.0 ± 1.3	1.2 ± 0.5

Table 4.3 continued.

Gaze at bat-ball contact									
%BBC$_{fixation}$	Skilled	10.0 ± 11.8	32.0 ± 26.3	16.1 ± 20.9	26.2 ± 22.1	19.3 ± 29.5	14.6 ± 16.5	13.2 ± 12.3	22.2 ± 27.0
	Club	14.4 ± 26.1	20.4 ± 28.5	9.4 ± 13.5	8.2 ± 10.4	14.8 ± 27.2	5.0 ± 10.0	5.2 ± 15.6	10.1 ± 14.0
%BBC$_{lagging}$	Skilled	62.6 ± 23.9	45.2 ± 29.1	57.4 ± 24.0	52.5 ± 17.4	61.6 ± 28.9	73.7 ± 22.7	66.1 ± 19.8	67.0 ± 22.5
	Club	61.8 ± 38.6	53.5 ± 26.3	60.3 ± 30.5	82.3 ± 8.1	69.6 ± 30.5	91.8 ± 12.5	75.6 ± 21.9	75.4 ± 16.7
%BBC$_{Post\text{-}Contact}$	Skilled	27.5 ± 25.3	22.7 ± 22.2	26.5 ± 22.4	21.3 ± 18.5	19.1 ± 22.6	11.7 ± 24.9	20.8 ± 24.8	10.8 ± 13.8
	Club	23.9 ± 35.0	26.1 ± 18.9	30.3 ± 30.1	9.5 ± 10.0	15.6 ± 24.7	3.2 ± 9.5	20.3 ± 16.7	14.5 ± 20.3
Type of saccades (%)									
Saccade towards ball-bounce	Skilled	59.8 ± 30.2	65.9 ± 24.3	40.4 ± 20.0	49.8 ± 28.5	28.2 ± 33.3	32.8 ± 18.4	30.3 ± 23.9	33.6 ± 24.8
	Club	34.2 ± 37.0	33.9 ± 25.6	35.5 ± 35.9	27.5 ± 25.5	31.3 ± 37.6	15.4 ± 26.2	29.1 ± 38.3	21.8 ± 19.5
Saccade towards bat-ball contact	Skilled	0 ± 0	1.4 ± 4.5	0.5 ± 1.7	1.5 ± 3.1	10.9 ± 22.4	17.2 ± 18.2	2.0 ± 3.8	11.7 ± 13.0
	Club	0 ± 0	0 ± 0	0.8 ± 2.6	0 ± 0	0 ± 0	0 ± 0	2.5 ± 7.9	3.3 ± 5.5
Oblique saccade towards ball-bounce	Skilled	3.2 ± 6.0	8.3 ± 21.2	12.0 ± 11.4	16.2 ± 18.6	0 ± 0	0 ± 0	2.8 ± 6.9	1.9 ± 4.2
	Club	7.9 ± 21.0	6.3 ± 10.7	14.7 ± 20.3	4.9 ± 9.4	5.0 ± 15.8	3.9 ± 8.7	3.3 ± 10.5	4.3 ± 10.7
Timing of saccade (following ball-release; ms)									
Saccade towards ball-bounce	Skilled	415 ± 29	398 ± 25	426 ± 23	405 ± 22	362 ± 41	383 ± 43	402 ± 37	368 ± 24
	Club	413 ± 19	420 ± 23	395 ± 38	419 ± 18	369 ± 57	387 ± 27	360 ± 32	392 ± 33
Saccade towards bat-ball contact	Skilled								
	Club								
Oblique saccade towards ball-bounce	Skilled	453 ± 23	415 ± 35	423 ± 15	423 ± 35				
	Club	450 ± 42	360 ± 106	422 ± 2			340 ± 85		

4.4.2.1. Batting performance.

Consistent with the hypothesis, there was a striking decrease in batting performance when batters attempted to hit balls that swung. When compared to hitting straight balls, there was a significant decrease in the percentage of good bat-ball contacts ($F(1, 38) = 45.14$, $p < .001$, $\eta_p^2 = .54$; random-straight $M = 70.3\%$, $SD = 16.1$; random-swing $M = 50.5\%$, $SD = 17.4$; see Chapter 2; Craig et al., 2011; Craig et al., 2006), with the lack of any higher-order interactions ($p > .109$) showing that this difference was present for all batters and when facing both ball-lengths. Despite the increase in difficulty, the batters did not significantly alter the forcefulness with which they attempted to hit the ball ($F(1, 38) = 1.18$, $p = .285$, $\eta_p^2 = .03$; random-straight $M = 41.0\%$, $SD = 21.0$; random-swing $M = 37.8\%$, $SD = 20.9$).

4.4.2.2. Gaze and head position relative to the ball.

Ball-swing resulted in skill-based differences in eye and head movements that were apparent when facing the swinging balls but not the straight balls. For instance, a skill x delivery interaction for gaze-ball angle ($F(1, 37) = 6.04$, $p = .019$, $\eta_p^2 = .14$; Figure 4.8) showed that the skilled batters were able to direct their gaze closer to the ball than the club batters were when facing swinging deliveries ($p = .022$, $d = 0.78$), but not when facing the straight ones ($p = .17$, $d = 0.43$). In contrast to when facing the straight trials, the skilled but not club batters aligned their head more closely with the ball when it was swinging (and kept the head-ball angle more consistent), though particularly so when facing the full-length deliveries (i.e., skill x delivery x length interactions for head-ball angle, $F(1, 36) = 6.48$, $p = .015$, $\eta_p^2 = .15$; straight vs. swing paired *t*-tests: skilled full-length, $p = .001$, $d = 0.43$; skilled good-length, $p = .053$, $d = 0.26$; club full-length, $p = .399$, $d = 0.08$; club good-length, $p = .31$, $d = 0.13$; and SD for head-ball angle, $F(1, 36) = 4.85$, $p = .034$, $\eta_p^2 = .12$; straight vs. swing paired *t*-tests: skilled full-length, $p = .006$, $d = 0.56$; skilled good-length, $p = .043$, $d = 0.31$; club full-length, $p = .704$, $d = 0.05$; club good-length, $p = .14$, $d = 0.27$).[16] Collectively, these results provide some support for the idea that the increased spatio-temporal precision required to hit a swinging ball would reveal new effects of skill

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[16] A four-way interaction for head-ball angle was also observed ($F(1, 36) = 4.32$, $p = .045$, $\eta_p^2 = .11$) reflecting a decrease in the head-ball angle in the presence of ball-swing for both the adult and junior skilled groups when facing the full-length trials ($p = .007$, $d = 0.58$; $p = .07$, $d = 0.3$ respectively), and for only the adult skilled group when facing the good-length trials ($p = .002$, $d = 0.82$).

and/or increase the magnitude of the existing skill-based differences found when facing straight deliveries.

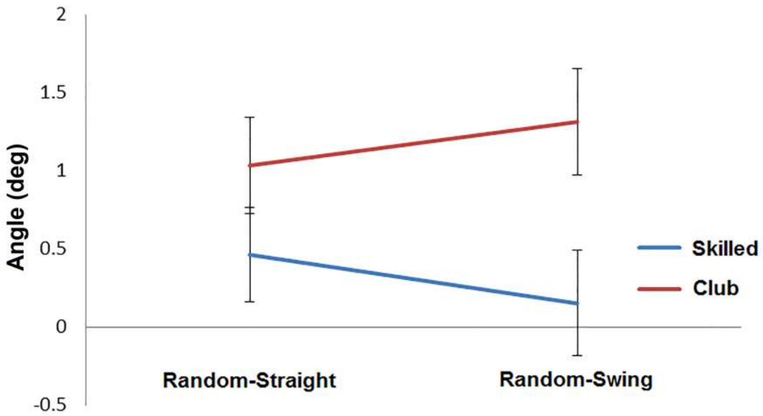

Figure 4.8. Mean group differences for gaze-ball angle as a function of the batter's skill when facing straight and swinging balls. All data are presented with standard error bars.

In addition to the differences found across skill, Figure 4.9 shows that there were other changes present for all batters as a result of ball-swing. The swinging deliveries reduced the likelihood of batters directing their gaze ahead of their head compared to when facing the straight balls (i.e., gaze-head angle; $F(1, 36) = 6.2$, $p = .018$, $\eta_p^2 = .15$; random-straight $M = -2.7$ deg, $SD = 2.2$; random-swing $M = -2.4$ deg, $SD = 2.0$). However, this was largely because the batters maintained a closer and more consistent head-ball coupling when facing the swinging balls (main effect for head-ball angle; $F(1, 36) = 6.27$, $p = .017$, $\eta_p^2 = .15$; see previous paragraph for higher-order interaction; random-straight $M = 3.6$ deg, $SD = 2.4$; random-swing $M = 3.2$ deg, $SD = 2.2$; main effect for SD of head-ball angle; $F(1, 36) = 9.32$, $p = .004$, $\eta_p^2 = .21$; random-straight $M = 5.1$ deg, $SD = 2.8$; random-swing $M = 4.3$ deg, $SD = 2.3$). Batters were also found to show more variability in their lateral head-ball angle when facing the swinging ball (SD of lateral head-ball angle; $F(1, 36) = 12.87$, $p = .001$, $\eta_p^2 = .26$; random-straight $M = 1.4$ deg, $SD = 0.8$; random-swing $M = 1.7$ deg, $SD = 0.8$), though this was probably because the analysis of the swinging trials combined both in-swinging and out-swinging deliveries in which cases gaze was most frequently outside and inside the direction of the ball respectively.

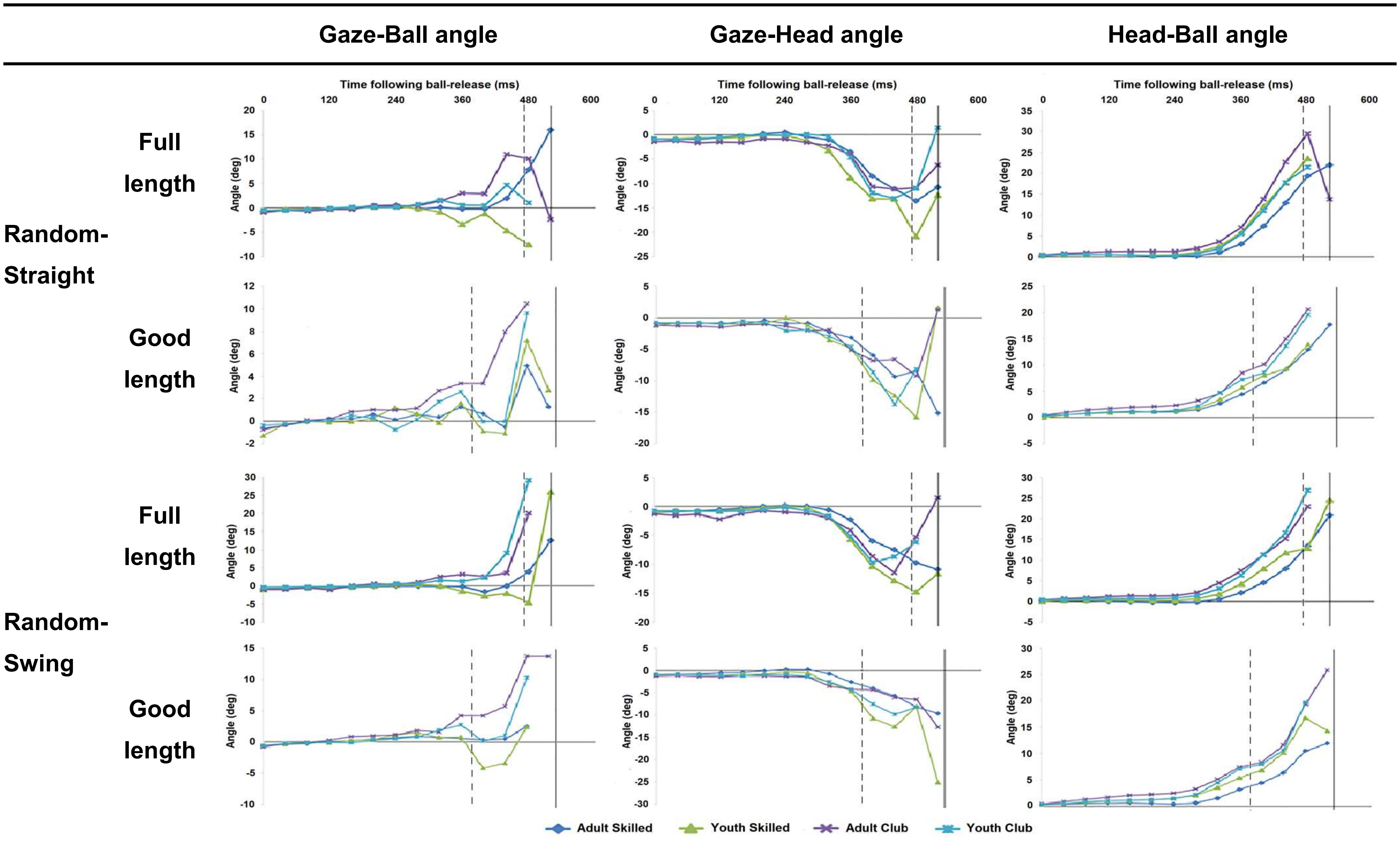

Figure 4.9. Comparisons of the mean (i) Gaze-ball, (ii) Gaze-head, and (iii) Head-ball angles of batters across skill and age when hitting straight and swinging balls bouncing on different ball-lengths. The broken line represents the mean time for ball-bounce, and the solid line represents the mean time for bat-ball contact following ball-release.

4.4.2.3. Predictive saccades.

Contrary to expectations, ball-swing *did not* reduce the likelihood that batters would initiate predictive saccades to ball-bounce. The frequency of saccades to ball-bounce was no different when facing straight or swinging deliveries ($F(1, 39) = 0.16$, $p = .69$, $\eta_p^2 = .00$; random-straight $M = 42.0\%$, $SD = 28.9$; random-swing $M = 41.0\%$, $SD = 29.6$), and this difference was not found to vary with the skill level of the batters ($F(1, 39) = 2.4$, $p = .13$, $\eta_p^2 = .06$) and showed no high-order interactions involving ball-swing (*p*s > .103).

The results for the *oblique* saccades provide evidence though to suggest that the skilled batters were better able to adapt their saccadic behaviour to discriminate between the straight and swinging deliveries. Batters in general performed more saccades towards ball-bounce that were oblique when hitting the swinging ball ($F(1, 39) = 9.51$, $p = .004$, $\eta_p^2 = .2$; random-straight $M = 4.3\%$, $SD = 9.0$; random-swing $M = 7.5\%$, $SD = 9.0$). However, Figure 4.10 shows a skill x delivery interaction ($F(1, 39) = 4.34$, $p = .044$, $\eta_p^2 = .1$) suggesting that the skilled batters performed more oblique saccades when the ball *did* swing, and less when the ball *did not* (random-straight $M = 2.7\%$, $SD = 7.2$; random-swing $M = 8.1\%$, $SD = 7.5$; $p = .001$, $d = 0.73$); whereas the club batters performed a similar number of oblique saccades irrespective of whether the ball did or did not swing (random-straight $M = 5.8\%$, $SD = 10.2$; random-swing $M = 6.8\%$, $SD = 10.3$; $p = .515$, $d = 0.1$).

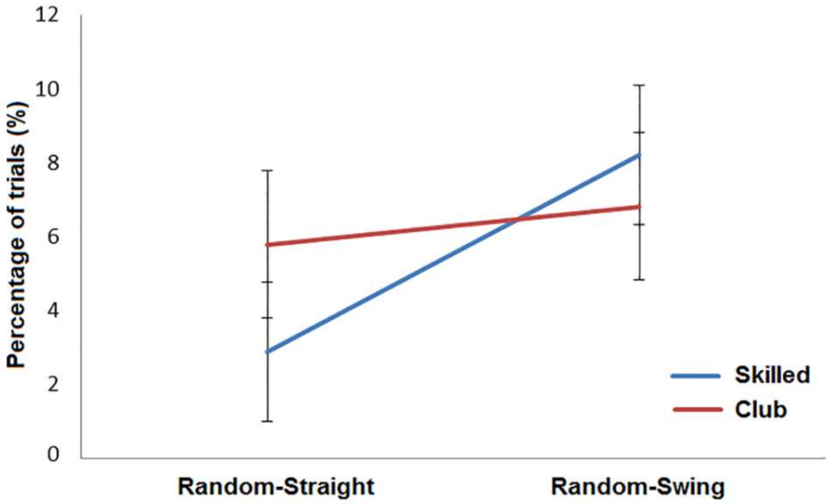

Figure 4.10. Mean group differences for the percentage of oblique saccades towards ball-bounce as a function of the batter's skill when facing straight and swinging balls. All data are presented with standard error bars.

Ball-swing altered the proportion of trials where saccades towards bat-ball contact were produced. Saccades to contact are typically produced on only a relatively small proportion of good-length trials (≈20%) and rarely ever against full-length trials (see Chapter 3). A three-way skill x delivery x length interaction ($F(1, 39) = 5.12$, $p = .029$, $\eta_p^2 = .12$; skill x delivery interaction, $F(1, 39) = 4.98$, $p = .031$, $\eta_p^2 = .11$) revealed skill-related differences for good-length trials. Ball-swing tended to reduce the frequency of saccades towards contact for the skilled batters (random-straight $M = 13.6\%$, $SD = 20.5$; random-swing $M = 6.2\%$, $SD = 10.0$; $p = .065$, $d = 0.36$), yet surprisingly club batters tended to only produce the saccade when the ball swung (random-straight $M = 0.0\%$, $SD = 0.0$; random-swing $M = 2.9\%$, $SD = 6.6$; $p = .064$, $d = 0.62$). Given the lack of saccades against full-length trials, as would be expected the ball-swing did not influence the very few saccades already initiated when facing balls that bounced on a full-length by either the skilled (random-straight $M = 0.6\%$, $SD = 3.0$; random-swing $M = 0.9\%$, $SD = 2.4$; $p = .629$, $d = 0.06$) or club-level batters (random-straight $M = 0.0\%$, $SD = 0.0$; random-swing $M = 0.4\%$, $SD = 1.9$; $p = .33$, $d = 0.32$)

4.4.2.4. Gaze at bat-ball contact.

In general, ball-swing did not significantly alter the ability of the batters to align their gaze with the ball at the moment of bat-ball contact ($F(1, 36) = 1.54$, $p = .223$, $\eta_p^2 = .04$; random-straight $M = 16.3\%$, $SD = 19.1$; random-swing $M = 13.8\%$, $SD = 16.0$). There was, however, a seemingly minor higher-order interaction, with ball-swing influencing the youth batters more than it did the adult batters. A significant three-way age x delivery x length interaction for $\% \, BBC_{fixation}$ ($F(1, 36) = 4.76$, $p = .036$, $\eta_p^2 = .12$) and for $\% \, BBC_{lagging,}$ ($F(1, 36) = 9.91$, $p = .003$, $\eta_p^2 = .22$) suggests that ball-swing increased the likelihood that the youth batters would direct their gaze behind the ball at the moment of bat-ball contact for full-length trials (random-straight $M = 49.1\%$, $SD = 27.4$; random-swing $M = 66.6\%$, $SD = 20.4$; $p = .021$, $d = 0.72$) but not for the good-length trials (random-straight $M = 78.2\%$, $SD = 27.0$; random-swing $M = 71.2\%$, $SD = 19.4$; $p = .339$, $d = 0.3$). No differences were found for the adult batters (ps > .499, ds < 0.13).

4.4.2.5. Discriminant function for swinging trials.

A stepwise discriminant function analysis accurately discriminated between random-straight and random-swing trials with the following prediction equation ($D = 0.36$ * [*gaze-ball angle*] + 0.05 * [*percentage of saccades to bat-ball contact*] + 0.05 * [*percentage of oblique saccade towards ball-bounce*]; $F = 41.61$; *df* 3, 82; $p < .001$; group centroids: random-straight = -1.22; random-swing = 1.22). The predictors in the model highlight that against the swinging ball, batters were more likely to direct their gaze closer to the ball, initiate fewer saccades towards bat-ball contact but increase the prevalence of oblique saccades towards ball-bounce. The model accurately predicted group membership for 90.7% of cases with 100.0% of random-straight and 81.4% of random-swing trials categorised correctly. Cross-validation correctly re-categorised 88.4% of cases with 97.7% of random-straight and 79.1% of random-swing trials.

4.4.3. Inswing vs Outswing Trials

The results comparing each of the dependent variables when facing the out-swinging and in-swinging trials are presented in Table 4.4. Here the main and interaction effects of swing are reported to determine whether the *direction* of ball-swing influenced the kinematic behaviour of the batters. For the sake of simplicity, the main effects of skill and age are not presented in this section as they largely replicate the differences seen in the higher-order interactions with swing reported in the previous section.

Table 4.4.

Descriptive Statistics across Skill and Age When Facing the Outswing and Inswing Trials across the Different Ball-Lengths

		Full				**Good**			
		Outswing		**Inswing**		**Outswing**		**Inswing**	
		Adult	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**
Batting performance									
%Good bat-ball contact	Skilled	60.2 ± 23.7	41.5 ± 30.4	47.6 ± 24.4	60.6 ± 16.3	51.7 ± 28.3	53.3 ± 44.3	77.4 ± 23.4	60.3 ± 35.6
	Club	12.3 ± 20.3	20.8 ± 28.7	42.5 ± 36.3	45.3 ± 27.3	56.7 ± 41.7	41.7 ± 44.6	62.5 ± 33.2	70.2 ± 26.3
%High FoBS	Skilled	58.6 ± 34.4	46.7 ± 44.3	73.9 ± 24.2	70.4 ± 32.0	20.0 ± 22.7	15.8 ± 27.3	19.4 ± 30.0	22.7 ± 18.9
	Club	38.5 ± 46.4	34.2 ± 39.0	62.5 ± 38.5	46.0 ± 32.3	0 ± 0	23.3 ± 32.4	36.7 ± 35.8	38.5 ± 37.2
Gaze and Head tracking (deg)									
Gaze-Ball angle	Skilled	0.6 ± 0.9	-0.1 ± 1.5	0.0 ± 1.2	-0.8 ± 1.3	0.9 ± 1.1	0.6 ± 1.8	0.3 ± 1.1	-0.6 ± 1.3
	Club	1.7 ± 2.8	1.4 ± 2.7	0.9 ± 2.3	1.1 ± 3.4	2.0 ± 1.7	0.9 ± 1.5	1.9 ± 2.4	0.6 ± 1.2
SD Gaze-Ball angle	Skilled	2.7 ± 1.6	3.1 ± 2.1	2.6 ± 1.5	2.5 ± 1.4	2.5 ± 1.9	3.7 ± 3.7	2.1 ± 1.3	3.8 ± 2.2
	Club	5.4 ± 3.1	3.9 ± 3.4	4.9 ± 2.1	4.2 ± 4.5	3.8 ± 1.9	2.4 ± 1.7	5.3 ± 2.1	2.7 ± 1.4
Gaze-Head angle	Skilled	-1.8 ± 2.2	-2.3 ± 2.9	-1.7 ± 1.8	-2.4 ± 2.3	-1.7 ± 1.7	-2.8 ± 2.7	-1.7 ± 1.7	-3.1 ± 2.2
	Club	-2.8 ± 2.9	-2.3 ± 1.4	-3.1 ± 2.5	-2.0 ± 2.1	-2.1 ± 2.5	-2.4 ± 1.1	-3.0 ± 2.3	2.7 ± 1.8
SD Gaze-Head angle	Skilled	3.2 ± 1.9	4.2 ± 2.4	3.7 ± 2.2	3.8 ± 2.1	2.6 ± 1.0	3.8 ± 2.7	3.2 ± 1.0	5.0 ± 2.9
	Club	3.9 ± 2.6	3.4 ± 1.6	3.8 ± 2.5	3.4 ± 2.3	2.6 ± 1.2	2.7 ± 1.4	3.1 ± 2.0	3.3 ± 1.9
Head-Ball angle	Skilled	2.4 ± 2.2	2.3 ± 2.7	1.8 ± 1.9	1.9 ± 2.3	2.6 ± 1.2	3.2 ± 2.7	2.1 ± 1.6	3.1 ± 2.3
	Club	4.6 ± 3.5	3.7 ± 3.0	4.1 ± 2.8	3.2 ± 2.7	4.3 ± 2.7	3.2 ± 1.9	4.9 ± 2.7	3.3 ± 1.9
SD Head-Ball angle	Skilled	4.8 ± 3.0	3.5 ± 2.9	3.8 ± 2.3	3.5 ± 2.2	3.8 ± 2.3	3.9 ± 3.3	3.2 ± 1.7	3.8 ± 2.9
	Club	5.5 ± 3.2	5.2 ± 4.1	5.4 ± 2.9	4.9 ± 3.4	3.8 ± 2.3	3.7 ± 2.2	5.1 ± 2.8	4.4 ± 2.5
% Gaze$_{ahead}$	Skilled	46.3 ± 29.2	59.0 ± 28.8	59.3 ± 30.6	67.7 ± 25.1	32.7 ± 26.1	52.7 ± 18.0	40.2 ± 25.9	46.1 ± 16.9
	Club	43.6 ± 32.5	51.5 ± 23.4	50.0 ± 18.9	54.9 ± 32.8	30.7 ± 20.2	47.6 ± 26.7	40.6 ± 22.7	54.1 ± 21.9
Lateral Gaze-Ball angle	Skilled	0.3 ± 0.9	0.4 ± 0.8	0.5 ± 1.1	0.5 ± 0.8	0.6 ± 1.1	0.4 ± 0.8	0.2 ± 0.9	0.2 ± 0.8
	Club	0.5 ± 1.3	0.2 ± 1.2	1.3 ± 1.8	0.0 ± 0.8	0.9 ± 1.2	0.4 ± 1.1	0.0 ± 2.4	0.1 ± 0.9
SD lateral Gaze-Ball angle	Skilled	1.7 ± 1.9	1.0 ± 0.5	1.2 ± 0.8	1.3 ± 1.1	1.1 ± 0.7	1.0 ± 0.6	0.9 ± 0.5	0.7 ± 0.3
	Club	2.3 ± 1.4	1.5 ± 1.3	2.4 ± 1.7	1.6 ± 1.9	1.4 ± 1.1	1.1 ± 0.8	2.8 ± 2.6	0.9 ± 0.5
Lateral Gaze-Head angle	Skilled	0.1 ± 1.9	0.5 ± 1.4	-0.7 ± 2.4	-0.2 ± 1.3	-0.1 ± 2.2	0.9 ± 2.4	-0.5 ± 2.6	0.0 ± 1.6
	Club	0.3 ± 1.9	0.3 ± 1.4	0.1 ± 2.0	-0.5 ± 1.3	0.3 ± 1.9	0.2 ± 1.5	-0.2 ± 2.3	-0.2 ± 1.7
SD lateral Gaze-Head angle	Skilled	2.1 ± 1.2	1.2 ± 0.8	2.2 ± 1.4	1.7 ± 1.0	1.8 ± 1.3	2.0 ± 1.7	2.3 ± 1.6	1.9 ± 1.1
	Club	2.1 ± 1.2	1.5 ± 1.2	2.3 ± 1.2	1.9 ± 1.2	1.6 ± 0.6	1.1 ± 0.9	2.2 ± 1.3	1.8 ± 1.2
Lateral Head-Ball angle	Skilled	0.4 ± 1.9	-0.1 ± 1.0	1.1 ± 2.0	0.7 ± 1.5	0.6 ± 1.5	-0.3 ± 1.3	0.8 ± 2.1	0.2 ± 1.4
	Club	0.2 ± 1.4	-0.4 ± 1.0	1.1 ± 0.7	0.9 ± 1.2	0.5 ± 0.9	-0.1 ± 0.8	0.4 ± 1.5	0.6 ± 1.3
SD lateral Head-Ball angle	Skilled	1.9 ± 1.8	1.2 ± 0.5	2.4 ± 1.3	2.0 ± 1.1	1.3 ± 0.9	1.3 ± 0.4	1.9 ± 1.3	1.9 ± 1.1
	Club	1.5 ± 0.8	1.4 ± 1.3	2.5 ± 0.9	1.9 ± 1.1	0.9 ± 0.4	0.9 ± 0.5	3.1 ± 2.5	1.5 ± 1.0

Table 4.4 continued.

Gaze at bat-ball contact									
%BBC$_{\text{fixation}}$	Skilled	9.1 ± 15.0	26.4 ± 23.9	21.5 ± 29.3	26.0 ± 31.2	11.6 ± 15.9	25.0 ± 41.0	12.7 ± 13.3	19.4 ± 22.5
	Club	11.9 ± 26.2	6.0 ± 9.7	7.0 ± 15.0	8.7 ± 16.4	6.7 ± 20.0	4.0 ± 12.7	3.7 ± 11.1	19.2 ± 23.9
%BBC$_{\text{lagging}}$	Skilled	73.9 ± 20.0	53.0 ± 24.7	46.4 ± 36.4	52.0 ± 28.3	71.9 ± 27.7	68.6 ± 37.7	64.2 ± 33.1	65.4 ± 29.1
	Club	59.8 ± 34.1	86.4 ± 16.0	60.7 ± 38.2	81.8 ± 16.0	84.9 ± 23.7	84.8 ± 32.4	64.2 ± 28.4	66.0 ± 26.7
%BBC$_{\text{Post-Contact}}$	Skilled	17.0 ± 19.1	20.6 ± 24.0	32.1 ± 30.4	22.0 ± 20.6	16.5 ± 26.9	6.4 ± 16.0	23.1 ± 37.6	15.2 ± 22.3
	Club	28.3 ± 30.4	7.6 ± 16.2	32.3 ± 33.6	9.5 ± 10.3	8.5 ± 17.0	11.3 ± 31.4	32.1 ± 25.9	14.9 ± 27.8
Type of saccades (%)									
Saccade towards ball-bounce	Skilled	48.2 ± 30.0	67.7 ± 26.7	56.5 ± 31.4	64.2 ± 34.1	26.4 ± 29.0	36.7 ± 28.9	39.9 ± 40.5	34.2 ± 30.5
	Club	41.4 ± 50.6	34.5 ± 37.6	58.8 ± 65.5	30.3 ± 27.7	27.5 ± 38.9	22.2 ± 33.3	37.3 ± 45.7	30.2 ± 24.7
Saccade towards bat-ball contact	Skilled	1.0 ± 3.5	1.7 ± 5.3	0 ± 0	1.3 ± 4.0	2.4 ± 5.8	8.3 ± 13.6	1.5 ± 5.6	15.1 ± 24.1
	Club	1.7 ± 5.3	0 ± 0	0 ± 0	0 ± 0	5.0 ± 15.8	2.5 ± 7.9	0 ± 0	4.17 ± 9.0
Oblique saccade towards ball-bounce	Skilled	7.2 ± 12.8	19.8 ± 27.7	16.7 ± 15.4	12.5 ± 17.1	0.0 ± 0.0	2.5 ± 7.9	5.6 ± 13.8	1.3 ± 4.0
	Club	6.3 ± 15.9	4.0 ± 12.6	23.1 ± 32.6	5.8 ± 9.7	1.7 ± 5.3	2.0 ± 6.3	5.0 ± 15.8	6.7 ± 21.1
Timing of saccade (following ball-release; ms)									
Saccade towards ball-bounce	Skilled	414 ± 22	393 ± 26	437 ± 30	417 ± 24	399 ± 38	347 ± 38	399 ± 38	387 ± 24
	Club	407 ± 19	421 ± 23	381 ± 65	373 ± 95	336 ± 41	392 ± 33	375 ± 28	411 ± 30
Saccade towards bat-ball contact	Skilled					520 ± 57	440 ± 33		454 ± 19
	Club								460 ± 85
Oblique saccade towards ball-bounce	Skilled	430 ± 26	417 ± 37	443 ± 42	440 ± 28			360 ± 57	
	Club	413 ± 19		356 ± 120	400 ± 0				

4.4.3.1. Batting performance.

As expected, batters found it more difficult to hit the out-swinging deliveries than they did the in-swinging deliveries (percentage of good bat-ball contacts, *F*(1, 38) = 9.25, *p* = .004, η_p^2 = .2; outswing *M* = 42.3%, *SD* = 26.7; inswing *M* = 58.3%, *SD* = 21.8). The poorer performance against the out-swinging trials was found despite the fact that the batters lowered their forcefulness of bat-swing against those deliveries (percentage of high FoBS, *F*(1, 38) = 13.01, *p* = .001, η_p^2 = .26; outswing *M* = 29.4%, *SD* = 26.9; inswing *M* = 46.3%, *SD* = 24.3; Chapter 2). The lack of any higher-order interactions (*p*s > .207) shows that this difficulty in hitting out-swinging deliveries holds irrespective of the skill and age of the batters and across both ball-lengths.

4.4.3.2. Gaze and head position relative to the ball.

Consistent with the hypothesis, batters were less likely to direct their gaze ahead of the ball when facing the out-swinging balls compared to the in-swinging balls (% $\text{Gaze}_{\text{ahead}}$, *F*(1, 37) = 6.47, *p* = .015, η_p^2 = .15; outswing *M* = 45.5%, *SD* = 24.9; inswing *M* = 51.6%, *SD* = 23.0). Instead, Figure 4.11 shows that gaze tended to lag further behind the ball (gaze-ball angle, *F*(1, 38) = 8.7, *p* = .005, η_p^2 = .19; outswing *M* = 1.0 deg, *SD* = 1.7; inswing *M* = 0.4 deg, *SD* = 1.7).

The direction of ball-swing did not alter the head-ball angle of batters when facing good-length trials (outswing *M* = 3.2 deg, *SD* = 2.2; inswing *M* = 3.2 deg, *SD* = 2.3; *p* = .976, *d* = 0.00), but the angle did increase (i.e., the head lagged further behind the ball) when full-length balls swung away from the batter (outswing *M* = 3.2 deg, *SD* = 2.8; inswing *M* = 2.7 deg, *SD* = 2.5; *p* = .008, *d* = 0.19; direction of swing x length interaction for head-ball angle, *F*(1, 37) = 4.63, *p* = .038, η_p^2 = .11). Despite the patent difficulty the batters experienced against the out-swinging trajectories, their *lateral* head-ball coupling was better when facing those deliveries than it was when facing the in-swinging deliveries. The lateral head-ball angle was lower and was more consistent when facing the out-swinging deliveries (*F*(1, 37) = 18.46, *p* < .001, η_p^2 = .33; outswing *M* = 0.1 deg, *SD* = 1.2; inswing *M* = 0.7 deg, *SD* = 1.5; SD for lateral head-ball angle, *F*(1, 37) = 17.49, *p* < .001, η_p^2 = .32; outswing *M* = 1.3 deg, *SD* = 0.8; inswing *M* = 2.2 deg, *SD* = 1.2), though a significant direction of swing x length interaction for the lateral head-ball angle (*F*(1, 37) = 11.8, *p* = .001, η_p^2 = .24) suggests that this effect was larger for the full-length trials (outswing *M* = 0.8 deg, *SD* = 1.4; inswing *M* = 1.0 deg, *SD* = 1.4; *p* < .001, *d* = .65) than it was for the good-length ones (outswing *M* = 0.2 deg, *SD* = 1.2; inswing *M* = 0.5 deg, *SD* = 1.6; *p* = .138, *d* = .2). Relatedly, batters also had a more consistent lateral *gaze-head* angle when facing the out-swinging deliveries (*F*(1, 37) = 4.29, *p* = .045, η_p^2 = .1; outswing *M* = 1.7 deg, *SD* = 1.0; inswing *M* = 2.0 deg, *SD* = 1.2). These results are probably best explained by the idea that the out-swinging balls generally follow a more head-on trajectory for a longer duration of ball-flight compared to the in-swinging balls (Diaz et al., 2009), meaning that less horizontal head movements are necessary to couple the direction of the head to the ball.

An interaction between the direction of ball-swing and ball-length for the lateral gaze-ball angle (*F*(1, 37) = 13.52, *p* = .001, η_p^2 = .27) revealed that the direction of ball-swing did not alter the batter's lateral gaze-ball angle when facing full-length trials (*p* = .296, *d* = 0.14), but batters did direct their gaze closer in line with the out-swinging ball compared to the in-swinging ball when facing good-length trials (*p* = .005, *d* = 0.38). This was superseded by a somewhat inconsequential three-way age x direction of swing x length interaction (*F*(1, 37) = 6.65, *p* = .014, η_p^2 = .15) whereby the difference was found to be a reflection of the adult (but not youth) batters directing their gaze more towards the outside line of the in-swinging ball when facing full-length (*p* = .187, *d* = .41) but not good-length deliveries (*p* = .839, *d* = .06). No differences were found when facing the more head-on trajectory of the out-swinging balls (*ps* > .348, *d*s < .3).

4.4.3.3. Predictive saccades.

As can be seen in Figure 4.11, the direction of ball-swing did not significantly alter the frequency of the saccades to ball-bounce (*F*(1, 39) = 1.92, *p* = .174, η_p^2 = .05; outswing *M* = 38.1%, *SD* = 31.3; inswing *M* = 43.9%, *SD* = 34.0); however batters did initiate their saccades *earlier* when facing the out-swinging deliveries (*F*(1, 14) = 6.42, *p* = .024, η_p^2 = .32; outswing *M* = 387 ms, *SD* = 30; inswing *M* = 404 ms, *SD* = 21). An age x direction of swing interaction for the percentage of oblique saccades to ball-bounce (*F*(1, 39) = 4.95, *p* = .032, η_p^2 = .11) suggests that the adult batters tended to initiate *more* oblique saccades than the youth batters did when the ball swung in (*p* = .143, *d* = 0.46), but fewer when the ball swung away (*p* = .25, *d* = 0.35).

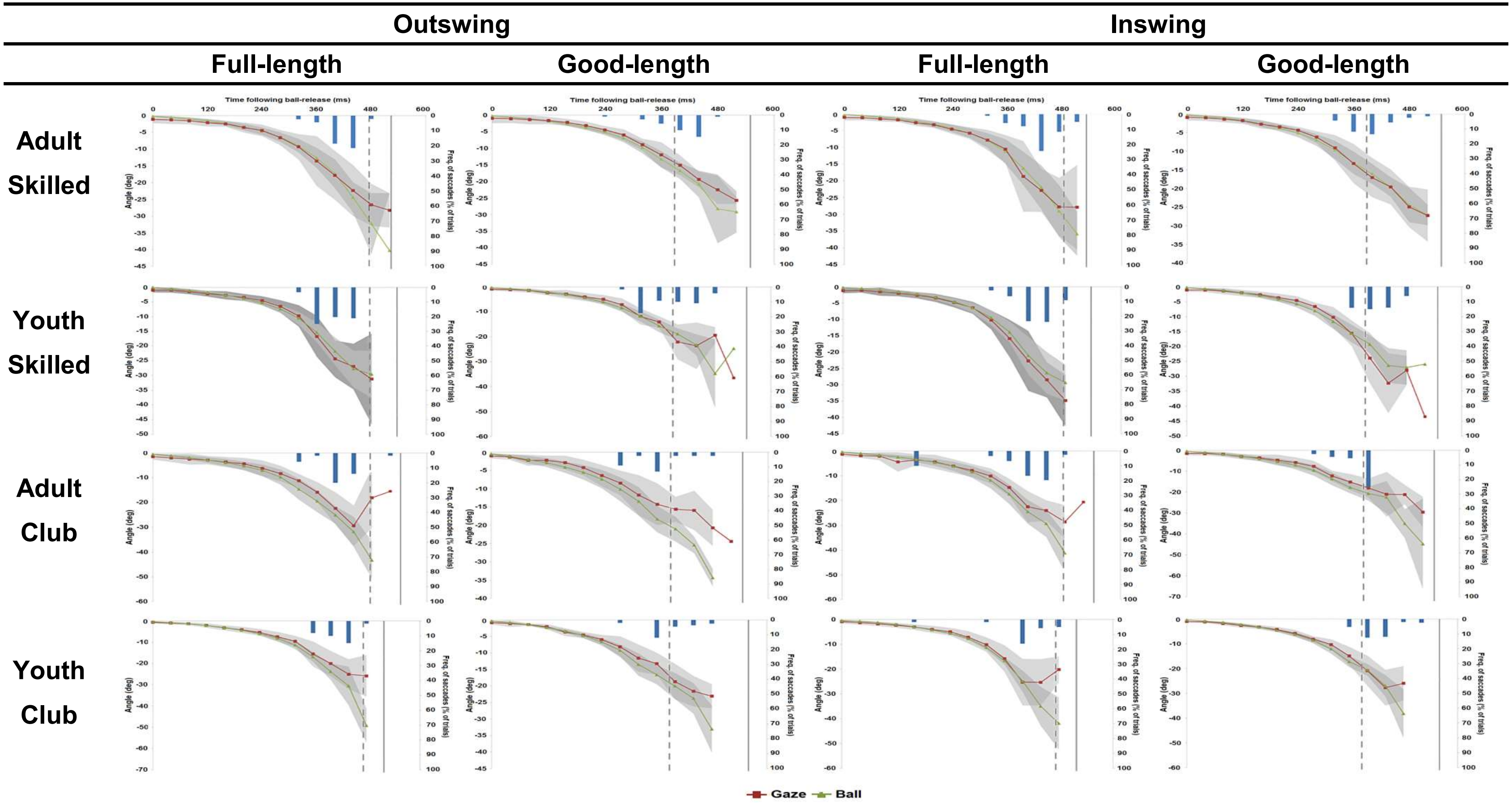

Figure 4.11. Direction of gaze relative to the ball averaged across all batters when facing outswing and inswing deliveries. For each combination of level of batting skill and length, (i) the mean vertical gaze and ball angles (red and green lines respectively), and (ii) for each moment in time following ball-release, the percentage of trials where a saccade was performed. The shaded area represents the standard deviation across trials, the broken black line indicates the mean time of ball-bounce, and the solid black line indicates the mean time of bat-ball contact.

4.4.3.4. Gaze at bat-ball contact.

The direction of ball-swing did not significantly alter the likelihood of batters aligning their gaze with the ball at the moment of bat-ball contact ($F(1, 38) = 0.47$, $p = .497$, $\eta_p^2 = .01$; outswing $M = 12.6\%$, $SD = 19.8$; inswing $M = 14.8\%$, $SD = 18.1$). There was a tendency for gaze to lag behind the ball more so when facing out-swinging deliveries (% $\text{BBC}_{\text{lagging}}$, $F(1, 38) = 4.08$, $p = .051$, $\eta_p^2 = .1$; outswing $M = 72.9\%$, $SD = 21.8$; inswing $M = 62.6\%$, $SD = 26.4$); however this was largely because batters against the in-swinging deliveries were more likely to direct their gaze towards the post-contact direction of the ball before the moment of bat-ball contact (% $\text{BBC}_{\text{post-contact}}$, $F(1, 38) = 4.97$, $p = .032$, $\eta_p^2 = .12$; outswing $M = 14.5\%$, $SD = 16.2$; inswing $M = 22.6\%$, $SD = 24.8$) rather than towards the ball.

4.4.3.5. Discriminant function for the direction of ball-swing.

A stepwise discriminant function analysis accurately discriminated between outswing and inswing trials with the following prediction equation (D = -9.87 + 0.71 * [*SD of lateral head-ball angle*] + 21.73 * [*timing of saccade to ball-bounce*]; $F = 6.65$; *df* 2, 45; $p = .003$; group centroids: outswing = -0.56; inswing = 0.51).The predictors of an out-swinging delivery were a more consistent lateral head-ball angle and an earlier saccade to ball-bounce. The model accurately predicted group memberships for 70.8% of cases with 69.6% of outswing and 72.0% of inswing trials categorised correctly. Cross validation revealed that the successful classification of straight and swinging trials did not change.

4.5. Discussion

The aim of this study was to examine the development of visual-motor expertise of cricket batters when hitting a ball in the presence of ball-swing. The flight-path of the ball was manipulated so that batters of different skill and age levels attempted to hit balls that followed either a straight or a swinging flight-path. Three broad hypotheses were made: (i) that hitting straight trials that were mixed with swinging trials would result in increased uncertainty when compared to hitting straight trials only, leading to a significant change in the gaze and decrease in interceptive performance of the batters. Moreover, these differences were expected to be more noticeable among the lesser-skilled batters; (ii) for trials where the ball did swing, there would be more novice-like gaze behaviour and decreased performance when compared to hitting straight trials; and (iii) the *direction* of ball-swing would significantly influence the visual-motor behaviour and performance of batters, with more profound changes expected when hitting balls that swung away from, when compared to balls that swung in towards, the batter.

4.5.1. The *Possibility* of Ball-Swing Influences Batting Performance and Visual-Motor Behaviour When Hitting Straight Balls

As expected, the awareness that the ball *could* swing significantly altered batting performance even though the ball continued to follow a rectilinear (straight) trajectory. The uncertainty in the ball's flight-path decreased the interceptive accuracy of the batters, but surprisingly this was largely attributable to a specific decrease in the performance of the skilled batters that reduced their interceptive quality to a level that was indistinguishable from that of the club batters. On the basis of findings in baseball batting, Gray (2002) had proposed that skilled batters should be better able to account for uncertainties in ball-fight by combining contextual and perceptual ball-flight information. This did not seem to be the case in the present study. For some reason, the batting performance of the skilled batters was more influenced by the increase in uncertainty about ball-flight than was the performance of the club batters. This finding is also in contrast to that reported in Chapter 2, where the batting performance and *kinematics* of batters were compared in the blocked-straight and random-straight conditions. In that case, when facing the random-straight trials, there was an increase in the frequency of defensive shots yet no difference in performance irrespective of the skill level of the batters. However, the results from Chapter 2 may not have accurately represented the influence of randomisation on batting performance because the analysis was restricted to (i) one particular type of movement (i.e., a forward defensive shot), and (ii) a particular ball-length (i.e., good-length trials). Based on a comparison of these two analyses, it would appear that the interceptive advantage apparent for the skilled batters is based largely on their more aggressive shots (i.e., those other than forward defensive shots) and that it is those shots that were more adversely affected by randomisation. Given the increased temporal precision necessary to successfully execute those actions, it may be that the kinematic delays found as a result of randomisation (presumably to wait and establish whether the ball will swing, see Chapter 2) more adversely affect performance in the more aggressive shots that demand higher temporal precision.

The changes in batting performance found as a result of randomisation were also accompanied by significant changes in gaze. In general, the uncertainty generated by the possibility of ball-swing resulted in changes in gaze that could be considered as 'more novice-like'; that is, gaze lagged further behind the ball, less predictive saccades were performed to both ball-bounce and bat-ball contact (and those saccades to ball-bounce that were performed were delayed), and ultimately batters were less likely to align gaze with the ball at contact. The alterations to the saccades were largely attributable to changes apparent when facing the good-length trials, evidently making it more difficult to face what is already the most challenging ball-length (Bradman, 1958; Chapter 3; Woolmer et al., 2008). There were increases in the *consistency* of the location of gaze and the head relative to the position of the ball when facing the random-straight trials, though this most likely reflects the decrease in anticipatory behaviour (e.g., less saccades) in that condition.

Although it is tempting to conclude that the increased uncertainty in the random-straight condition resulted in more 'novice-like' gaze behaviour that was less predictive, the findings do question the basis on which our understanding of what constitutes 'expert-like' gaze behaviour' have been developed. More predictive behaviour is generally considered to be characteristic of expert performance (e.g., earlier predictive saccades, more saccades, aligning gaze with the ball at contact), yet these findings have been demonstrated largely using experimental designs that encourage prediction (for a similar argument, see Chapter 3). Most studies have employed ball-projection machines that either present trials in a blocked fashion where the bounce point does not vary (e.g., Croft et al., 2009) or where the angle of the ball machine may help to predict the bounce point (e.g., Land & McLeod, 2000), and very few have previously considered how lateral deviations in ball-flight (e.g., ball-swing) could alter prediction. As a result, it is possible that these existing studies have accentuated the predictive nature of gaze as they presented scenarios in which experts were better able to assimilate their knowledge of previous trials to facilitate performance (and predictive gaze) in subsequent trials (e.g., Gray, 2002). In reality though, the competitive environment is likely to be less predictable than what is experienced in most experiments, and so it may be that the expert advantage in the performance environment requires less prediction than what has been captured in experimental conditions.

Collectively, the findings support the idea that the range of possible outcomes can influence the way the action is performed (Todorović, 2010). However, it is still unclear the extent to which uncertainty influences skilled performance. On the one hand, the findings from this study make it easy to conclude that there is a breakdown in the predictive ability of the batters following the possibility of ball-swing. The decrease in interceptive performance and predictive ability of the batters suggest that uncertainty can lead to more ‘novice-like’ behaviour. But on the other hand, these changes in gaze behaviour may reflect a functional adaptation by the skilled batters to more effectively compare predicted and actual ball-flight characteristics in a less predictable environment (e.g., Gray, 2002). For instance, the batters initiating fewer (and delayed) predictive saccades towards ball-bounce is consistent with the idea that when faced with a more challenging ball trajectory, batters generally sample more of ball-flight to more accurately predict the future location of the ball (see Bootsma & van Wieringen, 1990; Chapter 3). Irrespective of the interpretation of the present findings, they do highlight the surprising impact of uncertainty and therefore ‘top-down’ cognitive influences on interceptive performance. Crucially, this study shows that this influence is evident even in significant changes to kinematics (Chapter 2) and visual-motor behaviour (e.g., Sutton, 2007). Clearly top-down influences shape how dynamic time-constrained interceptive tasks like cricket batting are performed, tasks that are sometimes considered to occur rather automatically and outside of conscious awareness (see Shepherd, 2015). This raises an additional dimension for future studies to consider when designing an ecologically valid environment for the examination of the development of visual-motor expertise when performing a fast-paced interceptive action.

4.5.2. The *Presence* of Ball-Swing Significantly Alters Interceptive Performance and Visual-Motor Behaviour

As expected, batting performance when intercepting targets that followed a swinging trajectory was worse than it was for when batters intercepted straight trajectories. This supports the findings of previous studies performed in both *in situ* (Chapter 2) and virtual environments (Craig et al., 2011; 2006) that show performance decrements against curvilinear trajectories. Moreover, it is consistent with the hypothesis of Craig et al. (2009) that the same perceptual variables that allow performers to accurately predict the future arrival location of a target that follows a straight flight-path may be less reliable when the target follows a swinging flight-path (also see Port et al., 1997).

The decrease in batting performance when intercepting targets that swung was underpinned by significant changes in visual-motor behaviour. The discriminant function analysis revealed that the best discriminators of gaze on swinging trials were (i) a closer alignment between gaze and the ball, (ii) an increase in the proportion of oblique saccades to ball-bounce, (iii) and a decrease in the percentage of saccades to bat-ball contact. The first two discriminators suggest that the batters were able to functionally adapt their gaze to account for the ball-swing. That is, the better gaze-ball alignment suggests that batters attempted to track the ball more closely when the ball was swinging, and the increase in oblique saccades to ball-bounce shows that batters were able to predict the future location of the swinging ball. For the latter, the prevalence of all predictive saccades towards ball-bounce did not change when hitting balls that swung (contrary to the expectation), yet a proportion of those saccades were *oblique* rather than straight when hitting the swinging deliveries. Critically, these oblique saccades provide the first report of performers adapting their gaze when intercepting a swinging target *in situ*, supporting previous reports observed in a virtual environment (e.g., Smit et al., 1990). This also sheds new light on the current understanding of visual-motor behaviour during an interceptive action to suggest that perhaps the human visual system *may be* capable of predicting the future location of a swinging ball (*cf.* Craig et al., 2006; Port et al., 1997).

The examination of batting against swinging trajectories revealed new skill-based differences that were not evident when facing the straight trajectories. The better gaze-ball tracking in the presence of ball-swing was more evident for the skilled batters than it was for the club batters, suggesting that skilled batters may be better able to foveate the ball to provide a functional means of facilitating interception under the increasing spatio-temporal demands of ball-swing (e.g., Brenner & Smeets, 2011; Spering et al., 2011). The skilled batters also improved their head-ball tracking and decreased the variability of the tracking in the presence of ball-swing whereas the club batters did not, again suggesting that the skilled batters were better able to adapt their motor behaviour (in this case the head tracking) to assist in the prediction of the future location of the ball (Mann et al., 2013). Moreover, the predictive saccades of the skilled batters to ball-bounce were better attuned to the actual ball-flight characteristics. That is, the skilled batters were better able to adapt their saccades to ball-bounce so that they incorporated an oblique component when facing the swinging deliveries. In other words, the skilled batters produced oblique saccades when the ball swung, but straight saccades when the ball did not. In contrast, the club batters were just as likely to produce oblique saccades when the ball did or did not swing. This shows that the ability to discriminate between swinging and straight trajectories, and to use that information to better predict the future location of the ball, may be a skill that improves commensurate with the development of expertise in batting. Additionally, the lack of any significant interactions with age shows that these skills are likely to be present by late adolescence and continue into adulthood.

Although the comparison of the random-straight and random-swing trials in this section has revealed significant differences in visual-motor behaviour during interception, the magnitude of the changes are less than those found in the previous section when comparing the blocked-straight and random-straight trials. The requirement to hit targets that follow a swinging trajectory is generally considered to be much more challenging than when hitting targets that simply follow a straight trajectory (e.g., Craig et al., 2011; Dessing & Craig, 2010). However, there are typically two key differences between these tasks that could explain the increased difficulty. First, the presence of ball-swing makes the prediction of the location of bat-ball contact more difficult (Craig et al., 2006). Second, the presence of ball-swing more generally increases the uncertainty with which a batter can predict the likely outcome prior of each trial. In this study, these two key differences have been disentangled to better understand the source of the increased difficulty. The findings suggest that both the ball-swing and the uncertainty it creates contribute to the difficulty experienced against swinging trajectories, but it may be that the uncertainty generated by the presence of ball-swing best explains the decrease in performance. However, the results for the *direction* of ball-swing do suggest that the impact of swing is still substantial.

4.5.3. The *Direction* of Ball-Swing Shapes the Visual-Motor Behaviour of Batters

As expected, interceptive performance was significantly worse in trials where the ball swung *away from*, as opposed to *in towards*, the batter, and there was some suggestion that this difference could at least in part be explained by more novice-like gaze behaviour. In particular, gaze lagged further behind the ball when the ball swung away from the batter and this reduced the proportion of ball-flight in which gaze was located ahead of the ball. However, there were no differences in any of the other key markers of expertise (i.e., no difference in the likelihood of saccades towards ball-bounce or bat-ball contact, or in the likelihood of co-aligning gaze with the ball at the moment of bat-ball contact). In fact, the discriminant function analysis revealed that one of the two best discriminators of gaze was the timing of the saccades to ball-bounce; surprisingly revealing that saccades were performed *earlier* when facing the out-swinging balls compared to the in-swinging balls. This finding is in direct contrast to the assumption that earlier saccades are associated with better interceptive performance (e.g., Land & McLeod, 2000). In this case earlier saccades were associated with *poorer* interceptive performance.

It is not immediately clear why out-swinging trajectories result in earlier saccades, although the results for the lateral positions of the head and gaze relative to the ball may provide a clue and help to explain the difficulties experienced when the ball swings away.

The directions of gaze and the head were more closely orientated towards the ball in the horizontal direction when facing the out-swinging deliveries (mean lateral gaze-ball angle, mean and SD of lateral head-ball angle). This better lateral alignment is likely to be a reflection of the decrease in horizontal movements necessary to follow the out-swinging ball. Out-swinging balls generally follow a more head-on trajectory on their path towards the batter (Chapter 2), with the ball more likely to travel along the mid-sagittal plane of the direction in which the batter is facing. Balls that follow a more head-on trajectory have previously been shown to increase the difficulty in which the approach angle of the ball can be detected (Welchman et al., 2004), and the rate at which the ball is deviating laterally (Diaz et al., 2009). This may have resulted in the batters being deceived into thinking that the ball was following a straight rather than swinging trajectory, leading them to perform earlier though ultimately incorrect saccades. Evidently, the ball did swing on those trials and performance was markedly worse.

4.6. Conclusion

The eye and head movement strategies of cricket batters were examined to determine the development of visual-motor expertise when intercepting a fast-moving target in the presence of ball-swing. The results showed that the increased uncertainty present with the possibility of ball-swing significantly reduced the batting performance and predictive ability of batters when hitting straight balls. The changes in gaze would be generally considered to be more ‘novice like’, highlighting the top-down influence of expectations on visual-motor behaviour. When the ball did swing, there was a further decrease in interceptive performance. The presence of swing did result in some changes in gaze that would also be considered more novice-like; however it also resulted in functional adaptations including better gaze-ball alignment and the use of oblique rather than vertical saccades. Crucially, new visual-motor markers of expertise were found when the ball swung, yet also supported most of the existing markers of expertise when hitting straight balls, suggesting that interception in the presence of ball-swing may provide a more sensitive measure for differentiating performers of different skill levels. Balls that swung away from the batter were also more likely to influence batting performance and the ability of batters to align their gaze with the ball.

CHAPTER 5

VISUAL-MOTOR EXPERTISE: EXPLORING THE LINK BETWEEN GAZE AND KINEMATICS WHEN HITTING A FAST-MOVING TARGET

The findings from Chapters 2-4 shed new light on the development of visual-motor expertise when performing an interceptive action. However, examining the batter's gaze and kinematic behaviour in isolation makes it difficult to truly appreciate the intricate coordination of these systems in successful interception. To overcome this, Chapter 5 provides a unique examination of the relationship between gaze and kinematic behaviours for the interceptive task of cricket batting and explores the contribution this linkage makes towards interceptive expertise.

'*Opportunity is missed by most people because it is dressed in overalls and looks like work*'.

Thomas A. Edison

5.1. Abstract

The complex coordination of gaze and kinematic behaviour is essential for the successful execution of goal-directed interceptive actions. Although previous studies have shown that gaze precedes the motor action during the interception of a *stationary* target, this may not necessarily represent the relationship between the two when intercepting a *moving* target. Very little is known about the nature of the relationship between gaze and kinematic behaviour when dynamic interceptive task demands are coupled with severe spatio-temporal constraints, such as those in many fast-ball sports. The aim of this study was to examine whether a link between gaze and kinematic behaviour contributes to the development of visual-motor expertise when intercepting a fast-moving target. The gaze and motor actions of 43 cricket batters, who systematically differed in their skill and/or age level, were examined when hitting a fast-moving ball that bounced prior to arriving at the batter. Of particular interest was the relationship between gaze and kinematics when batters performed a *saccade* to shift their gaze towards the predicted location of ball-bounce. Results revealed that a systematic relationship may exist between gaze and kinematics, with the saccade to ball-bounce showing a stronger temporal relationship with the initiation of bat-downswing for the skilled batters and with the moment of ball-bounce for the lesser-skilled batters. This skill-related difference in the gaze-kinematic coupling was also evident for both youth and adult batters. Batters were not found to alter their kinematics as a result of the timing of the saccade to ball-bounce, but delayed key moments in their hitting action on the trials where a predictive saccade was not present. The saccade to ball-bounce was closely linked with skill-based differences in the temporal sequencing of movements and provides evidence for a functional interaction between gaze and kinematics underpinning successful interception. Overall, this study helps establish a clearer understanding of the coordination through which gaze and motor actions work together to support expertise in the interception of a fast-moving target.

5.2. Introduction

From picking up a cup of tea to hitting a ball, goal-directed interceptive movements require precise visually guided movements to successfully perform the task (Land & Hayhoe, 2001; Land et al., 1999; Tresilian, 2005). When intercepting an approaching target (e.g., a ball), existing studies reveal skill-based differences in the eye movement strategies of performers to guide the end effector (e.g., bat or hand) to coincide with the future arrival location of the target (e.g., Marinovic, Plooy, & Tresilian, 2009; Tresilian, 2004b). Historically, the examination of human perceptual-motor control when interacting with the environment has been approached through the exclusive investigation of either measures of gaze (e.g., Abernethy, 1990; Abernethy & Russell, 1984; Chapters 3 and 4; Land & McLeod, 2000; Müller et al., 2006) or kinematics (e.g., Chapter 2; Cork et al., 2008; Taliep et al., 2007; Weissensteiner et al., 2011). Although these studies have provided valuable (and at times highly influential) insights into the skilled-based differences that exist during interception, in isolation, however, they could fall short of capturing the true essence of why these differences may exist. By heeding the calls for a more multi-disciplinary exploration of goal-directed interceptive behaviours (e.g., Abernethy, 1993; Phillips et al., 2010; Sarpeshkar & Mann, 2011), the concurrent measurement of both gaze and kinematics may help establish a deeper understanding of the strategies surrounding the planning, organisation and execution of skilled movements.

When performing interceptive actions, eye movements have been shown to be strongly coupled, both spatially and temporally, with motor actions (e.g., Diaz, Cooper, Rothkopf, et al., 2013; Land et al., 1999). Specifically, eye movements are generally found to precede a motor action, providing perceptual information that allows the performer to (i) locate the target (ii) establish the target's direction in relation to the performer, (iii) guide the end effector towards the target, and (iv) monitor the action and provide feedback (see Land & Hayhoe, 2001). When examining the eye movements of performers during a well-learned automated task (making a cup of tea), Land et al. (1999) observed that performers typically directed their gaze very closely towards the targeted object, with fixations preceding the initiation of movement by approximately half a second. Performers were thought to utilise this time to obtain perceptual information that identified and located the target of interest, before generating the necessary motor signals to initiate the desired action (see Land & Hayhoe, 2001). Furneaux and Land (1999) observed skill-based differences when examining the coupling between the eye and hand movements of professional and amateur pianists. They reported that when performing a piece of music, the professional pianists, compared to the amateur pianists, were better able to direct their gaze further ahead of the specific note that their hand was currently playing. Critically, professional pianists showed lower variability in the time between the fixation of a specific note and the hand playing that note. The authors proposed that unlike the amateur pianists, who were more likely to read and process musical notes individually, the professional pianists were better able to rely on previous experiences to recognise patterns in the music that enabled them to direct their gaze further ahead of their hand (also see Land & Furneaux, 1997). This is consistent with the idea that skilled performers are better able to extrapolate intermittent visual information to better anticipate the target's future location (see Freyd & Johnson, 1987; Gorman, Abernethy, & Farrow, 2011).

Clearly, the aforementioned studies show that gaze closely guides the motor action when performing an interceptive task and the nature of this coupling may underpin expertise. However, this behaviour is observed when the interceptive target is *stationary* and it is not clear whether the same strategies underpin successful interception when the target is *moving*. A critical distinction required when intercepting moving rather than static targets is that, if the target moves, the sensorimotor system must account for the inherent visual-motor delay required to alter actions on the basis of visual feedback about the position of the target. This visual-motor delay is thought to be about 150 ms (see Saunders & Knill, 2005). This distinction between situations where the target is stationary and those where it is moving are especially pertinent for understanding skill in fast-ball sports where the spatial and temporal constraints of the task often test the boundaries of human achievement (see Walsh, 2014). For instance, when hitting a baseball or cricket ball, a batter typically has less than 600 ms from the moment of ball-release to when the ball must be hit (Regan, 1992, 1997; Regan & Gray, 2001). Considering these severe time constraints, the half a second that fixation would usually precede movement when interacting with stationary targets would not represent a functional or practical strategy to use. As a result, performers need to organise their movements by adopting a strategy that allows them to prospectively determine where the target will be in the near future rather than the present (see Diaz et al., 2009; Sarpeshkar & Mann, 2011).

A possible strategy for performers to anticipate the future location of a target is to use an experience-based model that can predict how the target's flight-path is likely to unfold. Land and Furneaux (1997) proposed that as performers learn the motor actions for a particular task, they also learn the eye movement strategies that go along with it. With practice and the accumulation of experience, performers are understood to develop learnt internal models of the dynamic properties of ball-flight that prepare their gaze and motor action in advance of an expected event. Diaz, Cooper, Rothkopf, et al. (2013) examined the gaze behaviour of naïve performers in an immersive virtual-reality racquetball environment where the ball speed and elasticity following ball-bounce were manipulated. They reported that shortly before ball-bounce, performers directed their gaze ahead of the moving ball to a location where they expected the ball would be 300-400 ms later (170 ms after bounce). This strategy was adapted to maintain the same timing even after changes in the speed and elasticity of the ball. These gaze movements in advance of the ball have been term *anticipatory saccades* (see Bahill & LaRitz, 1984; Land & McLeod, 2000; Mann et al., 2013). The adaptability of these rapid anticipatory shifts in gaze suggest that performers may use information from previous experiences to account for the ball's speed and elasticity to make accurate predictions of the future location of the ball after bounce. Diaz et al. proposed that the spatial and temporal accuracy of these saccades are reflective of performers using an experience-based model to predict future ball-flight trajectories (also see Diaz, Cooper, & Hayhoe, 2013; Diaz et al., 2009).

When examined in fast-ball sports, there is reason to believe that an experience-based model may help to explain the skill-based differences observed in gaze and kinematic behaviour. For instance, Land and McLeod (2000) reported that after cricket batters initially pursuit track the ball following ball-release, they initiate a predictive saccade towards ball-bounce, with the skilled batter initiating this saccade earlier than the lesser-skilled batter (though see Chapter 3). Although it is unclear what functional advantage an earlier saccade towards ball-bounce might provide, an interesting observation from Chapters 2 and 3 was that cricket batters were found to synchronise the timing of their saccade with specific moments in the hitting action when the ball bounced in a particular position (i.e., a *good-length* delivery). That is, when hitting a ball *in situ*, skilled cricket batters initiated their anticipatory saccade towards ball-bounce at a remarkably similar time (≈344 ms after ball-release) to when their foot stride was completed (≈337 ms after ball-release) and when bat-downswing was initiated (≈343 ms after ball-release). Considering that the close coupling of the foot-stride and bat-downswing has previously been shown to be a key marker of expertise in batting (see Chapter 2; Weissensteiner et al., 2011), initiating a predictive saccade at a similar time might be an additional correlate of expertise. The predictive saccade might be linked to the temporal sequencing of movements as batters seek to establish a stable foundation with their feet prior to swinging their bat (e.g., Abernethy, 1981). Specifically, saccades may be temporally aligned with the initiation of bat-downswing to help batters regulate their movement according to the predicted future location of the ball. In other words, a possible reason for this temporal synchronisation between the initiation of a saccade towards ball-bounce and bat-downswing could be that it allows batters to prepare their gaze and motor action based on a common prediction of the future arrival location of the ball (Diaz, Cooper, Rothkopf, et al., 2013; Diaz et al., 2009; Hayhoe et al., 2012). As a result, an experience-based model may allow skilled batters to predict where the ball is likely to bounce, and in turn, determine where (and when) it is likely to arrive. As bat-downswing is initiated, a predictive saccade towards ball-bounce could also provide batters with functional information as early as possible to promote a better detection of, and correction for, unexpected deviations in the ball's flight-path (see Chapters 3 and 4; Hayhoe et al., 2005; Mann et al., 2013). If there were to be a relationship between the timing of the saccade and bat-downswing, then batters who initiate an earlier saccade towards ball-bounce would be expected to also initiate their bat-downswing earlier. On the other hand, if no temporal relationship is present, then a predictive saccade towards ball-bounce would be initiated independent of when the bat-downswing starts (*cf.* Furneaux & Land, 1999).

The aim of the present study was to determine whether a link between gaze and motor actions contributes to the development of visual-motor expertise when intercepting a fast-moving target. To achieve this aim, the gaze and kinematic behaviour of four groups of cricket batters who systematically differed in their level of skill and/or age were examined. Three specific questions were explored. The first was whether a temporal relationship exists between gaze and kinematic behaviours in cricket batting. A temporal relationship was expected to be found between a saccade towards ball-bounce and the initiation of bat-downswing, with the skilled batters expected to show closer coupling between the timing of those two events than the lesser-skilled batters. The second question was whether the *timing* of an anticipatory saccade would shape kinematic behaviour. If an earlier predictive saccade were to provide batters with a functional advantage then beneficial changes in kinematic behaviour (e.g., better movement coordination) would be expected commensurate with earlier saccades. The third question was whether the mere *presence* of a predictive saccade would influence a batter's kinematic actions. It was expected that if a predictive saccade were to serve a functional purpose then superior interceptive accuracy and beneficial changes in motor behaviour would be observed in trials where a predictive saccade was evident.

5.3. Methods

5.3.1. Participants

Forty-three male cricket batters were examined and were categorised into one of four groups according to their level of proficiency in batting (‘skilled’ or ‘club’) and their age (‘adult’ or ‘youth’). The *adult skilled* group (13 batters, $M_{\text{age}} = 25.1$ years, age range: 19-37) comprised of batters who had represented their state/province at a senior level (four were members of the Australian national squad at the time of testing). The *youth skilled* group (10 batters, $M_{\text{age}} = 17.7$ years, age range: 16-18) consisted of batters who had represented their state/province at an under-19 and/or under-17 level (four were members of the Australian under-19s national squad at the time of testing). The *adult club* (10 batters, $M_{\text{age}} = 31.7$ years, age range: 26-39) and *youth club* groups (10 batters, $M_{\text{age}} = 21$ years, age range: 18-23) consisted of lesser-skilled recreational batters who played competitive club cricket for their local district and had not achieved any higher level representative selection. Informed consent was obtained from all batters to a protocol that was approved by the University ethics committee.

5.3.2. Experimental Design

The experiment was conducted at an indoor facility designed to replicate the dimensions and ball rebound characteristics of a synthetic cricket surface. The facility housed a ProBatter ball-projection machine (PX-2-PB2005-87; ProBatter Sports, Milford, CT), which was used to project balls towards the batters (see Portus & Farrow, 2011; ProBatter Sports, 2015). The distance between the batter and the projection machine (≈17.68 m) and the height of ball-release from the ground (2.08 m [subtended angle of 6.66 deg]) replicated those dimensions typically experienced during competition. The ball’s approach angle towards the batter was chosen (≈0.6 m [bearing angle of 1.94°]) to replicate the angle of release during competition. This was achieved by offsetting the batter’s location to the left of the location of ball-release.

The ProBatter ball-projection machine was located behind a large screen (2.6 m x 3.5 m) that displayed a video projection (Hitachi CP-X809 LCD projector, Tokyo, Japan) of a life-sized cricket bowler in their full approach towards the batter (for specific advantages of the ProBatter machine when compared to a live bowler and traditional bowling machines, see Mann et al., 2013). The ProBatter machine was programmed to show a series of different video recordings of a particular bowler (recorded live during competition) so that the ball-flight seen for that delivery was similar to that actually bowled in the video footage. This ensured that any kinematic information offered by the bowler's action matched the actual ball-flight. At the moment of ball-release, a composite ball commonly used in training (Jugs Inc., Tualatin, Oregon) was projected through a hole in the screen at a velocity of ≈33 $m.s^{-1}$ (119 $km.h^{-1}$). This ball-speed was chosen as representative of that commonly encountered during competition, but was also not too fast to be unsafe for the younger batters. Batters used their own cricket equipment (i.e., leg and thigh guards, gloves and cricket bat) and attempted to hit the ball projected towards them. Participants were instructed to bat as they would during a match (i.e., to hit the ball in a manner that would enable them to score runs whilst also minimising the likelihood of being dismissed).

Three distinct areas on the playing surface were selected (*lengths*) to represent the different positions of ball-bounce typically experienced during competition. These *full*, *good*, and *short* lengths were defined relative to the location of the stumps; the batter typically stands ≈1 m in front of the stumps. In the full-length trials (or *deliveries*), the ball bounced 3.5-4.5 m from the stumps, typically requiring them to step *forward* to hit the ball. In the good-length trials, the ball bounced 7.0-8.0 m from the stumps to represent the bounce position commonly considered to be the most challenging to face in cricket because it typically causes indecision as to whether to step forward or backward to hit the ball (e.g., Woolmer et al., 2008). In the short-length trials, the ball bounced 9.0-9.5 m from the stumps, typically requiring the batter to step backward to hit the ball (Figure 5.1; see Chapters 2-4; Pinder et al., 2011a). The arrival location of the ball was also varied according to one of two different *lines* that differed in whether the ball was directed towards or away from the batter's body. These variations in line served only to minimise the likelihood of the batter anticipating the bounce point of the ball and were of no particular experimental interest.

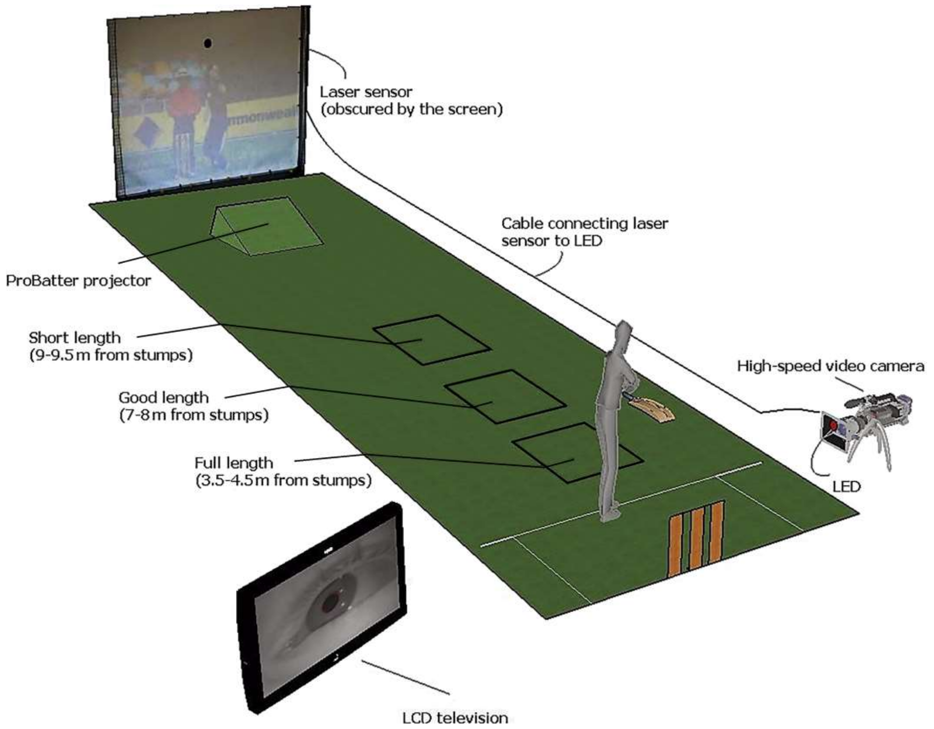

Figure 5.1. Schematic illustration of the experimental set-up. A laser was placed adjacent to the release point on the ProBatter machine so that when broken, the laser would trigger the LED located in the view of the video camera to signal ball-release. The LCD TV was placed adjacent to the test area to monitor the eye tracking system. Bounce areas are shown on the pitch for schematic purposes only and were not present in the experiment proper.

5.3.3. Data Collection

To examine gaze behaviour, participants wore a *Mobile Eye* monocular eye tracker (25 Hz; Applied Science Laboratories, Bedford, MA) while batting. Footage from the Mobile eye was recorded on a portable video recording unit (Sony GV-D 1000 Portable MiniDV Video Walkman, ≈1 kg) that was housed in a lightweight pouch worn around the batter’s waist. Batters wore a customised helmet with a portion of the brim removed to allow sufficient space for the eye tracker camera. To facilitate real time monitoring of the gaze footage, a radio transmitter was also connected to the recording unit to wirelessly transmit the video footage from the eye tracker to an LCD television located adjacent to the test area.

The batter’s movements were recorded using a high-speed video camera (Casio EX-F1, Tokyo, Japan; 300 Hz) located perpendicular to the batter (≈5 m from the batter in the sagittal plane). To record the moment of ball-release, a laser sensor was placed adjacent to the release point of the ProBatter machine, the beam of which, when broken by the ball, would trigger the illumination of a LED placed within the field of view of the high-speed camera (Figure 5.1). There was a 12 ± 0.2 ms delay from the moment of ball-release to the moment the LED was triggered and so this time was subsequently accounted for in the movement times of the batters to reflect timing relative to the true moment of ball-release.

5.3.4. Procedure

Prior to the experiment proper, a short warm-up period (≈10-15 deliveries) was provided for the batters to familiarise themselves with the ProBatter machine, the eye tracker and the range of possible deliveries. Calibration of the eye tracker was performed prior to, and after, the completion of each condition and if the unit was disturbed. Calibration was achieved by using predetermined locations in the visual field when the batter adopted their typical batting stance. During the experiment proper, batters faced two separate counterbalanced blocks of trials. In the block of *blocked-straight* trials, batters faced 18 trials that followed a straight flight-path and were equally distributed across the three different ball-lengths and two lines. In the block of *random* trials, batters faced a mixture of straight (*random-straight*) and swinging deliveries (*random-swing*; the ball followed a curved flight-path). Specifically, the random block consisted of 48 trials that were equally distributed across straight, in-swinging or out-swinging flight-paths for two lines and only two lengths (i.e., full and good-lengths) as the ProBatter machine was unable to project short-length deliveries while imparting swing on the ball. The order of the trials within the blocks followed a predetermined but random sequence that started at a random point in the sequence for each batter. It took approximately one hour for each batter to complete the experiment.

5.3.5. Data Analysis

5.3.5.1. Gaze behaviour.

The eye movement footage was manually viewed frame-by-frame to detect the timing of predictive saccades that took place between the moment of ball-release and bat-ball contact. A saccade was recorded when a distinctive shift in gaze location occurred that was not commensurate with the flight-path of the ball. Specifically, a *saccade towards ball-bounce* was recorded when the change in the rate of movement of gaze was quicker than the flight-path of the ball, was initiated *prior* to ball-bounce, and brought gaze ahead of the ball to a stationary position towards the impending position of ball-bounce (also see

Chapters 3 and 4). The timing of the saccade was reported relative to the moment of ball-release (*mean* ± *standard deviation* in milliseconds). The manual coding of saccadic behaviours for four batters revealed a high degree of intra- and inter-tester reliability (97% and 82% agreement respectively; with intra-tester coding performed four weeks apart).

5.3.5.2. Kinematic behaviour.

Manual inspection of the video footage from the high-speed video camera was performed (Dartfish Classroom Plus, Dartfish Video Solutions, Fribourg, Switzerland, 2012) to determine key kinematic moments in each trial: (i) *the initiation of bat-backswing*, defined as the first frame where the bat moved upward from the ground and continued on to reach the highest vertical point of the bat from the ground during bat-swing, (ii) *the initiation of front-foot stride* was defined as the first frame where the front foot (i.e., the foot furthest from the stumps) started to lift off the ground to move the foot forwards towards the direction of the approaching ball, (iii) *the completion of front-foot stride* was the first frame where any part of the batter's front-foot made contact with the ground following the initiation of front-foot stride, (iv) *the initiation of bat-downswing* was the first frame where the bat moved downwards towards the ground and continued on towards bat-ball contact, and (v) *bat-ball contact* was the moment the bat made contact with the ball. If contact was not achieved, then the moment of bat-ball contact was taken at the moment the bat was closest to the ball (also see Chapter 2).

In addition to the key movement phases, six spatial kinematic measures *of displacement and velocity* were also calculated: (i) the *angular velocity of the bat-downswing*, calculated by dividing the change in bat angle by the time between the initiation of bat-downswing and bat-ball contact (rad.s^{-1}), (ii) *stride length*, the horizontal displacement of the front-foot from the initiation to the completion of the front-foot stride (mm), (iii) *stride velocity*, the stride length divided by the time between the initiation and completion of front-foot stride (m.s^{-1}), (iv) *location of bat-ball contact relative to the stumps*, the horizontal distance from the stumps to the position that bat-ball contact took place (mm), (v) *location of the batter's head relative to the stumps*, the horizontal distance from the stumps to the position of the batter's head at the moment of bat-ball contact (mm), and (vi) the batter's *head position relative to bat-ball contact*, the horizontal distance from the head to the position that bat-ball contact took place (mm). A positive value indicates the head was closer to the stumps than the ball at the moment of contact (Taliep et al., 2007). Calibration of the two-dimensional video footage was performed using known distances of the pitch dimensions in the horizontal direction (from the base of the stumps to the batting crease) and vertical direction (from the base to the top of the stumps). The timing for all key phases of movement for a single participant showed high levels of intra- and inter-tester reliability (minimum 92% and 89% agreement respectively; with intra-tester coding performed six weeks apart).

For this study, only the front-foot defensive responses to good-length deliveries that followed a straight flight-path were analysed. The front-foot defensive shot is a common hitting action where the batter moves forward on their front foot and hits the ball with minimal follow-through (Figure 5.2). Because of the difficulties in comparing the wide range of actions that a cricket batter can perform, this shot is commonly used as an exemplar action to investigate the coordination of movement in batting (e.g., Pinder et al., 2011a; Renshaw et al., 2007; Stretch et al., 1998; Stuelcken et al., 2005). A separate analysis revealed that the gaze and kinematic behaviour of the batters when playing a front-foot defensive shot did not differ when facing straight balls that were presented in a blocked manner or when co-presented with the swinging balls (see Chapters 2-4). As a result, the straight deliveries (i.e., *blocked-straight* and *random-straight* trials) were collapsed together. A total of 198 out of 560 possible good-length trials were analysed: 174 trials were excluded because the batter did not swing their bat to hit the ball (31% of good-length trials); 130 trials because the batter played a shot other than a front-foot defensive shot (23% of good-length trials); 16 trials because of technical difficulties with the eye tracker (3%); and 42 trials because of technical difficulties with the high-speed video camera for three batters (8%). A total of 53 out of the 198 trials analysed showed that batters produced a predictive saccade towards ball-bounce.

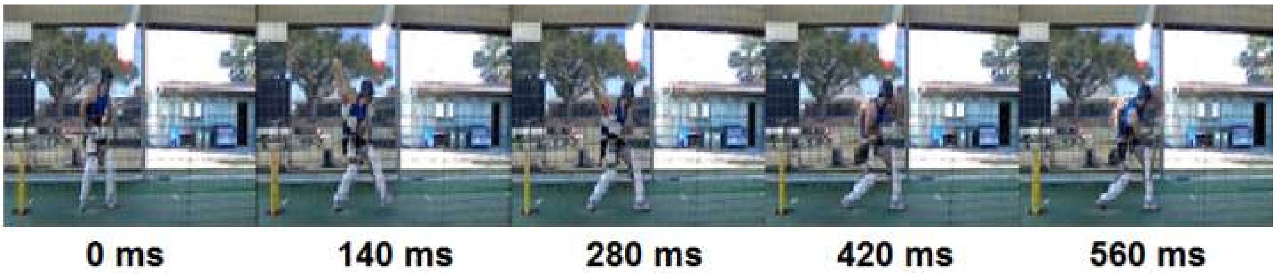

Figure 5.2. Images depicting the temporal sequence of the key phases of the front-foot defensive movement.

5.3.6. Dependent Variables

A number of key variables that were previously found to distinguish batters of different skill levels were measured in this study to examine (a) batting performance, and (b) the relationship between the saccade to ball-bounce and key temporal and spatial kinematic measures.

(a). Batting performance: Batting performance was assessed in real-time by the primary investigator using a measure of *quality of bat-ball contact* (QoC; see Müller & Abernethy, 2008). The QoC provides a simple and validated categorical means of determining whether the batter successfully made contact with the ball, with a score of two, one, or zero given for each trial to represent ‘good’ (ball makes contact with the bat and travels in a direction consistent with the plane of bat motion), ‘poor’ (ball makes contact with the bat and travels in a direction inconsistent with the plane of bat motion) or ‘no contact’ (ball makes no contact with the bat) respectively (see Müller & Abernethy, 2008). This enabled the calculation of the *number of trials with ‘good’ bat-ball contact* (for a similar type of analysis, see Chapters 2-4; Müller & Abernethy, 2006).

(b). Relationship between the saccade to ball-bounce and key temporal and spatial kinematic measures: An exploratory approach was used to determine the relationship between the timing of key gaze and kinematic events. First, the mean and standard deviation of the time-delay between the moment of ball-release and the timing of a *saccade to ball-bounce* were calculated (see Chapters 3 and 4; Land & McLeod, 2000; Mann et al., 2013). Second, the mean and standard deviation were calculated for the time-delay from the moment of ball-release to when each of the following five key kinematic events took place: (i) the *initiation of bat-backswing* (*iBS*), (ii) the *initiation of front-foot stride* (*iFFS*), (iii) the *completion of front-foot stride* (*cFFS*), (iv) the *initiation of bat-downswing* (*iDS*), and (v) *bat-ball contact* (*BBC*; see Abernethy, 1981; Chapter 2; Weissensteiner et al., 2011)*.* This allowed for the calculation of the mean and standard deviation of the time between the saccade to ball-bounce and each of the kinematic events. A positive value reflects a saccade that was initiated *after* the kinematic event whereas a negative value reflects a saccade that was initiated *before* the kinematic event. To examine changes in movement coordination, the mean and the standard deviation of the time between the initiation of front-foot stride and initiation of bat-backswing (*iFFS-iBS*) and the time between the completion of the front-foot stride and initiation of bat-downswing (*cFFS-iDS*) were also calculated (see Chapter 2; Weissensteiner et al., 2011). Additionally,

the mean and standard deviation of the time-delay between the saccade to ball-bounce and the actual moment of ball-bounce was calculated. The moment of ball-bounce was determined by manually viewing the eye movement footage because it was not visible in the high-speed video footage. As a result, the movement of ball-bounce was defined as the moment when the ball made contact with the ground. If ball-bounce was not clearly visible, then the moment of ball-bounce was taken when the ball was closest to the ground. All timing data are reported as the *mean ± standard deviation* in milliseconds.

Two additional analyses were performed to examine the influence of: (i) the relative timing of the saccade to ball-bounce, and (ii) the presence or absence of a saccade to ball-bounce, on the batter's kinematic actions. These analyses examined whether the timing or the mere presence of a saccade to ball-bounce changed the timing of each of the key kinematic events, and movement coordination outlined above. Furthermore, these analyses also examined the influence of a saccade to ball-bounce on key spatial measures of kinematics. This included calculating the mean and standard deviation for the: (i) *angular velocity of bat-downswing* ($rad.s^{-1}$), (ii) *stride length* (mm), (iii) *stride velocity* ($m.s^{-1}$), (iv) *location of bat-ball contact relative to the stumps* (mm), (v) *location of the batter's head relative to the stumps at bat-ball contact* (mm), and (vi) *the batter's head position relative to the ball at bat-ball contact* (mm; see Chapter 2).

5.3.7. Statistical Analyses

For the purposes of statistical analysis, each trial was examined as an individual observation due to the low number of trials per participant. Although this violates the assumption of independence of observations (Field, 2005), previous gaze studies have adopted similar approaches (e.g., Land & McLeod, 2000; Mann et al., 2013).

The interceptive performance of the batters was examined using the Chi-Square (X^2; two-sided) test because the quality of bat-ball contact on each trial was measured using a categorical variable ('good' QoC = 2; 'poor' QoC = 1 and 0). When the expected count for any cell was less than five, the Fisher's Exact Test (FET) was used to determine significant differences. The effect size is reported using the odds ratio (e.g., Field, 2005).

To examine the relationship between gaze and kinematics, three separate analyses were performed. First, to determine whether any relationship between the saccade and key kinematic events differed across the groups of batters, a 2 (Skill: skilled, club) x 2 (Age: adult, club) ANOVA was performed with the time between the saccade and each kinematic event being the dependent variable. A Pearson correlation co-efficient (two-tailed) was also performed to establish the extent to which the pairs of variables were related. Second, to examine whether the timing of the saccade to ball-bounce altered the batters' kinematics, trials were organised into two groups based on the timing of the saccade to ball-bounce (i.e., '*early*' and '*late*'; *n*s = 28 and 25 respectively). When compared across all batters, an 'early' saccade to ball-bounce was defined as a saccade that was initiated closer to ball-release; whereas a 'late' saccade was initiated closer to ball-bounce. A 2 (Skill) x 2 (Age) x 2 (Timing of saccade: early, late) ANOVA was then performed to determine whether the timing of the saccade to ball-bounce influenced the kinematic measures. Third, to determine whether the batters' kinematics altered when a saccade to ball-bounce was present or absent, a 2 (Skill) x 2 (Age) x 2 (Presence of saccade: present, absent) ANOVA was performed using the temporal and spatial kinematic measures as dependent variables. Where the assumption of sphericity was violated, the Greenhouse-Geisser correction was used. Alpha was set at 0.05 for all comparisons. Partial eta squared (η_p^2) and Cohen's *d* values were calculated to indicate the effect size where appropriate.

5.4. Results

5.4.1. Temporal Relationship between Gaze and Kinematics

The skilled batters clearly outperformed the lesser-skilled batters, demonstrated by a significant effect for skill when examining the number of good bat-ball contacts achieved, $X^2(1, N = 198) = 14.37$, $p < .001$; skilled = 85.5%, Club = 60.4%; *OR* = 1.4. There were no differences as a result of age, $X^2(1, N = 198) = 0.05$, $p = .818$; adult = 71.4%, youth = 72.9%; *OR* = 1.0.

Consistent with the results for batting performance, when examining the relationship between gaze and each of the kinematic measures there were no main or interaction effects of note attributable to the age of the batters (see also Chapters 2 and 3). This suggests that differences across groups were present by late adolescence and continued into adulthood. Therefore for the sake of simplicity, the remainder of the results are reported with the groups collapsed across age to simply compare all skilled and club batters.

Table 5.1.

Means, standard deviations and correlations of the time between a saccade towards ball-bounce and each kinematic event across the batter's skill level.

Kinematic event		**Time between saccade to ball-bounce and the kinematic event (ms)**	*Skilled vs. Club*		*Correlations for each group*	
			p	η_p^2	***r***	***p***
Initiation of bat-backswing	Skilled	304 ± 57	.943	.00	.29	.107
	Club	306 ± 94			.11	.641
Initiation of front-foot stride	Skilled	283 ± 69	.312	.02	.06	.734
	Club	259 ± 108			-.12	.612
Completion of front-foot stride	Skilled	-10 ± 79	.819	.00	-.04	.833
	Club	-5 ± 131			-.34	.148
Initiation of bat-downswing	Skilled	-2 ± 49	.124	.05	.22	.213
	Club	-37 ± 107			-.30	.194
Bat-ball contact	Skilled	-212 ± 42	.101	.05	-.09	.627
	Club	-242 ± 83			-.65	.002*
Ball-bounce	Skilled	-55 ± 47	.018*	.11	.074	.681
	Club	-91 ± 57			.738	<.001*

Note: A positive value indicates the saccade took place *after* the kinematic event; whereas a negative value indicates the saccade took place *before* the kinematic event.

r represents the Pearson correlation coefficient (two-tailed) between the timing of the saccade to ball-bounce and the kinematic actions across the batter's skill level. The *p* value indicates whether this relationship was significant or not.

Significant differences are indicated (* *p* < .05).

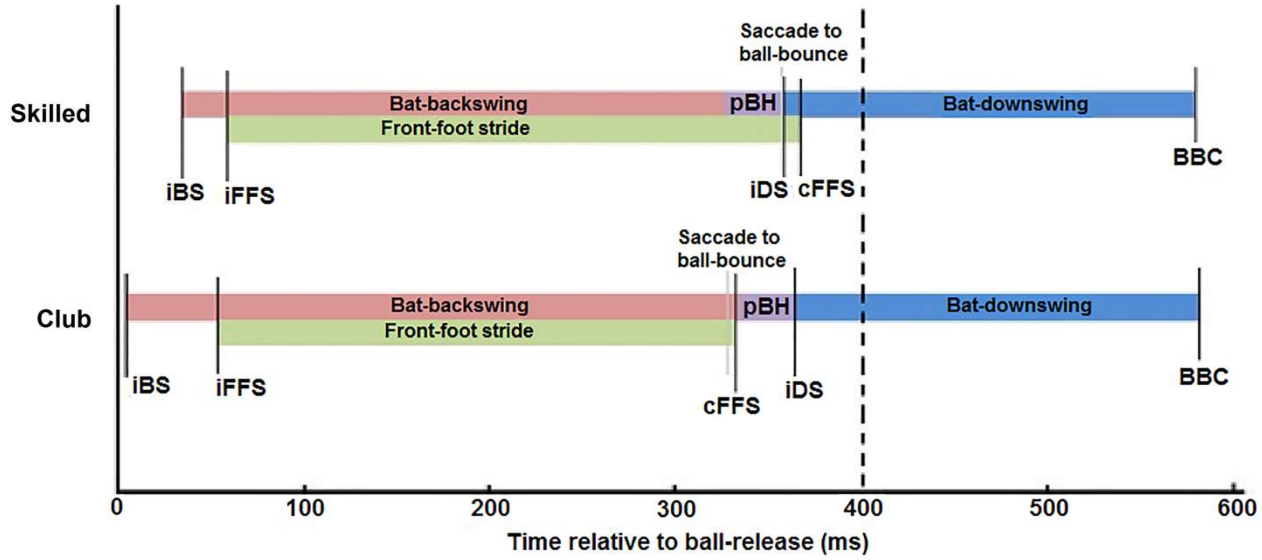

Figure 5.3. Timeline of the key gaze and kinematic events for skilled and club batters. The solid vertical grey line represents the mean timing of the saccade to ball-bounce. The solid vertical black lines represent the mean timing of initiation/completion of each key kinematic moment: iBS, initiation of bat-backswing; *iFFS*, initiation of front-foot stride; *cFFS*, completion of front-foot stride; *pBH*, peak bat-height; *iDS*, initiation of bat-downswing; *BBC*, bat-ball contact. The broken vertical line represents the mean time of ball-bounce.

When performing a front-foot defensive shot in cricket, batters typically initiate their movement by lifting their bat while moving their front-foot forward, and typically only initiate their bat-downswing after their front-foot has made contact with the ground. As Figure 5.3 shows, the batters generally initiated their saccade to ball-bounce at a similar time to those two latter events (completion of front-foot stride and initiation of bat-downswing). To further demonstrate this, Table 5.1 shows the timing of the saccade to ball-bounce relative to each of the five key kinematic events in the front-foot defensive shot. The timing of the saccade was most closely related to the moment the front-foot stride was completed ($M_{time\text{-}delay}$ = -8 ms, *SD* = 100) and to when the bat-downswing started ($M_{time\text{-}delay}$ = -15 ms, *SD* = 77). Although there was no significant difference between the skilled and club level batters for the mean time-delay of any of the five comparisons (from saccade to kinematic moment, *p*s > .1; see Table 5.1), the *standard deviation* of the delay was noticeably lower for the skilled batters for each of the five comparisons.[17] This is consistent with the skilled batters possessing stronger coupling between the saccade and kinematics. Notably, the

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[17] Unfortunately, the statistical comparison of the standard deviations is not possible as each trial is treated as a separate observation and so only the standard deviation across all trials can be reported.

strongest coupling was found between the saccade and the initiation of bat-downswing (lowest standard deviation), suggesting that if a relationship between gaze and kinematics were to exist then it would most likely be an association between these two events. To examine this further, Figure 5.4a shows the saccade-downswing delay across all trials for the skilled and club batters, with the skilled batters clearly showing a more consistent time-delay between the two events. In contrast, the club batters appear to more closely couple their saccades to the moment of ball-bounce. Figure 5.4b shows the time-delay from saccade to the moment of ball-bounce for the skilled and club batters, with the coupling of the club batters (demonstrated by the variability of the time-delay) being much stronger to ball-bounce than it was to bat-downswing. In support, the correlation between the timing of the saccade and the moment of ball-bounce is consistent with there being a fundamental difference in the way that the skilled and club-level batters timed their saccades. Only the club batters had a significant correlation between the timing of the saccade and ball-bounce (r = .738; p = < .001; see Table 5.1). Figure 5.5 shows that the club batters scaled the initiation of their saccade to the moment of ball-bounce, whereas the skilled batters did not. Overall, the skilled batters appeared to couple their saccades more closely with their kinematic actions than the club batters did (more specifically, to the initiation of bat-downswing; Figure 5.4 and Table 5.1).

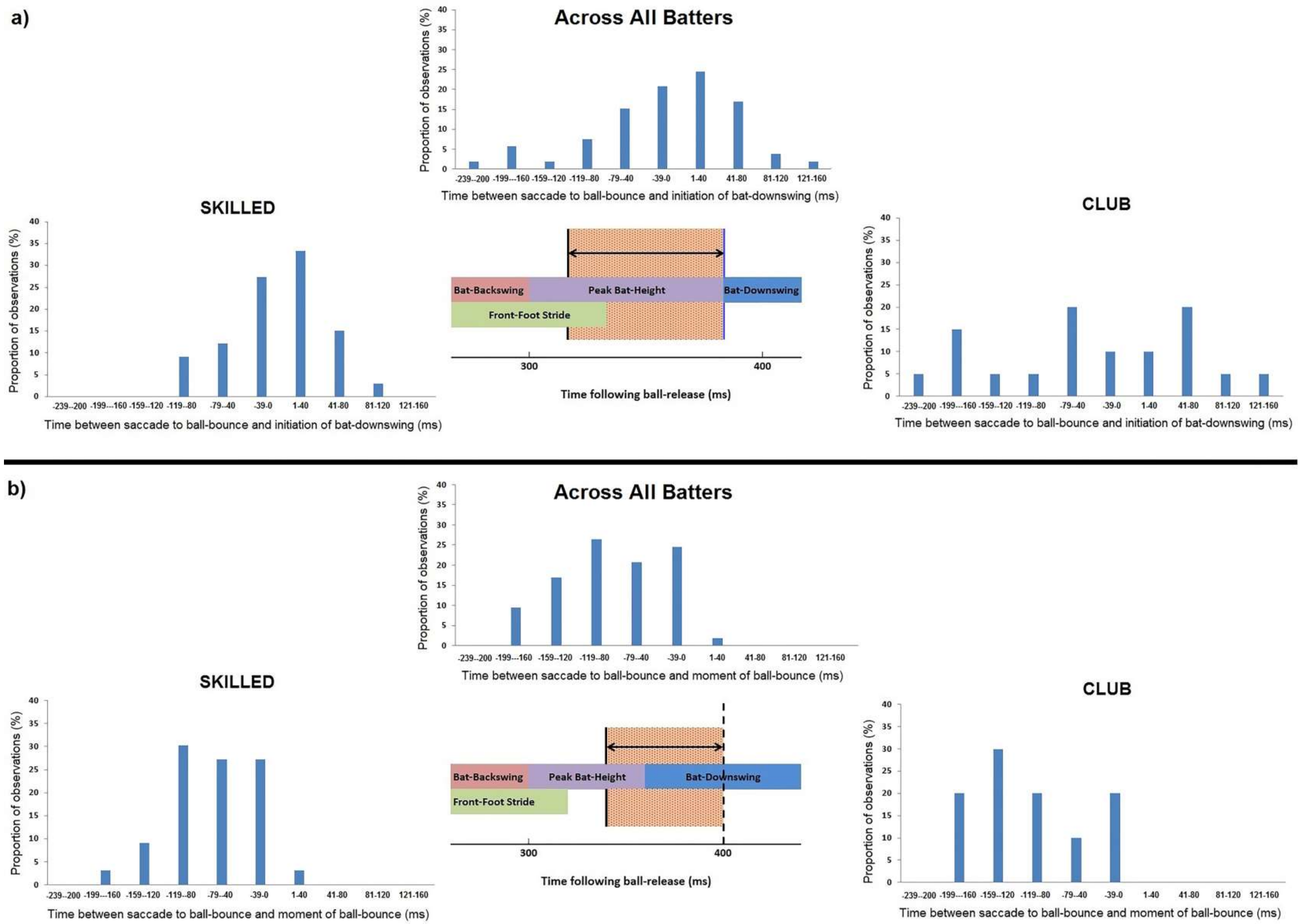

Figure 5.4. Frequency distributions for bins of timing of saccade towards ball-bounce relative to the a) initiation of bat-downswing, and b) moment of ball-bounce. Note that negative timing means that the saccade occurred before the initiation of bat-downswing or ball-bounce. Inset figures show the time-delay (orange area) between the saccade to ball-bounce (solid black line), initiation of bat-downswing (solid blue line) and the moment of ball-bounce (broken black line) relative to the other key kinematic events.

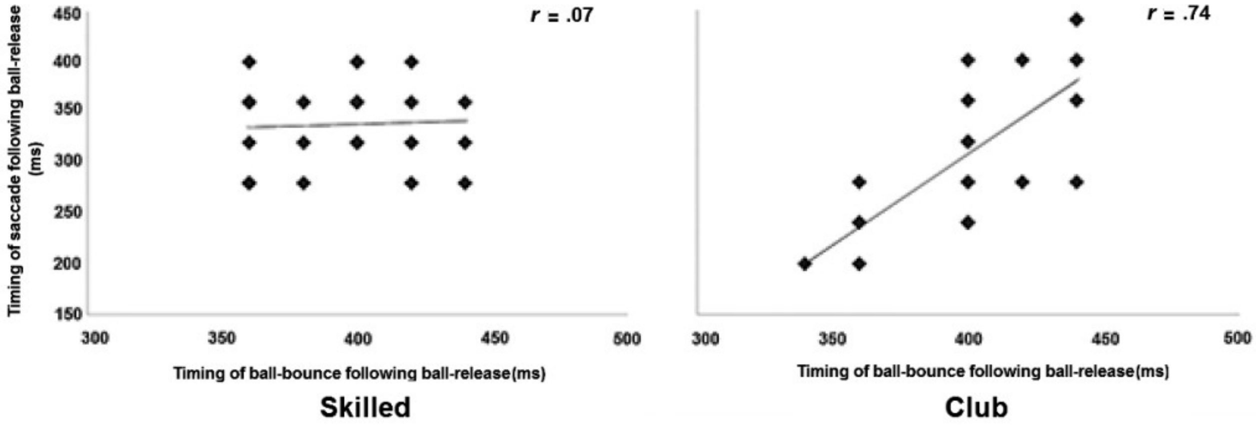

Figure 5.5. Relationship between the timing of the saccade to ball-bounce and the actual moment of ball-bounce for skilled and club-level batters. Regression line and *r* value are included.

It is noteworthy that the timing of the saccades relative to ball-bounce is markedly dissimilar to those timings reported previously. The saccade to ball-bounce was initiated only 68 ms prior to the actual moment of ball-bounce (*SD* = 54 ms; range: -160 to 40 ms), meaning that the saccades were performed much closer to the moment of ball-bounce than the 150-200 ms reported by Diaz, Cooper, Rothkopf, et al. (2013). Moreover, the skilled batters initiated their saccades significantly *later* than the club batters did (*F*(1, 52) = 5.96, *p* = .018; η_p^2 = .11; skilled *M* = -55 ms, *SD* = 47; club *M* = -91 ms, *SD* = 57; also see Chapter 3), a finding that is in stark contrast to the association between skill and earlier saccades reported in the landmark paper by Land and McLeod (2000).

5.4.2. Influence of the Timing of the Saccade on the Kinematic Behaviour of Batters

The mean results comparing each of the kinematic variables as a function of the timing of the saccade to ball-bounce (and the skill level of the batter) are presented in Table 5.2. In this section, the main and interaction effects are presented to determine whether the timing of the saccade to ball-bounce shapes the kinematic behaviour of the batters.

Table 5.2.

Means and standard deviations for the dependent variables relative to the batter’s skill and the timing of the saccade to ball-bounce.

				Timing of saccade		***Skill x Timing of saccade***	
				p	**η_p^2**	***p***	**η_p^2**
Timing of kinematic event following ball-release (ms)							
Initiation of bat-backswing	Skilled	Early	16 ± 50	.309	.02	.09	.06
		Late	49 ± 55				
	Club	Early	6 ± 73				
		Late	2 ± 46				
Initiation of front-foot stride	Skilled	Early	50 ± 62	.869	.00	.296	.02
		Late	60 ± 59				
	Club	Early	58 ± 74				
		Late	37 ± 56				
Completion of front-foot stride	Skilled	Early	344 ± 48	.34	.02	.269	.03
		Late	351 ± 81				
	Club	Early	332 ± 84				
		Late	284 ± 78				
Initiation of bat-downswing	Skilled	Early	330 ± 36	.822	.00	.049*	.08
		Late	349 ± 41				
	Club	Early	357 ± 59				
		Late	328 ± 45				
Bat-Ball contact	Skilled	Early	550 ± 9	.033*	.1	.17	.04
		Late	550 ± 15				
	Club	Early	556 ± 8				
		Late	546 ± 5				
Movement coordination (ms)							
iFFS-iBS	Skilled	Early	-34 ± 52	.292	.03	.713	.00
		Late	-11 ± 63				
	Club	Early	-53 ± 59				
		Late	-35 ± 74				
cFFS-iDS	Skilled	Early	-15 ± 51	.286	.03	.91	.00
		Late	-2 ± 62				
	Club	Early	25 ± 63				
		Late	44 ± 92				

Table 5.2 continued.

				Timing of saccade		Skill x Timing of saccade	
				p	η_p^2	p	η_p^2
Spatial kinematics measures							
Stride speed ($m.s^{-1}$)	Skilled	Early	1.0 ± 0.3	.934	.00	.881	.00
		Late	1.0 ± 0.3				
	Club	Early	1.1 ± 0.5				
		Late	1.2 ± 0.9				
Angular velocity of bat-downswing ($rad.s^{-1}$)	Skilled	Early	10.6 ± 1.2	.805	.00	.384	.02
		Late	10.9 ± 1.6				
	Club	Early	9.7 ± 2.4				
		Late	9.0 ± 1.5				
Stride length (mm)	Skilled	Early	278 ± 100	.47	.01	.278	.03
		Late	289 ± 120				
	Club	Early	315 ± 153				
		Late	254 ± 112				
Location of bat-ball contact relative to the stumps (mm)	Skilled	Early	1573 ± 307	.445	.01	.384	.02
		Late	1681 ± 289				
	Club	Early	1568 ± 319				
		Late	1563 ± 112				
Location of bat-ball contact relative to the batter's head (mm)	Skilled	Early	98 ± 99	.041*	.09	.113	.06
		Late	104 ± 108				
	Club	Early	73 ± 157				
		Late	190 ± 110				
Location of the batter's head relative to the stumps (mm)	Skilled	Early	1475 ± 240	.891	.00	.075	.07
		Late	1578 ± 241				
	Club	Early	1495 ± 300				
		Late	1373 ± 186				

Note: Significant differences are indicated (* $p < .05$).

A significant relationship between the timing of the saccade to ball-bounce and interceptive performance was found for the skilled batters (*N* = 33; *p* = .021; FET) but not for the club batters (*N* = 20; *p* = .354; FET; Figure 5.6). Skilled batters achieved good bat-ball contact on all of their trials when initiating an earlier saccade (100%) but not when initiating a later saccade (66.7%).

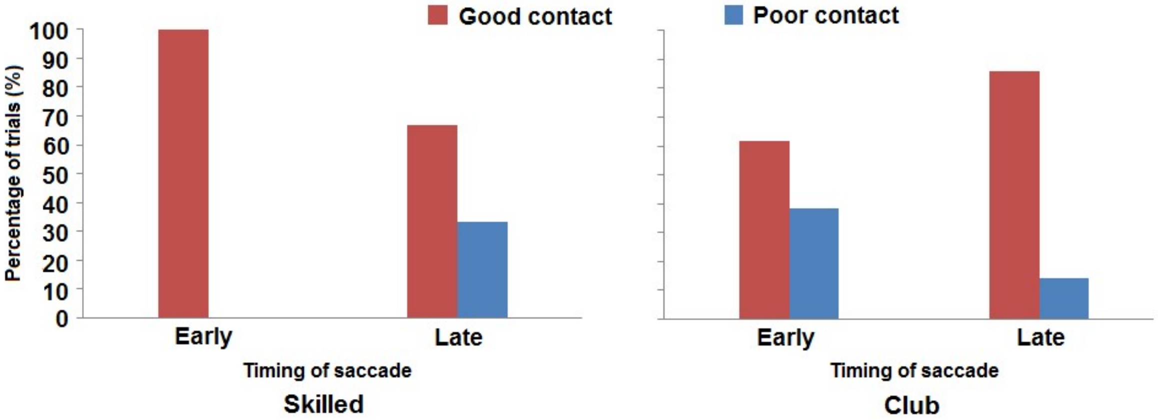

Figure 5.6. Interceptive performance of batters across skill relative to the timing of the saccade to ball-bounce.

Generally, the time at which the saccade to ball-bounce was performed did not alter the timing or spatial measure of the batters' movements (Table 5.2). There were however two broad exceptions. First, an earlier saccade was associated with batters hitting the ball slightly later (i.e., timing of bat-ball contact, *F*(1, 52) = 4.86, *p* = .033; η_p^2 = .1; early *M* = 553 ms, *SD* = 9; late *M* = 549 ms, *SD* = 13) and therefore hitting the ball closer to their head (i.e., head position relative to the ball at bat-ball contact, *F*(1, 52) = 4.41, *p* = .041; η_p^2 = .09; early *M* = 86 mm, *SD* = 127; late *M* = 128 mm, *SD* = 113). Second, consistent with the findings from Section 5.4.2, the initiation of bat-downswing was later on the trials where a later saccade was performed for the skilled batters but not club batters (skill x timing of saccade interaction for the timing of iDS; *F*(1, 52) = 4.09, *p* = .049; η_p^2 = .08). This result further highlights the extent to which the skilled batters synchronised their gaze and kinematics when hitting the ball.

5.4.3. Differences in Kinematics When a Saccade to Ball-Bounce Was Present vs. Absent

The mean results comparing each of the kinematic variables as a function of the presence of a saccade to ball-bounce (and the skill level of the batters) are presented in Table 5.3. In this section, the main and interaction effects are presented to examine the influence of a predictive saccade on the kinematic behaviour of the batters.

Table 5.3.

Means and standard deviations for the dependent variables relative to the batters' skill and the presence of a saccade to ball-bounce.

				Presence of saccade		***Skill x Presence of saccade***	
				p	η_p^2	***p***	η_p^2
Timing of kinematic events following ball-release (ms)							
Initiation of bat-backswing	Skilled	Saccade present	34 ± 54	.001*	.05	.309	.01
		Saccade absent	83 ± 62				
	Club	Saccade present	5 ± 63				
		Saccade absent	38 ± 89				
Initiation of front-foot stride	Skilled	Saccade present	56 ± 59	.901	.00	.298	.01
		Saccade absent	40 ± 60				
	Club	Saccade present	51 ± 67				
		Saccade absent	60 ± 76				
Completion of front-foot stride	Skilled	Saccade present	348 ± 67	.881	.00	.096	.01
		Saccade absent	328 ± 55				
	Club	Saccade present	315 ± 83				
		Saccade absent	340 ± 83				
Initiation of bat-downswing	Skilled	Saccade present	340 ± 40	.167	.01	.716	.00
		Saccade absent	351 ± 67				
	Club	Saccade present	347 ± 55				
		Saccade absent	352 ± 39				
Bat-Ball contact	Skilled	Saccade present	550 ± 12	.783	.00	.196	.01
		Saccade absent	548 ± 15				
	Club	Saccade present	552 ± 9				
		Saccade absent	553 ± 11				
Movement coordination (ms)							
iFFS-iBS	Skilled	Saccade present	-21 ± 59	.001*	.058	.044*	.02
		Saccade absent	42 ± 57				
	Club	Saccade present	-46 ± 63				
		Saccade absent	-23 ± 88				
cFFS-iDS	Skilled	Saccade present	-8 ± 57	.295	.01	.036*	.02
		Saccade absent	23 ± 53				
	Club	Saccade present	32 ± 73				
		Saccade absent	12 ± 76				

Table 5.3 continued.

				Presence of saccade		***Skill x Presence of saccade***	
				p	**η_p^2**	***p***	**η_p^2**
Spatial kinematics measures							
Stride speed (m.s^{-1})	Skilled	Saccade present	1.0 ± 0.3	.681	.00	.005*	.04
		Saccade absent	1.1 ± 0.4				
	Club	Saccade present	1.1 ± 0.7				
		Saccade absent	0.9 ± 0.4				
Angular velocity of bat-downswing (rad.s^{-1})	Skilled	Saccade present	10.8 ± 1.4	.724	.00	.155	.01
		Saccade absent	10.3 ± 1.5				
	Club	Saccade present	9.5 ± 2.1				
		Saccade absent	9.8 ± 1.6				
Stride length (mm)	Skilled	Saccade present	284 ± 110	.88	.00	.044*	.02
		Saccade absent	321 ± 111				
	Club	Saccade present	294 ± 140				
		Saccade absent	254 ± 112				
Location of bat-ball contact relative to the stumps (mm)	Skilled	Saccade present	1632 ± 298	.893	.00	.662	.00
		Saccade absent	1649 ± 330				
	Club	Saccade present	1566 ± 262				
		Saccade absent	1538 ± 271				
Location of bat-ball contact relative to the batter's head (mm)	Skilled	Saccade present	101 ± 102	.025*	.03	.487	.00
		Saccade absent	67 ± 103				
	Club	Saccade present	114 ± 151				
		Saccade absent	59 ± 145				
Location of the batter's head relative to the stumps (mm)	Skilled	Saccade present	1531 ± 243	.384	.00	.887	.00
		Saccade absent	1582 ± 311				
	Club	Saccade present	1452 ± 267				
		Saccade absent	1479 ± 281				

Note: Significant differences are indicated (* $p < .05$).

Consistent with the findings from Chapter 3, the batters did not always initiate a saccade towards ball-bounce when hitting a ball that bounced on a good-length. The batter's ability to intercept the ball was found to be no different when comparing the trials where a saccade was or was not present (i.e., number of good bat-ball contacts when batters *did/did not* initiate a saccade to ball-bounce, $X^2(1, N = 198) = 0.95$, $p = .329$; saccade present = 77.4%, saccade absent = 70.3%; *OR* = 1.1). No relationship was found independently for either the skilled ($X^2(1, N = 97) = 0.28$, $p = .595$; saccade present = 81.8%, saccade absent = 85.9%; *OR* = 0.95) or the club-level batters ($X^2(1, N = 101) = 0.96$, $p = .327$; saccade present = 70.0%, saccade absent = 58.0%; *OR* = 1.2).

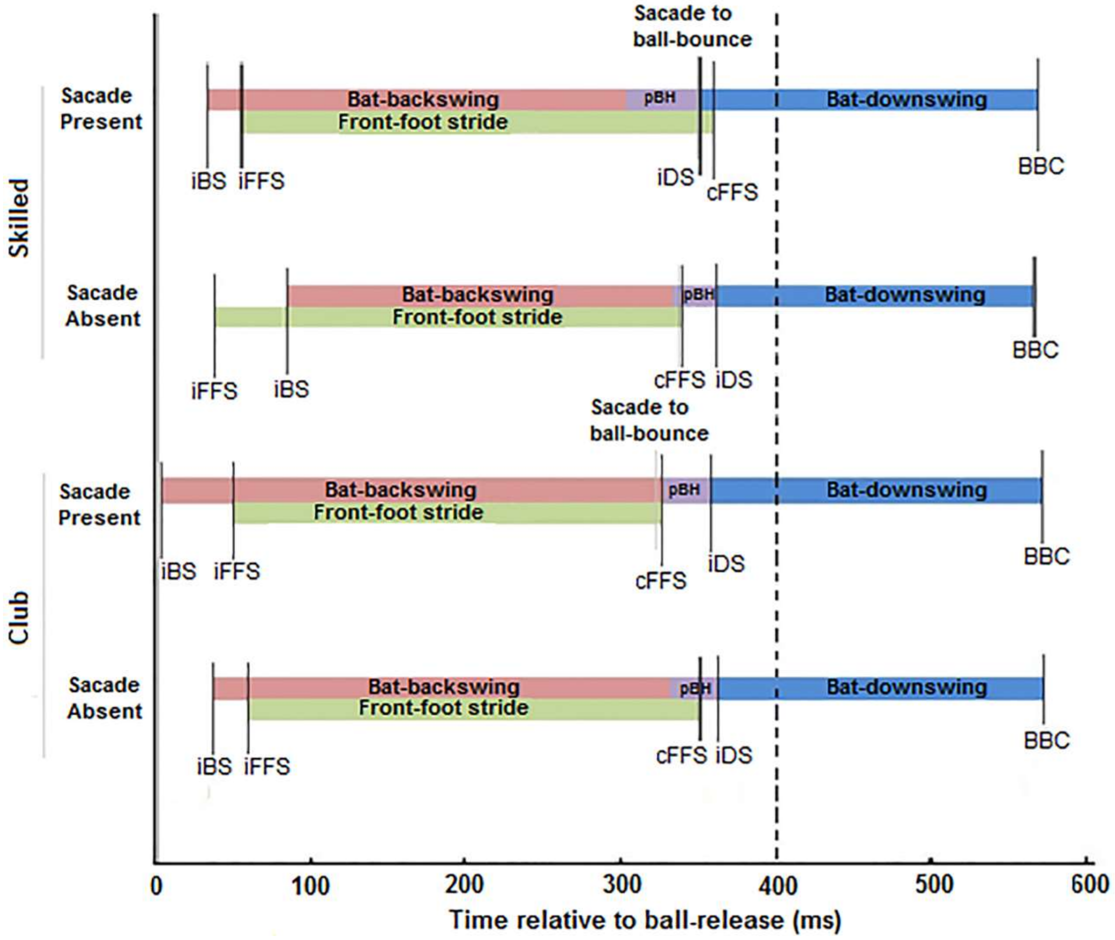

Figure 5.7. Timeline of the key kinematic events across skill when batters did and did not initiate a saccade to ball-bounce. The solid vertical grey line represents the mean timing of the saccade to ball-bounce. The solid vertical black lines represent the mean timing of initiation/completion of each key kinematic moment: iBS, initiation of bat-backswing; *iFFS*, initiation of front-foot stride; *cFFS*, completion of front-foot stride; *pBH*, peak bat-height; *iDS*, initiation of bat-downswing; *BBC*, bat-ball contact. The broken vertical line represents the mean time of ball-bounce.

In general, the absence of a predictive saccade towards ball-bounce was associated with significant differences in the movement kinematics of the batters (Table 5.3). On the trials where saccades were absent, batters delayed the initiation of their bat-backswing (typically the first movement performed) when compared to trials were saccades were present (*F*(1, 197) = 10.61, *p* = .001; η_p^2 = .05; saccade present *M* = 23 ms, *SD* = 59; saccade absent *M* = 57 ms, *SD* = 81). This was true regardless of the skill level of the batters (*F*(1, 197) = 1.04, *p* = .309; η_p^2 = .01). However, Figure 5.7 shows that the coordination of the bat-backswing and initiation of front-foot stride was more influenced by the absence of a saccade in the skilled batters than it was for the club batters, and this was reflected by a skill x presence of a saccade interaction for the timing between the two events (time between iFFS-iBS, *F*(1, 197) = 4.1, *p* = .044; η_p^2 = .02)[18]. Specifically, the skilled batters moved their bat before their front-foot when the saccade was present, but moved their foot before their bat when the saccade was absent. The movement coordination of the club batters was less influenced by the presence or absence of a saccade.

The absence of a saccade was also found to be associated with a change in the other key marker of movement coordination, the time between the completion of the front-foot stride and the initiation of bat-downswing. Skilled batters generally have a closer alignment between these two events than do lesser-skilled batters (see Chapter 2; Weissensteiner et al., 2011). This was the case in the present study when a saccade was present (skilled *M* = -8 ms, *SD* = 57; club *M* = 32 ms, *SD* = 73; *p* = .032, *d* = 0.61). However, a significant interaction between skill and presence of saccade (*F*(1, 197) = 4.44, *p* = .036; η_p^2 = .02) revealed that this expert advantage disappeared when the saccade was absent. In that case, the time between the events was not different between the skilled batters and the club batters (skilled *M* = 23 ms, *SD* = 53; club *M* = 12 ms, *SD* = 76; *p* = .329, *d* = 0.16). This provides some suggestion that the saccade to ball-bounce may play a role in coordinating the temporal sequence of movements of the skilled batters, allowing them to establish a stable foundation from which to facilitate bat-downswing (e.g., Abernethy, 1981; Chapter 2).

In addition to differences in the timing of the kinematic actions, there were also differences in the spatial measures of the batters' front-foot movements when a saccade

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[18] This interaction superseded the main effect for the presence of a saccade *F*(1, 197) = 11.76, *p* = .001; η_p^2 = .06; saccade present *M* = -31 ms, *SD* = 61; saccade absent *M* = 6 ms, *SD* = 82).

was absent. An interaction between the batters' skill and the presence of a saccade was found for the batters' stride speed (*F*(1, 197) = 8.1, *p* = .005; η_p^2 = .04) and their stride length (*F*(1, 197) = 4.09, *p* = .044; η_p^2 = .02). The absence of a saccade did not influence the skilled batters' stride speed (*p* = .254, *d* = 0.35) or stride length (*p* = .785, *d* = 0.08), but it was associated with a decrease in the stride speed of the club batters (*p* = .001, *d* = 0.56) and a shorter stride length (*p* < .001, *d* = 0.6). Considering that the batters' stride was likely to be completed *before* the saccade was initiated (if one was to be produced; see section 5.4.2), then this behaviour may be a reflection of the inability of the club batters to accurately predict the location of ball-bounce on those particular trials.

5.5. Discussion

The purpose of this study was to determine whether a link between gaze and kinematics contributes to the development of visual-motor expertise when intercepting a fast-moving target. The gaze and kinematic behaviour of cricket batters of different skill and age levels were examined to address three specific questions. The first was whether a temporal relationship between gaze and kinematics exists when hitting a fast-moving target. It was hypothesised that, if a relationship was found, the skilled batters would possess closer coupling between the timing of their anticipatory saccade to ball-bounce and a key kinematic event than would the lesser-skilled batters. The second question was whether the time at which the saccades were performed would influence the kinematic behaviour of the batters. It was expected that if an earlier saccade was to be beneficial then it should lead to beneficial changes in movement kinematics. The third question was whether the presence of a predictive saccade towards ball-bounce would be associated with advantageous changes in the batters' kinematic actions. It was hypothesised that on the trials where a saccade was performed, superior interceptive accuracy and visible changes in the batter's kinematics would be observed when compared to trials where no saccade was performed.

5.5.1. The Relationship between Gaze and Kinematics When Hitting a Fast-Moving Target

Consistent with the findings of previous studies (e.g., Mann et al., 2013), the skilled batters in this study were more successful in their interceptive accuracy than were the club batters. Furthermore, the magnitude of these skill-based differences did not change with age. Comparisons across age did not reveal any notable differences in the gaze and/or kinematic behaviour of the batters. This too supports previous reports of skill-based differences in batting performance that suggest that expertise-related differences are evident by late adolescence and are sustained into adulthood (Chapters 2 and 3). It appears that the likely differences in skill between elite adult and youth batters are not evident in their gaze or kinematic behaviour.

The overall findings of this study suggest that a functional relationship between gaze and kinematics may exist and that skilled batters couple their gaze and kinematics more closely than club batters do. The batters in this study initiated their saccades to ball-bounce at a similar time to when their front-foot made contact with the ground and their bat-downswing had started. The strongest relationship was between the timing of the saccade and the initiation of bat-downswing, suggesting that if the gaze and kinematics were to be coupled then it would most likely to be between these two events. Crucially, the coupling between these two events was stronger for the skilled batters than it was for the club batters. This is consistent with the findings from Furneaux and Land (1999) who reported that professional pianists showed a stronger relationship in the time between the fixation of a specific note and the hand playing that note, whereas the amateur pianists were more likely to process these notes individually. This supports the idea that skilled batters were better able to rely on previous experiences to prepare their motor action based on the predicted future location of the ball (also see Diaz et al., 2009; Gorman et al., 2011; Land & Furneaux, 1997). In contrast, the club batters were more likely to couple the timing of their saccades to the moment of ball-bounce rather than with the initiation of bat-downswing. The significant correlation between the timing of the saccade and ball-bounce (r = .738; p = < .001) suggests that the club batters scale the timing of their saccades to the moment of ball-bounce. Collectively, this suggests a fundamental difference in the way that skill and club-level batters mapped the timing of their predictive saccades.

The time-delay between the saccade to ball-bounce and the initiation of bat-downswing may represent a crucial moment in ball-flight where the future location of the ball is predicted, and so the saccade and bat-downswing can be initiated. Generally, batters in this study were found to initiate their saccade and bat-downswing simultaneously. This is similar to the findings from Gribble, Everling, Ford, and Mattar (2002) who reported that EMG activation of the arm during a rapid pointing task was within 20-80 ms of a predictive saccade. Similarly, Hayhoe et al. (2005) reported that when catching a ball thrown with a bounce, the initiation of hand movement occurred at the same time as a predictive saccade. Crucially, the skilled batters in this study coupled their saccade and bat-downswing more closely than the club batters did (skilled vs. club batters, *SD* = 49 vs. 107 ms respectively; see Table 5.1). The strength of this temporal synchronisation could therefore represent a defining characteristic of skilled performance. It may be that the timing of the saccade and bat-downswing are contemporaneous because this is the moment at which the future location of the ball can be predicted. As a result, a saccade can be produced to verify the future location of the ball and the bat movement can commence on the basis of the predicted location.

The results also show that the anticipatory saccade to ball-bounce was initiated at a moment in ball-flight that was considerably *later* than what has been reported previously. Batters were found to initiate their saccade only 68 ms prior to the actual moment of ball-bounce, and within a temporal range of -160 to 40 ms (see Figure 5.4b). This is considerably shorter than the 150-200 ms reported by Diaz, Cooper, Rothkopf, et al. (2013). There are two possible reasons for this. First, the ball-speed used in this study (≈33 m.s^{-1}) was considerably faster than the fastest ball-speed used in the Diaz et al. study (9 m.s^{-1}). As a result, the faster ball-speeds would have carried the ball closer to the moment of ball-bounce before the batters were able to predict the location of ball-bounce. Second, the ball bounced closer to the performer in the Diaz et al. study (≈3 m) than it did in this study (≈7 m); consistent with the idea that the location of ball-bounce can influence the timing of the saccade to ball-bounce (see Chapter 3). In other words, a ball that bounces on a good-length (such as the ones analysed in this study) has been shown to markedly reduce the predictive ability of batters, compared to a ball that bounces closer to the batter (e.g., full-length; see Chapter 3), further supporting the idea that good-length deliveries are the most challenging bounce position from which to hit a ball during cricket batting (see Bradman, 1958; Woolmer et al., 2008). Another crucial point is that in this study, the skilled batters were found to produce *later* saccades to ball-bounce than the club batters were. This is in contrast to the landmark findings of Land and McLeod (2000) who reported that skilled batters make *earlier* (rather than later) saccades than lesser-skilled batters. It is worth noting that the batters in the Land and McLeod study could better predict where the ball would bounce prior to ball-release (as changes in the angle of release from the bowling machine were clearly visible), whereas this was not possible in this study (as the ProBatter machine was located behind a large screen). Let’s now turn to a deeper consideration of this point.

5.5.2. The Influence of the Timing of the Saccade to Ball-Bounce on Kinematics

Motivated by the previous claims that earlier predictive saccades were associated with expertise in interception (Land & McLeod, 2000; though see Chapter 3), this study sought to establish whether there might be a functional advantage in performing an earlier saccade, and if so, what that advantage might be. Despite finding that skilled batters produce significantly *later* saccades than club batters do, the results from this study also show that an earlier saccade to ball-bounce is, in some cases, associated with more successful interception. The interceptive performance of the skilled batters improved when an earlier saccade was performed (in fact, they made good bat-ball contact on all trials with an early saccade), but no relationship was found for the club batters. It is difficult to establish with any certainty whether the performance of the skilled batters became worse *because* of the later saccades, or whether the later saccades are more simply a reflection of the poorer ability to predict the future location of the ball on those trials. The former appears less likely given that the club batters performed earlier saccades yet performed significantly worse. Instead, the timing of the saccade might reflect a crucial moment at which the batter has confidence in the future location of the ball. In Land and McLeod's study, batters could better predict where the ball would bounce in most trials and so the earlier saccades by the skilled batter may be explained by their superior capacity to learn from previous trials and use that information to predict the bounce point in subsequent trials (see Farrow & Reid, 2012). In this study, the position of ball-bounce was more difficult to determine prior to each trial and so effective prediction relied more on the evaluation of real-time ball-flight information. Skilled batters seemed better able to adjust their saccades according to the certainty of their judgements; later saccades were associated with later initiation of bat-downswing and poorer performance. It may be that in those trials the skilled batters were waiting later before initiating their saccade in an effort to extract additional information about how the ball-flight was likely to unfold (Bootsma & van Wieringen, 1990; Chapter 3) to generate a more accurate prediction of where (and when) the ball is likely to arrive (e.g., Diaz et al., 2009; Hayhoe, 2008; Land & Furneaux, 1997). In contrast, there was no association between the timing of the saccade and the performance for the club batters, suggesting that they performed more stereotyped saccades that were initiated at a consistent moment relative to ball-bounce. These findings are consistent with the idea that the skilled batters more flexibly altered the timing of their saccade (and also their final movement) to adapt to the certainty with which they could predict the future location of the ball.

Perhaps surprisingly, the timing of the saccade to ball-bounce was found to have only a limited association with changes in the batters' movements. Most importantly though, the timing of the saccade was related to the moment of bat-downswing initiation in the skilled batters, further underpinning the idea that the timing of their saccades was coupled to the downswing (and not the other measured kinematic variables).

5.5.3. The Influence of the Presence of a Predictive Saccade on Kinematics

Batters in this study did not always initiate a predictive saccade towards ball-bounce (only ≈29% of the trials analysed). This is consistent with the findings from Chapter 3 where it was found that the likelihood that batters would initiate a predictive saccade to ball-bounce was lower on trials where the ball bounced on a good-length (≈39%) when compared to the other bounce locations (full and short-length ≈59 and 42% respectively). However, contrary to this hypothesis and the findings of the previous section, the interceptive performance of the batters did not change if they did or did not initiate a predictive saccade towards ball-bounce. This was surprising given the significant changes in kinematics in the absence of a saccade. It might be that the initiation of a predictive saccade towards ball-bounce provides batters with a more efficacious visual strategy to predict the future location of the ball and promote successful interception. Whereas in the absence of a predictive saccades, batters may change different aspects of their kinematics to sample more of ball-flight and rely more heavily on previous experiences to predict the future location of the ball (e.g., Chapter 2; Diaz, Cooper, Rothkopf, et al., 2013). Considering that the ball followed a straight flight-path in this study, the influence of the presence of a saccade on interceptive performance may be more discernible when intercepting targets with lateral deviations in ball-flight.

In general, batters delayed different aspects of the batting action on the trials where a saccade towards ball-bounce was absent compared to when it was present. When the saccade was absent, all batters delayed the initiation of their bat-backswing, and this particularly influenced the coordination of the skilled batters who, in the absence of a saccade, initiated their front-foot *before* the bat-backswing rather than after (which is what they would typically do in the presence of a saccade, Figure 5.7 *cf*. Chapter 2). The skilled batters also delayed their initiation of bat-downswing (relative to the completion of front-foot stride), with this adaptation resulting in more novice-like behaviour. The club batters produced a foot-stride that was slower and shorter, and ultimately all batters hit the ball closer to the position of their head in the absence of a saccade (i.e., typically later in ball-flight). Each of these observations are consistent with the idea that the batters waited later to initiate and complete their movements in the absence of a saccade. Crucially again though, it cannot be said that the actions were delayed *because* the batters did not initiate a saccade, as most of these actions were performed prior to the initiation of a predictive saccade (if one was performed). Rather, it may represent the trials where batters have poorer knowledge of the ball's present and/or predicted flight-path, resulting in delayed kinematic actions and the absence of a predictive saccade (e.g., Chapters 2-4).

There is also some evidence to suggest that batters may demonstrate more novice-like behaviour on the trials where a saccade towards ball-bounce was absent. Specifically, the close temporal coupling between the completion of front-foot stride and the initiation of bat-downswing has previously been shown to be a key marker of batting expertise (see Chapter 2; Weissensteiner et al., 2011). Although the skilled batters closely coupled those two kinematic events when the saccade was present, this was not the case when the saccade was absent. When there was no saccade, the movement coupling of the skilled batters was indistinguishable from that of the club batters. The skilled batters may have delayed the initiation of their bat-downswing to sample more of ball-flight in the absence of a suitable prediction of the ball's future position (e.g., Chapters 2 and 3).

Collectively, the findings from this study provide evidence of a functional interaction between gaze and kinematics to support successful interception of a fast-moving target. In particularly, the strong temporal relationship between the saccade to ball-bounce and the initiation of bat-downswing may represent a defining characteristic of skilled performance, and could play a crucial role in the temporal sequencing of movements. A potential avenue for future work could be to examine the nature of this relationship following alterations to the task constraints. For example, manipulating the mass of the bat may cause batters to change the timing of the initiation of their bat-downswing (e.g., Fleisig, Zheng, Stodden, & Andrews, 2002). As a result, if this relationship is to be maintained, then changes in the timing of the initiation of bat-downswing would be expected commensurate with changes in the timing of the saccade to ball-bounce. Another possibility could be to examine this relationship when intercepting targets that follow a swinging flight-path. Given that batters significantly change both their kinematic (Chapter 2) and gaze (Chapter 4) behaviour when hitting swinging balls, this may provide a more sensitive measure to determine whether the strength of this temporal relationship is a defining characteristic of skilled performance. The results from these studies can help to better understand the coordinative fashion in which gaze and kinematics might work together to underpin expertise in interception.

5.6. Conclusions

The gaze and kinematic behaviour of cricket batters were examined to determine whether a link between those two parameters would contribute to the development of visual-motor expertise when intercepting a fast-moving target. It was revealed that a general relationship between gaze and kinematics may exist, with a fundamental difference in the way that skilled and club-level batters scale their predictive saccades. Skilled batters appeared to alter their saccades relative to their ability to predict the future location of the ball, and in doing so, also altered the timing of their final movement (the initiation of bat-downswing). In contrast, the club batters coupled the initiation of their saccades to the moment of ball-bounce irrespective of their level of performance on that trial. These skill-related differences were also found to be present regardless of whether youth or adult batters were examined. An earlier saccade was associated with successful interception for the skilled batters, but not the club batters, with skilled batters delaying their final movement when later saccades were performed. The absence of a saccade was associated with significant delays in the initiation and completion of movements and resulted in more novice-like movement coordination in skilled batters. This provides some evidence for skill-based differences in the functional interaction between gaze and kinematics when intercepting fast-moving targets.

CHAPTER 6

DISCUSSION AND CONCLUSIONS: VISUAL-MOTOR STRATEGIES THAT UNDERPIN EXPERTISE IN A FAST-PACED INTERCEPTIVE TASK

‘It’s a long way to the top if you wanna Rock ‘n’ Roll’.

AC/DC

This thesis aimed to establish a comprehensive understanding of the development of visual-motor expertise using interception in the presence of ball-swing as a model of a highly demanding interceptive task. Through the task of cricket batting, the gaze and kinematic behaviour of batters were examined to help determine the visual-motor strategies that underpin successful interception. This final chapter seeks to bring the thesis to a close by drawing conclusions from the key findings of the experimental chapters and outlining the contributions this thesis has made in advancing the current knowledge base regarding expertise in interception. The first section of this chapter seeks to provide a brief overview of the key findings from the four experimental chapters, before drawing on these findings to address the specific aims outlined at the commencement of the thesis. The second section of this chapter outlines the practical implications of these findings, evaluates the limitations in the methodology used throughout the thesis, and offers exciting recommendations that future research may seek to explore.

6.1. Overview of Key Findings

The series of four experimental chapters in this thesis collectively report the findings from one large-scale experiment that examined the gaze and kinematic behaviour of cricket batters *in situ*. In the experiment, four groups of batters, who systematically differed according to their batting skill and age, attempted to hit balls that followed straight and swinging flight-paths and travelled at speeds that more closely replicated those experienced during competition (≈33 m.s^{-1} [119 km.h^{-1}]). The experimental framework adopted throughout the thesis also overcame several limitations of previous studies by examining: (i) a larger number of participants, (ii) a broader range of skill and age groups, and (iii) tasks performed in an environment that more closely replicated that experienced during competition.

6.1.1. Chapter 2: Perceptual Influences of Swinging Flight-Paths Shape the Timing and Coordination of Dynamic Interceptive Actions

The first experimental chapter (Chapter 2) in this thesis sought to examine the movement strategies of performers who attempted to hit balls in the presence and absence of ball-swing. The kinematic behaviour of the batters performing a front-foot defensive shot was examined through the manual examination of high-speed video footage, with interceptive performance assessed in real-time through a simple and validated categorical tool used to determine the quality of bat-ball contact (Müller & Abernethy, 2008).

The interceptive performance was found to clearly discriminate batters of different skill levels, with skilled batters better able to achieve successful bat-ball contact than the club batters when hitting balls that followed a straight flight-path. However, interceptive performance when hitting swinging trajectories was significantly worse than it was when hitting straight balls, irrespective of the skill and/or age level of the batter. These findings are consistent with previous reports which suggest that performers make more errors when predicting the future arrival location of a swinging ball (Craig et al., 2011; Diaz et al., 2009). Moreover for those balls that did swing, batting performance was significantly worse when hitting balls that swung *away* from the batter, compared to ones that swung *in towards* the batter.

Kinematic variables were found to reliably discriminate batters of different skill levels, but not of different ages. In particular, the coupling between the completion of the front-foot stride and the initiation of bat-downswing is a distinguishable quality of skilled batters, supporting previous reports (Weissensteiner et al., 2011). However, it is proposed that the *consistency* of this coupling, rather than the *timing* between those two events, may be better able to differentiate batters of different skill levels. With respect to age, very few differences were found in movement coordination, or in batting performance, between the two age groups. It was therefore concluded that skill-based differences observed in adulthood are also present by late adolescence (see Daum et al., 2007; Haywood et al., 1981), presenting a potentially useful marker for the purposes of talent identification.

The presence (and absence) of ball-swing was found to significantly influence the kinematic behaviour of the batters. The *possibility* that the ball could swing clearly altered the performance and kinematic behaviour of the batters when attempting to hit straight balls, with the uncertainty in the ball's flight-path influencing the club batters more than it did the skilled batters (Gray, 2002). Specifically, the adult club batters, more so than the other groups, showed a significant change in their movement strategy that was consistent with a shift from a pre-programmed movement when the straight balls were blocked together, to a more online control of movement when the straight balls were co-presented with swinging balls. Given that the ball-flight trajectories were identical when facing both the blocked-straight and random-straight trials, this provides evidence to support the idea that the contextual environment in which an action is performed (and the cognitive engagement that goes with it) can significantly influence how that action is accomplished (Shepherd, 2015; Todorović, 2010).

Batters of all skill and age levels were found to significantly delay the timing of each phase of the hitting action in the *presence* of ball-swing. These delays in movement were found as early as ≈50 ms following ball-release, suggesting that batters were able to differentiate straight from swinging balls at a very early point in ball-flight. Batters predominantly compensated for these delayed movements by increasing the angular velocity of bat-downswing, consistent with the idea that batters regulated their movement as late as was permissible on the basis of updated visual information (Bootsma & van Wieringen, 1990). This behaviour also provides evidence to support the anecdotal reports that batters should '*move late, move quickly*' to promote successful interception when facing swinging deliveries (e.g., Woolmer et al., 2008). The results also supported the anecdotal reports that the *direction* of ball-swing significantly influences the behaviour of batters, particularly when hitting balls that swung *away* from the batter. It was hypothesised that the asymmetry between the batter's position and the location of ball-release may be responsible for batters finding it more challenging when facing an out-swinging delivery to detect both the smaller perceived differences in the approach angle of the ball (Welchman et al., 2004) and the rate at which the ball was deviating laterally (Diaz et al., 2009). Collectively, the findings show that the presence of ball-swing significantly influences the interceptive performance and shapes the kinematic behaviour of cricket batters, irrespective of their skill and/or age.

6.1.2. Chapter 3: The Development of Visual-Motor Expertise when Hitting a Ball

The second experimental chapter (Chapter 3) sought to examine the eye and head movement strategies that underpin the development of visual-motor expertise when intercepting a fast-moving target. The batter's eye and head movements were examined through a head-mounted eye tracking system, with interceptive performance assessed in the same manner as in Chapter 2. The visual-motor behaviour of batters was examined across numerous locations of ball-bounce (i.e., *full*, *good*, and *short* length) to avoid inaccurate generalisations that could be made when examining only one stereotypical bounce point (Mann et al., 2013).

Skill-based differences in the frequency with which batters produced a second anticipatory saccade towards bat-ball contact, and maintained gaze at that location when hitting the ball, were found to be key markers of batting expertise (see Mann et al., 2013). Club batters were less likely to direct their gaze ahead of the ball, but instead were more likely to lag behind the ball at the moment of bat-ball contact, meaning they may have less capacity to '*watch the ball onto the bat*'. Consistent with Chapter 2, very few differences in visual-motor behaviour were found across the youth and adult age groups, suggesting that almost all skill-based differences present in adulthood are skills that are likely to be present by late adolescence. However, only the adult-skilled batters, and not batters from the other groups, were found to coordinate the movement of their eyes *and* head direction together when tracking the ball across the different ball-lengths. As a result, maintaining the ball within a consistent reference frame relative to their gaze and head is thought to provide batters with a functional advantage to better predict where the ball is likely to bounce, and also where it is likely to arrive (e.g., Oudejans et al., 1999; Zaal & Michaels, 2003). This ability to do so is proposed to be an additional hallmark of visual-motor expertise. The previous claims that a skilled batter maintains the ball within a single egocentric direction relative to their head (Mann et al., 2013) and initiates earlier saccades to ball-bounce (Land & McLeod, 2000) were not found in this chapter. The difference in the findings across these studies are probably because of the simplified task designs (especially by Land and McLeod; i.e., facing slower ball-speeds and predictable ball trajectories) and/or the limitations of case-study designs employed by those studies that may not accurately capture the visual-motor behaviour seen across the wider population.

Manipulations in the location of ball-bounce significantly influenced the visual-motor behaviour of all batters. Batters regulated the forcefulness with which they swung their bat in order to maintain consistency in their interceptive accuracy across the different ball-lengths, with batters swinging their bat more forcefully when the ball bounced close to them (i.e., full-length delivery). When facing full-length deliveries, club batters were able to direct their head closer to the ball in a manner that was more similar to that of the skilled batters, possibly because of the lower rate at which the vertical height of the ball changes during its flight. Furthermore, club batters also tended to demonstrate expert-like gaze behaviour when the ball bounced further away from them (i.e., short-length delivery; Mann et al., 2013). Although batters were better able to direct their gaze ahead of the ball prior to bat-ball contact irrespective of their skill level, skill-based differences were most evident when facing short-length deliveries. That is, skilled batters performed significantly more saccades to bat-ball contact than the club batters did, and ultimately ensured gaze was directed towards the ball at contact. However, when the ball bounced in between these two ball-lengths (i.e., good-length delivery), batters across skill and age showed more novice-like behaviour by directing gaze behind the ball, producing fewer predictive saccades towards bat-ball contact, and lowering the forcefulness with which they swung their bat. Moreover, the skilled batters initiated their saccade to ball-bounce *later* than the club batters did (*cf.* Land & McLeod, 2000), providing support for the anecdotal reports of good-length deliveries being the most challenging ball-length from which to hit a ball in cricket (Woolmer et al., 2008). Critically, these findings highlight the importance of examining the visual-motor behaviour of performers across the wider population, and in an environment that closely replicates competition, to better understand the development of visual-motor expertise in interception.

6.1.3. Chapter 4: Visual-Motor Adaptations in the Presence of Ball-Swing when Performing a Dynamic Interceptive Action

The third experimental chapter (Chapter 4) sought to examine the eye and head movement strategies of performers when intercepting a ball in the presence of ball-swing. This investigation compliments the movement strategies of batters reported in Chapter 2 when hitting a ball in the presence of ball-swing, whilst also extending the findings from Chapter 3 to determine whether the eye and head movement strategies that allowed performers to hit straight balls would also allow them to account for the increased spatio-temporal demands of hitting balls that swung. The same methods used in Chapter 3 to record eye and head movements and interceptive performance were employed.

The results of Chapter 4 revealed that the *possibility* of ball-swing had a profound influence on batting performance and the predictive ability of the batters when hitting straight balls, supporting the findings from Chapter 2. Surprisingly, the interceptive performance of the skilled batters was indistinguishable from that of the club batters when straight balls were co-presented with swinging balls. With the interceptive advantage of the skilled batters appearing to be based on playing more aggressive shots, the increased temporal precision needed to successfully execute those actions may have adversely affected performance, given that batters also delayed their movements on those trials where ball-swing was possible to establish whether the ball would swing or not (Chapter 2). By simply being aware that the ball could swing, batters of all skill and age groups were also found to demonstrate more novice-like gaze behaviour (*viz.* direct their gaze behind the ball for a larger proportion of ball-flight, delay their saccade to ball-bounce, initiate fewer saccades towards bat-ball contact, and ultimately lag behind the ball at the moment of bat-ball contact). This behaviour was especially true when facing good-length deliveries. This suggests that good-length deliveries (which are already considered to be the most challenging ball-length from which to hit a ball in cricket; Chapter 3) may become even more challenging with the knowledge that the ball could swing (see Todorović, 2010). Collectively, the findings highlight the influence of uncertainty on the gaze and interceptive performance of batters, and is consistent with the idea of ‘top-down’ cognitive influences shaping the performance of tasks that are considered to occur automatically and without thought (see Shepherd, 2015).

The results also revealed a significant decrease in interceptive performance when hitting balls that did swing (Chapter 2; Craig et al., 2011). However, there was evidence that batters functionally adapted their gaze strategies to account for ball-swing by (i) directing their gaze closer to the swinging ball, and (ii) increasing the prevalence of oblique saccades towards ball-bounce. This was more evident for the skilled batters than it was for the club batters, suggesting that skilled batters were better attuned to, and able to account for, the actual ball-flight characteristics. That is, the skilled batters were better able to discriminate between straight and swinging balls by producing oblique saccades when the ball swung and straight saccades when the ball did not. In contrast, the club batters were equally as likely to produce oblique saccades when the ball did or did not swing. This suggests that the ability to discriminate between straight and swinging balls may be a skill that improves with the development of expertise. Critically, this provides the first report of performers adapting their gaze when intercepting a swinging target *in situ*, supporting previous reports of oblique saccades observed in a virtual environment (e.g., Smit et al., 1990). This also suggests that perhaps the human visual system *may be* capable of predicting the future location of a swinging ball (*cf*. Craig et al., 2006; Port et al., 1997).

Performance was also influenced by the *direction* of ball-swing, with batters finding it more difficult to hit out-swinging balls compared to in-swinging balls (Chapter 2). When facing the out-swinging deliveries, batters were found to direct their gaze and head closer to the ball in the horizontal direction, which supports the idea that the out-swinging balls follow a more head-on trajectory towards the batter. This head-on trajectory however, is thought to have made it more challenging for batters to predict the future location of the ball (Chapter 2; Diaz et al., 2009; Welchman et al., 2004), ultimately reducing their interceptive performance.

6.1.4. Chapter 5: Visual-Motor Expertise: Exploring the Link between Gaze and Kinematics when Hitting a Fast-Moving Target

The final experimental chapter in the thesis (Chapter 5) aimed to determine whether a link between gaze and kinematics contributes to the development of visual-motor expertise when performing an interceptive action. Importantly, this is the first investigation to examine the relationship between the gaze and motor actions of a large group of participants when intercepting a fast-moving target *in situ*. The same methods used to record the eye and head movements, the kinematic behaviour, and interceptive performance of the batters throughout the thesis were employed to examine trials where batters performed a front-foot defensive shot when hitting a straight ball.

A functional relationship was found to exist between gaze and kinematics, with batters typically initiating a predictive saccade to ball-bounce at a similar time to the completion of front-foot stride and the initiation of bat-downswing. Particularly, the strongest gaze-kinematic relationship was found for the coupling between the saccade and the initiation of bat-downswing, suggesting that if a relationship were to exist then it would most likely be an association between these two events. Crucially, skilled batters showed a stronger temporal relationship, and a shorter time-delay between these two events when compared to the club batters. This supports the idea that the skilled batters may have relied on previous experiences to extrapolate ball-flight information and prepare their gaze and motor action based on the predicted future location of the ball (Gorman et al., 2011; Land & Furneaux, 1997). In contrast, the club batters were found to be less likely to couple the timing of the saccade with the initiation of bat-downswing, but showed a stronger relationship with the moment of ball-bounce (an external rather than internally timed event). This was thought to suggest a fundamental difference in the way batters of different skill levels timed their predictive saccades. Moreover, these skill-based differences were also not found to differ with age, suggesting that this relationship is comparable for adult and youth batters of the same skill level.

The timing of the saccade to ball-bounce was found to be initiated considerably *later* than was reported previously (e.g., Diaz, Cooper, Rothkopf, et al., 2013). More importantly, skilled batters were found to initiate their saccade to ball-bounce *later* than the club batters did (Chapters 3 and 4); a finding that is in direct contrast to the association between skill and earlier saccades reported by Land and McLeod (2000). Rather, this is consistent with the idea that the skilled batters waited longer for updated visual information to more accurately determine where the ball was likely to bounce (as changes in the angle of release from the ball-projection machine were clearly visible in the Land and McLeod study, but this was not possible in this chapter). The results suggest that perhaps the timing of the saccade to ball-bounce reflects the moment at which the batter has confidence in the future location of the ball. This was supported by skilled batters showing more flexibility in altering the timing of their saccades according to the certainty of their judgements (i.e., a later saccade was associated with a later initiation of bat-downswing, ultimately leading to poorer performance). This relationship was not found in the club batters, which further supports the idea that they were more likely to scale the timing of their saccade relative to the moment of ball-bounce. The timing of their saccades to ball-bounce was found to only have a limited association with their movements. This provides some evidence to suggest that the temporal synchronisation between gaze and kinematics could be a defining characteristic of skilled performance.

The findings also showed that batters did not always initiate a predictive saccade towards ball-bounce (Chapters 3 and 4). Although the interceptive performance of the batters did not change if they did or did not initiate a predictive saccade, considerable changes in kinematics were observed in the absence of a saccade. Specifically, batters were found to delay different aspects of the batting action on the trials where a saccade was absent compared to when one was present. Those delayed actions may be a result of batters possessing poorer knowledge of the ball's present and/or predicted flight-path on those trials rather than being a direct result of the absence of a saccade (as most of the actions would have been performed prior to a predictive saccade if one was initiated). These delays were also associated with a breakdown in the coupling between the completion of front-foot stride and the initiation of bat-downswing, a key marker of batting expertise (Chapter 2; Weissensteiner et al., 2011). This provides some evidence for skill-based differences in the functional interaction between gaze and kinematics when intercepting fast-moving targets. Crucially, these findings establish a foundation for better understanding the coordination through which gaze and motor actions work together to underpin expertise when intercepting a fast-moving target.

6.2. Synthesis of the Findings

6.2.1. The Development of Visual-Motor Expertise and the Expert Advantage

The experimental series provides overwhelming evidence to suggest that group-based differences in the development of visual-motor expertise are attributable to the skill of the performer and that these qualities are likely to be evident by late adolescence. The interceptive performance of the skilled batters was superior to that of the lesser-skilled batters, providing evidence to support the idea that interceptive accuracy can effectively discriminate skilled from lesser-skilled performers (e.g., Müller & Abernethy, 2006; Weissensteiner et al., 2011). However, this difference was mostly found when hitting straight balls that were blocked together (Chapters 3 and 5), and sometimes not in the presence of ball-swing (Chapters 2 and 4). For instance, Chapter 4 showed that the decrease in performance when facing the swinging balls was consistent with the findings of previous studies performed in the virtual environment (Craig et al., 2011; 2006); however, finding that the simple knowledge that the ball could swing reduced the interceptive performance of the skilled batters was remarkable. When compared to the skill-based differences in interceptive performance found in Chapter 2 (where only defensive shots were analysed), Chapter 4 suggests that the poorer performance may be because of the more aggressive shots played by the skilled batters. Given the higher temporal precision required to successfully execute those actions, this may have adversely affected the performance of the skilled batters. The absence of any differences in interceptive expertise between age groups throughout the thesis is consistent with the idea that coincidence timing is likely to have developed at around 15 years of age (Dorfman, 1977). Evidently, valid comparisons of skill-based differences in interceptive performance can be made across different studies between adult and developmental-aged performers.

The results from the thesis also show that there are significant skill-based differences in the gaze and kinematic behaviour of the batters. The skilled batters showed that they were better than the lesser-skilled batters in (i) maintaining close temporal coupling between the completion of the front-foot stride and initiation of bat-downswing (Chapter 2), (ii) directing their gaze ahead of the ball, (iii) initiating a second anticipatory saccade towards bat-ball contact, and (iv) maintaining gaze at that location when hitting the ball (Chapters 3 and 4). Moreover, the skilled batters demonstrated a stronger temporal synchronisation between gaze and kinematics (Land & Furneaux, 1997) by adopting a shorter and more consistent time-delay between the saccade to ball-bounce and the initiation of bat-downswing, whereas the lesser-skilled batters did not (Chapter 5). This functional relationship between these two events further highlights the remarkable visual-motor strategy used by skilled performers to presumably predict the future (arrival) location of the ball and be positioned at the right place at the right time to hit the ball. These findings not only support existing markers of batting expertise in gaze (e.g., Mann et al., 2013) and kinematics (e.g., Weissensteiner et al., 2011), but for the most part, these behaviours were also found to be an important element of expertise when hitting balls that swung (Chapter 4). Specifically against swing, skilled batters were found to be better than the lesser-skilled batters in directing their gaze and head closer to the ball (Mann et al., 2013), whilst also adapting their saccades to ball-bounce (so that they included an oblique component) based on the actual ball-flight characteristics (Chapter 4). As a result, these may form additional markers of skilled interception, which could also potentially be useful for the purposes of talent identification and development.

Overall, the experimental findings from this thesis extend the current knowledge base in two broad ways. First, the findings from this thesis question the basis on which the current understanding of what constitutes ‘expert-like’ gaze behaviour has been developed. Given that most previous studies have employed case-study designs and/or simplified task constraints, these existing studies may not accurately represent the expert advantage (for a similar argument, see Vilar, Araújo, Davids, & Renshaw, 2012). Notably, the experimental findings throughout the thesis challenge the widely held assumption that skilled batters perform earlier saccades when intercepting fast-moving targets (Land & McLeod, 2000). With the findings of the thesis also highlighting the influence of uncertainty on the visual-motor behaviour of performers, it may be that previous studies may not have truly captured the visual-motor behaviour seen across the wider population and within a competitive environment. Second, very few differences were found in the visual-motor behaviour of performers across the two age groups examined, suggesting that skill-based differences are likely to be present by late adolescence and sustained into adulthood. This is not only an important finding for the purposes of talent identification, but also suggests that key markers of expertise (e.g., directing gaze ahead of the ball, initiating a saccade towards bat-ball contact, co-locating gaze with the ball at the moment of bat-ball contact, and adaptive gaze behaviours to discriminate between straight and swinging balls) may be skills that are learnable during the early stages of development.

6.2.2. The Influence of Ball-Swing on Visual-Motor Behaviour during Interception

The experimental findings from this thesis are the first to examine the gaze and kinematic behaviour of performers when intercepting a target following a swinging flight-path *in situ*, with the results providing a clear indication of the significant influence of ball-swing on visual-motor behaviour. Although some of the key markers of batting expertise were found when facing both straight *and* swinging trajectories, Chapters 2 and 4 revealed considerable adaptations in the kinematic and gaze behaviour of performers when accounting for the *possibility*, *presence* and *direction* of ball-swing. In other words, the visual-motor strategies that allowed performers to account for the increased spatio-temporal demands to successfully intercept a target following a *swinging* flight-path may not necessarily be the same as the strategies that allowed performers to intercept a target following a *straight* flight-path.

Simply being aware of the *possibility* of ball-swing was found to significantly alter the visual-motor behaviour of batters of all skill and age groups when hitting straight balls. For instance, Chapter 2 showed that the lesser-skilled batters were more likely to regulate their movement in an online manner when straight balls were mixed with swinging balls, compared to the pre-programmed movement strategy observed when straight balls were blocked together. Furthermore, Chapter 4 also remarkably showed that the interceptive accuracy of the skilled batters was indistinguishable from that of the lesser-skilled batters when straight balls were co-presented with swinging balls. Although this contrasts the findings from Gray (2002), who reported that skilled batters are better able to account for uncertainties in ball-fight by combining contextual and perceptual ball-flight information, this does highlights that uncertainty, and therefore 'top-down' cognitive influences, can have a significant impact on the kinematics (Chapter 2) and visual-motor behaviour of the batters even at the elite level (e.g., Sutton, 2007). Chapter 4 also showed that the uncertainty in ball-flight resulted in batters: delaying their predictive saccade to ball-bounce; initiating fewer saccades towards bat-ball contact; and ultimately lagging behind the ball at the moment it was hit. However, this less predictive gaze behaviour may not necessarily reflect 'novice-like' behaviour as very few studies have previously considered how the possibility of ball-swing could alter the predictive ability of performers. It may be that the experimental designs of previous studies have facilitated prediction, whereas skilled performers during competition may require less prediction than what has been previously captured in experimental conditions. This not only supports the idea that the context in which the action is performed shapes the performance of dynamic interceptive tasks (Shepherd, 2015; Todorović, 2010), but highlights that contextual variability, such as that typically experienced during competition, is crucial for establishing a clearer understanding of the development of visual-motor expertise (Pinder, Davids, Renshaw, & Araújo, 2011b). This representative design should therefore form the cornerstone for future investigations and training paradigms seeking to improve batting performance (see Sarpeshkar & Mann, 2011).

The increased spatio-temporal precision required to hit a ball in the *presence* of ball-swing also significantly altered the visual-motor behaviour of batters. Given the previous hypothesis by Port et al. (1997), and more recently by Craig et al. (2006), that performers do not account for the continuous lateral deviation of ball-flight when predicting the future location of a swinging ball, the collective findings of the thesis may not be fully support this claim. Batters showed adaptations in the timing of their movement when facing the swinging deliveries by delaying the key moments of the hitting action, before compensating for this delay by increasing the angular velocity of bat-downswing (Chapter 2). This behaviour is consistent with the need to obtain updated visual information as late as was permissible before regulating movements in an online manner (e.g., Bootsma & van Wieringen, 1990). Intriguingly, Chapter 2 showed that these changes in movement were found ≈50 ms following ball-release, suggesting that batters may be able to obtain information prior to ball-release to help them differentiate straight from swinging balls very early in ball-flight (e.g., Müller et al., 2006). This ability to discriminate straight from swinging balls was also found to reveal new markers of expertise when examining their eye and head movement strategies. That is, the skilled batters were better than the lesser-skilled batters in directing their gaze and head closer to the ball when facing the swinging balls, but not the straight balls (Chapter 4). Moreover, evidence of predictive *oblique* saccades when intercepting swinging balls *in situ* not only support previous reports of oblique saccades in a virtual environment (e.g., Mrotek & Soechting, 2007), but suggests that the skilled batters were better able to differentiate straight from swinging balls. That is, the skilled batters were better able to adapt their saccadic behaviour by producing oblique saccades when the ball swung, and producing straight saccades when the ball did not. On the other hand, the lesser-skilled batters produced oblique saccades irrespective of whether the ball did or did not swing. This suggests that the ability to predict the future location of a swinging ball may be a skill that improves with the development of expertise in batting. Evidently, the collective findings from this thesis improves the current understanding of the visual strategies used by performers during interception, highlighting that perhaps the human visual system *may be* capable of predicting the future location of a swinging ball (*cf*. Craig et al., 2006; Port et al., 1997). Given though the relatively low proportion of saccades that had an oblique component (≈8% of swinging trials for skilled batters), this is evidently a challenging task to perform.

The thesis also provides empirical support for the anecdotal observations about interception in the presence of ball-swing. First, Chapters 2 and 4 clearly showed that the *direction* of ball-swing significantly influenced the kinematics and visual-motor behaviour of batters, with balls that swung *away* from their body found to be clearly more challenging compared to those that *swung in* towards their body. This not only supports the idea that it would be more challenging to detect the approach angle of a ball that travels along the mid-sagittal plane of the batter (Welchman et al., 2004), and/or to detect the rate at which it was deviating laterally (Diaz et al., 2009), but also shows that this behaviour is observed *in situ* and across different skill and age groups. Second, evidence also provides support for cricket batters following common coaching adages that seek to promote successful interception of a swinging ball. That is, Chapter 2 showed that performers were able to '*move late, move quickly*'; however, adhering to the childhood mantra to '*watch the ball onto the bat*' may be too difficult of a feat for batters to achieve consistently when hitting a swinging ball (Chapter 4; see Cricket Australia, 2005; Woolmer et al., 2008).

The overall findings from this thesis clearly highlight that interception in the presence of ball-swing significantly influences the development of visual-motor expertise when performing an interceptive task. The *possibility*, *presence* and *direction* of ball-swing all influenced the gaze and kinematic behaviour of batters in a number of different ways, revealing new markers of batting expertise and/or increasing the magnitude of existing skill-based differences. It is clear that both ball-swing *and* the uncertainty it creates contribute to the increased difficulty experienced when facing swinging deliveries. As a result, this thesis puts forward a case for using the presence of ball-swing as an effective model from which to examine the development of visual-motor expertise when performing an interceptive task, and a potentially more sensitive measure for differentiating the visual-motor behaviour of skilled from lesser-skilled performers.

6.2.3. The Relationship between Gaze and Kinematics when Intercepting Fast-Moving Targets

Another unique contribution to the current literature made by this thesis was to establish whether a link between gaze and kinematics contributes to the development of visual-motor expertise when intercepting a fast-moving target. Extending the findings from Land et al. (1999), who reported that gaze was closely coupled with movement when intercepting *stationary* targets, Chapter 5 showed a functional relationship between gaze and kinematics when intercepting a *moving* target.

The findings from Chapters 2 and 3 showed that batters typically initiated a predictive saccade towards ball-bounce at a remarkably similar time to when completing their front-foot stride and when initiating their bat-downswing. Moreover, Chapter 5 revealed that this gaze-kinematic relationship was strongest between the saccade and the initiation of bat-downswing, suggesting that if gaze and kinematics were to be coupled then it would most likely to be between these two events. Crucially, the coupling between these two events was closer, and stronger, for the skilled batters than it was for the lesser-skilled batters. This is consistent with the idea that skilled batters are better able to rely on previous experiences to extrapolate ball-flight information and prepare their motor action based on the prediction of the future location of the ball (see Furneaux & Land, 1999; Gorman et al., 2011; Land & Furneaux, 1997). In other words, this temporal synchronisation may provide skilled batters with a functional advantage where a saccade to ball-bounce helps predict the future location of the ball, and bat movement can commence on the basis of the predicted location. In contrast, the lesser-skilled batters were more likely to couple the timing of the saccade with the moment of ball-bounce rather than with the initiation of bat-downswing. This is proposed to reflect a fundamental difference in the way skilled and club-level batters time their predictive saccades. It was also fascinating to find that the magnitude of these skill-based differences did not change with age. This not only supports previous reports of skill-based differences that are present by late adolescence (Chapters 2-4), but also suggests that any differences in skill between age groups among these skilled performers may not be attributable to their gaze or kinematic behaviour.

Chapter 5 also showed that batters initiated their saccade towards ball-bounce at a moment in ball-flight that was considerably *later* than has been previously reported (e.g., Diaz, Cooper, Rothkopf, et al., 2013). This was not surprising considering the faster ball-speed and the fact that the ball bounced in a location that has been shown to reduce the predictive ability of batters (i.e., good-length; Chapter 3). What was surprising though was that skilled batters sometimes initiated their saccade to ball-bounce *later* than the lesser-skilled batters did (Chapters 3-5); a finding that is in stark contrast to the association between skill and earlier saccades reported by Land and McLeod (2000). However, considering that batters could predict where the ball would bounce by more easily detecting changes in the angle of release from the bowling machine in the Land and McLeod study, this was not possible throughout the thesis, suggesting that batters presumably sought to sample more of ball-flight by delaying the timing of their saccade to better predict where (and when) the ball is likely to bounce. As a result, the timing of the saccade to ball-bounce may instead reflect the moment at which the batter has confidence in the future location of the ball, which ultimately influences their performance. This can be seen with the skilled batters who were better able to adjust the timing of their saccade based on the certainty of their judgements (i.e., a later saccade was associated with a later initiation of bat-downswing and poorer performance). This association was not found in the lesser-skilled batters, further supporting the idea that that they were more likely to scale the timing of the saccade relative to the moment of ball-bounce and not with their kinematics (Chapter 5).

There is evidence throughout the thesis to suggest that batters do not always initiate a saccade towards ball-bounce (Chapters 3-5), but surprisingly, the presence or absence of a saccade was not found to influence their interceptive performance (Chapter 5). However, significant changes in the kinematic behaviour of the batters were found in the absence of a saccade. Specifically, Chapter 5 showed that batters delayed different aspects of their hitting action on occasions where the saccade was absent compared to when it was present. This may reflect a strategy that allows batters to overcome the challenges of a later prediction of the future location of the ball to promote successful interception. Crucially however, this delay in movement cannot be because the batters did not initiate a saccade as most of these actions were performed prior to the initiation of a predictive saccade if one was performed. Rather, this may reflect a poorer knowledge of the ball’s present and/or predicted flight-path, resulting in delayed kinematic actions and the absence of a predictive saccade. Moreover, the coupling between the completion of front-foot stride and the initiation of bat-downswing, which has previously been shown to be a key marker of batting expertise (Chapter 2; Weissensteiner et al., 2011), was found to breakdown in the absence of a saccade but not when the saccade was present. This is consistent with the idea that the saccade to ball-bounce may play a crucial role in the temporal sequencing of movements, and highlights the functional interaction between gaze and kinematics when intercepting fast-moving targets.

6.3. Practical Implications

The collective findings from the experimental series of this thesis help establish a foundation from which coaches and sportspeople alike can work towards developing and modifying existing practices to enhance batting performance and talent identification. The knowledge gained from Chapters 2-5 provide coaches with new empirical evidence to support the widely held anecdotal observations and reports when hitting balls in the presence of ball-swing, but also highlight the development of visual-motor expertise across skill and/or age groups to provide exciting avenues for improving batting performance. The ecological approach taken throughout the thesis also demonstrates how the gaze and kinematic behaviour of the batters are very sensitive to changes in the contextual environment in which they are embedded, raising concerns about a number of training methods currently employed in practice (e.g., the use of bowling machines and straight ball trajectories).

The findings from Chapters 2-4 clearly show that batters of all skill and age groups modify their visual-motor behaviour when uncertain about the future location of the ball. For instance, Chapter 2 showed that the range of possible outcomes significantly influenced the way that the action is performed, ultimately influencing when batters hit the ball (Gray, 2002). Furthermore, Chapter 4 showed that simply being aware that the ball *could* swing, in addition to the variations in ball-length altering the future arrival location of the ball, had a profound influence on the visual-motor behaviour of batters across skill level. Considering that contextual variability is commonly encountered during competition, and the importance of maintaining ecological validity has previously been highlighted (see Pinder et al., 2011a), it is critical for training paradigms to replicate this degree of uncertainty. Although blocked training paradigms are useful for beginners to learn effective movement coordination (see Schmidt & Wrisberg, 2008), prolonged exposure can lead to predetermined motor-actions that are organised prior to movement initiation. As a result, emphasis should be placed on establishing task-specific training environments that are performed under high contextual variety, such as those typically experienced during competition. Collectively, this random presentation can promote the development, and retention, of visual-motor strategies that allow batters to cope with the uncertainty of the future location of the ball (Wrisberg & Liu, 1991).

It is also clear throughout the thesis that swinging trajectories significantly influence the visual-motor behaviour of batters. Currently, it is not uncommon for coaches to implement training sessions where batting practice involves considerable time facing a bowling machine and/or live bowlers using old, battered cricket balls to achieve good form and/or ‘technique’. However, these conditions do not replicate the perceptual information that is available to batters during competition to help them develop the necessary strategies that account for the lateral deviations in ball-flight. It is advocated that there needs to be a shift in training methodologies to specifically address the visual-motor behaviour of batters hitting swinging balls by encouraging them to face live bowlers bowling with balls (either new or manipulated) that are conducive to swing. This approach will not only help batters accumulate greater experience facing the swinging ball, but the *possibility* of ball-swing further adds to the aforementioned argument of training paradigms promoting a degree of uncertainty. Additionally, interventions designed to modify specific gaze and movement strategies may be useful, such as those that help batters to maintain close coupling between the completion of front-foot stride and the initiation of bat-downswing (Chapter 2), direct gaze closer to the ball and retain the ball within a single egocentric direction relative to the head (Chapter 4). It is thus proposed that training paradigms aimed to improve batting performance when facing swinging balls should focus on developing the visual-motor strategies that underpin successful interception, rather than simply gauging performance based on whether or not successful contact was achieved.

Training interventions designed to teach batters how to account for ball-swing should also be considered for children early in their development. Chapters 2 and 4 clearly show that expert-like gaze and kinematic behaviour are evident by late adolescence when hitting straight *and* swinging balls. This suggests that by the time batters reach late adolescence, they are able to functionally adapt their visual-motor behaviour to account for ball-swing. As a result, it can be speculated that training practices that adopt a more constraints-led approach (see Davids, Button, & Bennett, 2008) can help batters accumulate experience facing the swinging deliveries and develop higher-level cognitive strategies to account for the increased spatio-temporal demands of hitting swinging balls at an earlier age. This could promote the development of learnt internal models of ball-flight to help batters better predict the future location of the swinging ball (e.g., Diaz, Cooper, Rothkopf, et al., 2013; Hayhoe et al., 2005). There is also evidence to suggest that batters should follow the common coaching adage to '*move late, move quickly*' to cope with the swinging ball (Chapter 2); however, expecting batters to '*watch the ball onto the bat*' may be too unrealistic for batters to achieve consistently when facing swinging balls (Chapter 4).

Understanding the visual-motor strategies of batters when hitting swinging balls can also present an ideal opportunity for bowlers to gain an advantage by developing the necessary skills to swing the ball, thus improving *their* performance. Although coaches should primarily focus on developing the basic skills and movement coordination of bowling, whilst minimising the prevalence of injury, identifying and encouraging bowlers who have already mastered these basic skills to develop the ability to swing the ball can further enhance their performance. As bowlers develop greater control and knowledge of their skill over time, they can more readily take advantage of the batter's perceptual-motor vulnerability in predicting the future arrival location of a ball, particularly when it bounces on a good-length (Chapters 3 and 4) and/or swings away from the batter (Chapters 2 and 4).

Finding skill-based differences by late adolescence throughout the thesis also promotes exciting opportunities for the purposes of talent identification and/or development. As a result, the key markers of gaze and kinematics found to separate skilled from lesser-skilled adult batters throughout the thesis, and elsewhere in the literature (e.g., Mann et al., 2013; Weissensteiner et al., 2011), may also be potentially useful to discriminate skill and potential in youth batters. With coaches and administrators often seeking to find talented young batters on the basis of batting traits found in elite performers, the collective findings from the experimental series provides suitable markers of expertise. A longitudinal study is however needed to further validate this method to help determine whether young batters identified in this manner go on to achieve a similar degree of batting success as the elite adult batters have.

Collectively, the development of visual-motor expertise in the presence of ball-swing observed during a cricket batting task may also be applicable to other interceptive actions in fast-ball sports such as baseball batting and/or soccer goalkeeping. This experimental series furthers our understanding of the influence of ball-swing on the visual-motor behaviour of performers during an interceptive action and highlights the importance of adopting an ecologically valid approach when designing training paradigms. This provides new and exciting avenues for future theoretical research and/or practical applications for identifying potentially talented young athletes, and for the development of training paradigms aimed at improving sport performance.

6.4. Experimental Limitations and Future Directions

The methodological framework adopted throughout this thesis reflects the aspiration to address and overcome several limitations of previous studies. Although the results have helped to further our current understanding of the visual-motor behaviour of skilled performers during an interceptive action, a number of key issues still remain unclear, whilst the findings from the experimental series raise new questions that warrant further investigation.

The desire to maintain ecological validity throughout the experimental series was achieved for the most part, however, considerable sacrifices had to be made, and accepted, in order for the experimental design to maintain as much experimental control as possible. For example, experimentation was performed using an indoor batting facility that housed the hybrid ProBatter ball-projection machine. Although the ProBatter machine has better face validity compared to traditional bowling machines, further validation is necessary to determine whether batting against the ProBatter machine elicits similar gaze and kinematic behaviour of batters to when facing a live bowler *in situ*; before, and after ball-release. Limitations with the ProBatter machine also meant that ball-swing was achieved by imparting lateral spin onto the ball rather than by relying on a difference in the shine on the two sides of the ball (as most live bowler would rely on), and that it was not possible to project short-length deliveries when the ball was swinging. Despite accepting these default characteristics as limitations of the experiment, the ProBatter machine brings researchers a step closer towards both replicating match-like conditions and also maintaining experimental control; qualities that may be very difficult to achieve when using a bowling machine or a live bowler.

Maintaining ecological validity also meant examining the batters' visual-motor behaviour in their natural environment, calling for the use of a portable eye tracking system. Like most modern eye trackers (for an example of the features available on modern eye trackers, see Applied Science Laboratories, 2015), the accuracy of the Mobile Eye system used in this thesis is highly influenced by the quality of the calibration process and reliant on the subjective examination of video footage following stringent criterion for event detection. Although the timing and type of saccades detected throughout the thesis revealed high intra- and inter-tester reliability scores, the subjective approach adopted presents the potential for large variances in interpretation. As a result, there is a need to (i) develop newer portable eye tracking systems with higher temporal resolution, and (ii) move towards an effective and efficient method that *objectively* measures the timing, and type of saccades (for an attempt, see Appendix). By doing so, this could potentially help establish a gold standard for the accurate and reliable detection of saccades.

The experimental design adopted throughout the thesis was also shaped by the resources available and the time allocated for each batter. Particularly, the assessment of the skilled batters (both adult and youth) was part of a battery of tests performed during a training camp that was held by Cricket Australia. Batting performance was examined using simple categorical measures (Mann et al., 2010b; Müller & Abernethy, 2008) that provided a quick and easy assessment of the batter's quality of bat-ball contact and forcefulness of bat-swing. However, this approach was subjective and did not consider the likelihood of the batter being dismissed, or the amount of 'runs' they could potentially score both critical factors to consider when examining performance during cricket batting. Developing an objective measure that takes into account these interceptive variables, which could then be validated during competition, may provide a more accurate score of the batter's overall performance (for one such attempt, see the doctoral thesis by Mann, 2010). Furthermore, the examination of the kinematic behaviour of the batters throughout the thesis was performed using a single high-speed video camera located along the sagittal plane of the batter to provide simple spatial and temporal measures of movement. Although a more in-depth, and objective kinematic analysis through a motion-capture system might be possible (e.g., using Vicon 3D kinematic analysis), the limited time allocated for each batter made it difficult to set-up and administer such an examination. A motion-capture system would provide a more thorough understanding of the movement strategies of the batters, especially when hitting swinging balls along the frontal and transverse planes of movement. This approach could also provide a better indication of the adaptations (or lack thereof) in kinematic behaviour to lateral deviations in ball-flight, and shed new light on the skill-based differences in the movement strategies of batters.

Analysis of the visual-motor behaviour of performers in this thesis was limited to only one particular type of shot and/or ball-length in some chapters. Chapter 2 examined the kinematic behaviour of the batters when performing a forward defensive shot against good-length deliveries. Given that the batter can perform a wide range of different actions to hit a ball that arrives at the same location, the forward defensive shot provides an exemplar response that can be easily compared with previous studies. Furthermore, batters were more likely to perform a forward defensive shot when facing good-length deliveries compared to the other ball-lengths. In the interest of increasing the number of trials examined, whilst also managing the already lengthy analysis in the chapter, the decision was made to only examine good-length deliveries. This also meant that Chapter 5 only examined forward defensive shots against good-length deliveries. This saved time with the analysis (as only the gaze data needed to be analysed to accompany the kinematic variables), but more importantly focused the chapter on the link between gaze and kinematics without complicating the analysis with the effects of shot type and/or length. Chapters 3 and 4 on the other hand, examined the gaze behaviour of the batters across all ball-lengths and shot types. This was performed to examine how the gaze behaviour of the batters differed across a broader range of ball-flight trajectories, compared to previous studies that mostly examined gaze behaviour from a single (more predictable) trajectory (e.g., Croft et al., 2009). Additionally, these chapters helped better determine the extent to which ball-flight trajectory influenced interceptive performance. For instance, Chapter 4 revealed that the aggressive shots were more likely to be adversely affected by randomisation than the defensive shots (Chapter 2).

By scrutinising, and improving, the methodological and analytical approach adopted throughout this thesis, future studies could extend the current knowledge base and better understand the development of visual-motor expertise. A noticeable limitation of the thesis was the differences in age (or lack thereof) across the batters. Although the youth batters, on average, were younger than the adult batters, the ability to age-match batters was somewhat tempered by the availability of both skilled and club-level batters. This meant that differences in age were just not large enough to adequately examine the effects of age on the visual-motor behaviour of the batters, which may explain why hardly any effects of age were found throughout the thesis. To progress our understanding of the development of visual-motor expertise, future studies may seek to examine younger performers in their formative or early-adolescent years to better understand at what age skill-based differences in visual-motor behaviour are likely to emerge. This can also have practical implications in determining whether factors that discriminate skill in adult batters can also be used as markers to identify talent much earlier in development.

A logical extension from this current investigation is to explore the benefits of introducing swinging balls into current training practices. Although the thesis suggests that expert-like gaze and kinematic behaviour when hitting swinging balls are present by late adolescence (Chapters 2 and 4), it can only be speculated at this stage that increasing the batter's experience to both ball-swing, and the uncertainties it creates, can help develop specific yet flexible visual-motor strategies to promote successful interception. Despite the duration of this doctoral project hindering any attempt to develop an intervention-based study, it is envisaged that implementing task-specific training practices that seek to emulate the visual-motor behaviour of skilled batters would enhance batting performance. A pre- and post-test study paradigm can then determine the usefulness of such training paradigms in improving batting performance and provide a clearer picture of the development of visual-motor expertise in the presence of ball-swing.

Future studies may also seek to examine the effectiveness of incorporating ball-swing for the purposes of talent identification. The findings from the experimental series suggest that examining interception in the presence of ball-swing may provide an effective model from which to differentiate skilled from lesser-skilled batters (Chapter 4). As a result, a talent identification criterion that takes into account the gaze and kinematic behaviour of the batters in the presence of ball-swing can not only inform coaches of the batter's ability to hit the swinging ball, but would also provide a deeper insight into their development of expert-like visual-motor behaviour to account for the increased spatio-temporal demands of ball-swing. Monitoring over time the visual-motor behaviour and/or batting performance (e.g., through simple measures such as their total aggregate runs and/or batting average) of batters who were/were not identified with a criteria that took into consideration the presence of ball-swing, can help evaluate the usefulness of swinging balls in successfully identifying potentially talented young batters.

Another exciting direction for future research is to more thoroughly examine the link between gaze and kinematics when intercepting a fast-moving target. Building on the foundations established in Chapter 5 researchers can seek to better understand the functional interaction between gaze and kinematics when performing a goal-directed interceptive task, while sports coaches can work towards developing more effective training paradigms to help improve batting performance. With the strength of the temporal relationship between the initiation of a saccade to ball-bounce and bat-downswing expected to be a defining characteristic of skilled performance, future studies could help further establish the nature of this relationship by altering specific task constraints. One example would be to manipulate the mass of the bat to cause batters to change the timing of the initiation of their bat-downswing (e.g., Fleisig et al., 2002). If a strong temporal synchronisation does exist between these two events, then changes in the timing of the initiation of bat-downswing should also change the timing of the saccade to ball-bounce. Furthermore, it would also be interesting to explore this relationship in the presence of ball-swing, where considerable changes in the batters' gaze and kinematics are reported (Chapters 2 and 4) to determine whether the strength of this relationship is held under the increased spatio-temporal demands of the task. This provides future studies with a fruitful opportunity to better understand the coordinative fashion in which gaze and motor actions work together, and in turn, establish the visual-motor strategies that underpin expertise in the interception of a fast-moving target.

The collective findings of this thesis provide a significant contribution in advancing the current knowledge regarding expertise in interception. However, there are still significant gaps in the literature that demand further attention. Nonetheless, this provides new and exciting opportunities for future studies to examine the visual-motor strategies that underpin expertise, particularly when using interception in the presence of ball-swing as a model of a highly demanding interceptive task. Through further refinement of the methodological and analytical framework employed throughout this thesis, we can move a step closer towards establishing a comprehensive understanding of the development of visual-motor expertise in interception.

'I made it, I made it'

Kevin Rudolph

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APPENDIX

THE DEVELOPMENT OF AN OBJECTIVE METHOD FOR THE DETECTION OF SACCADIC EYE MOVEMENTS DURING INTERCEPTIVE TASKS

This appendix sought to develop an automated, objective approach towards saccade detection for a more effective and efficient evaluation of the batter’s gaze behaviour. Due to the subsequent result, this approach was not used in the thesis.

Introduction

The examination of gaze behaviour when performing an interceptive action provides valuable insights into the sources of perceptual information that are critical for interception, and the visual strategies that allow performers to predict the future location of a moving target (e.g., Land & McLeod, 2000; Mann et al., 2013). Of particular interest, as highlighted throughout the thesis, is when performers rapidly shift their gaze ahead of the target (i.e., they perform an anticipatory saccade; see Bahill & LaRitz, 1984; Land & McLeod, 2000). However, most examinations of eye movements have, to-date, employed the subjective assessment of gaze footage to determine if and when saccades occur. Furthermore, the laborious and tedious task of manually examining the eye movement data could lead to significant inter- and intra-tester variation. As a result, there is a clear need for the development of an accurate, reliable and *objective* approach for the assessment of saccadic eye movements that can form the gold standard for future examinations.

Early examinations of gaze behaviour employed the magnetic search coil technique, whereby movements of the eye correlated to changes in electric currents providing very accurate measurements of eye movements (e.g. Collewijn, Steen, Ferman, & Jansen, 1985; Robinson, 1963). However, recent calls for studies to be performed in-situ and within the performer's natural environment (e.g. Abernethy, 1993; Farrow & Abernethy, 2003; Phillips et al., 2010; Sarpeshkar & Mann, 2011), have seen the emergence of portable eye trackers that allow researchers to manually inspect video footage of the performer's eye movements (for an example of the features of modern eye trackers, see Applied Science Laboratories, 2015). Although these eye trackers provide portability, a digital interface and an overall ease of use, their accuracy can be highly influenced by the quality of the calibration process. Furthermore, the sensitivity of the software to accurately locate the pupil, thus providing an indication of gaze location, can also be influenced by external sources of lighting (e.g. sunlight or artificial lighting) and/or sudden movements of the head. Though preventative measures can be taken to minimise these effects, testers may have to perform additional analysis to confirm that the location of gaze in the visual field moves commensurate with the recorded eye movement footage.

This laborious and time-consuming task is further exacerbated by the need to manually view the video footage to establish the timing and type of saccades produced. Although clear definitions can be used to help guide the subjective evaluation of different types of saccades, the ability to do so is greatly influenced by the subjective interpretations of the evaluations. Additionally, testers need to ensure that these eye movements occur independently from head movement. For instance, Mann et al. (2013) reported that elite cricket batters adopted a unique strategy that allowed them to retain the ball within a single egocentric direction relative to their head. This ensured that their gaze was also directed towards the ball if the eyes simply remained still relative to the movement of the head. As a result, testers also need to be able to discriminate between eye movements that occur commensurate with head movements and those that occur independently from head movement. This further highlights the subjective nature of the current approach towards saccade detection. Although these analyses are often accompanied by intra- and inter-tester reliability measures, it provides an inefficient method for the accurate and reliable analysis of visual gaze.

Another critical, yet often overlooked aspect of subjective saccade detection is the error associated with the location of the target in relation to the performer. In other words, for interceptive tasks such as baseball or cricket batting where the target (i.e., a ball) approaches a stationary performer, the optical size of the target on the retina increases as the target moves closer to the performer (for more information, see Bootsma, 1991; Craig et al., 2009). As a result, the margin of error for whether gaze is directed towards the ball increases as the ball comes closer. That is, the size of an eye movement necessary to constitute a saccade should increase as the ball comes closer as the ball itself is getting larger on the retina. As a result it can be difficult to accurately differentiate between the initiation of a saccade and the continuous tracking of the target, especially when the target gets closer to the performer. This increases the likelihood of testers falsely detecting (or not detecting) a saccade, thus providing an inaccurate representation of the performer’s gaze behaviour.

Previous studies have attempted to objectively identify saccadic eye movements with sophisticated equations; however, these findings are more applicable for a laboratory based setting. For instance, Salvucci and Goldberg (2000) and later Nyström and Holmqvist (2010) developed an equation for the detection of saccades, but they did so with the head in a stationary position and without generalising their findings to the performance environment; where the performer’s freedom of movement is paramount. To develop an equation specifically for the performance environment, it may be necessary to establish a large set of eye movement data from which the parameters for the detection of saccades can then be determined. The properties of Signal Detection Theory (SDT) provide a clear and simple approach that allows for the categorisation of the presence, or absence, of a stimulus through a “yes-no” paradigm (for more information, see Green & Swets, 1966). SDT is based on four simple evaluations of signal detection: (i) ‘*Hits*’, when the presence of a signal is correctly recognised by the observer, (ii) ‘*Correct rejection*’, when the absence of a signal is correctly recognised by the observer, (iii) ‘*False Positive*’, when the absence of a signal is mistakenly recognised as being present by the observer, and (iv) ‘*False Negative*’, when the presence of a signal is mistakenly recognised as being absent by the observer. In the case of saccade detection, this can permit a structured approach for the identification of a saccade at a given time. As a result, the eye movement footage obtained throughout this thesis can be used to employ SDT and develop an equation for the objective detection of saccades.

The aim of this report was to develop an objective means of detecting the occurrence of predictive saccades. The gaze behaviour of cricket batters from different skill and age groups (all of whom took part in the studies reported in this thesis) were randomly selected and examined to determine whether an automated method of saccade detection could accurately detect when saccades were initiated. Through the use of Signal Detection Theory, a unique single equation was developed to optimise the detection of saccades that (i) had a unique capacity to adjust for the subtended angle of the ball as it approached the batter, and (ii) examined the saccadic behaviours independent from head movement. It was envisaged that the equation would provide a quick, reliable and objective means of detecting saccades. If not, then at the very least it could help to provide a foundation for future examinations to harness and modify this approach to reach a gold standard from which to efficiently and accurately examine the saccadic behaviour of performers when intercepting a fast-moving target.

Methods

Participants

Ten cricket batters from different skill and age groups were randomly selected from the pool of batters examined throughout the thesis. The gaze behaviour from an exemplar trial when facing each of the nine different types of ball-trajectories was randomly selected for each batter (Figure A.1). As a result, 90 representative trials were examined to develop the equation for the objective detection of saccades.

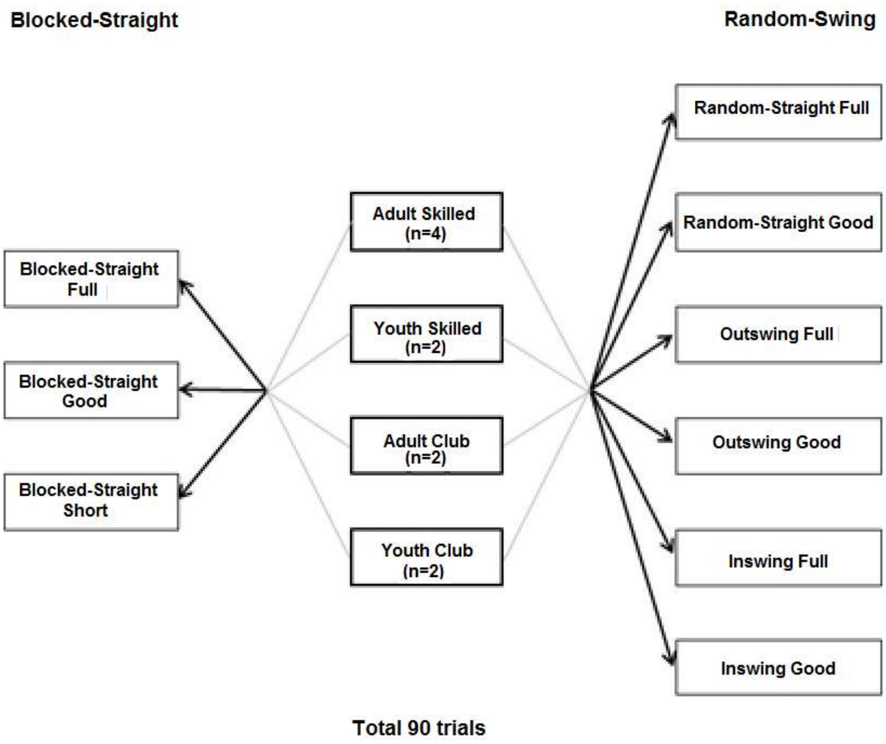

Figure A.1. The four groups of batters and the different types of deliveries examined.

Identification of saccades

The direction of the batter's gaze while batting was examined using a *Mobile Eye* monocular eye tracking system (25 Hz; Mobile Eye, Applied Science Laboratories, Bedford, MA). The head-mounted camera of the *Mobile Eye* meant that any movement of a fixed location, such as the location of ball release, was indicative of the batter's head movement. Footage from the *Mobile Eye* unit was manually digitised (each frame represents 40 ms) to obtain the x-y coordinates of five specific spatial locations in the visual field throughout ball-flight (Kinovea 8.15, 2011): (i) gaze, (ii) location of ball release, (iii) the ball, (iv) bottom left of the projection screen, and (v) bottom right of the projection screen. The first three reference points allowed for the calculation of the raw angles (in degrees) for gaze, head, and ball respectively subtended at the eye. The coordinates of the projection screen was used to correct for head rotation to ensure that the visual angles were reported relative to the global rather than local coordinate system. To account for the rotation of the batter's head and gaze when tracking the ball in flight, three relative angles were also calculated: (i) *gaze-ball angle*, (ii) *gaze-head angle*, and (iii) *head-ball angle*.

During the manual inspection of the gaze footage, a saccade was recorded when a distinctive shift in gaze location occurred that was not commensurate with the flight-path of the ball. Although examining the gaze-ball angle would provide an indication of the batter's position of gaze in relation to the ball, it could be that the gaze position moved as a result of either movement of the eyes and/or head. Therefore the examination of the *gaze-head* angle provides a better indication of whether the eye movements occurred independently from head movement. As a result, examining the changes in the gaze-head angle across successive video frames can help to establish whether the size of any eye movement is large enough to constitute a saccade when taking into account a threshold that allows for the subtended angle of an approaching ball. In other words for a saccade to be recorded, the change in the gaze-head angle needs to be greater than a threshold that accounts for the increase in the subtended angle of the ball as it approached the batter (Figure A.2).

To determine the subtended angle of the ball as it approached the batter, the frame rate of the Mobile Eye camera, the average speed of the ball, and the distance of the batter from the location of ball-release were obtained. Prior to data collection, it was determined that the batter stood ≈17.68 m from the location of ball-release, the ball-speed was assumed to be 119 km.h^{-1} (≈33 m.s^{-1}) throughout the trial, and the frame rate of the camera was 25 Hz (40 ms intervals). It was thus calculated that the ball would travel approximately 1.32 m every 40 ms (i.e. 33 x 0.04 = 1.32). Table A.1 summarises the distance of the ball from the batter following ball release for a representative trial.

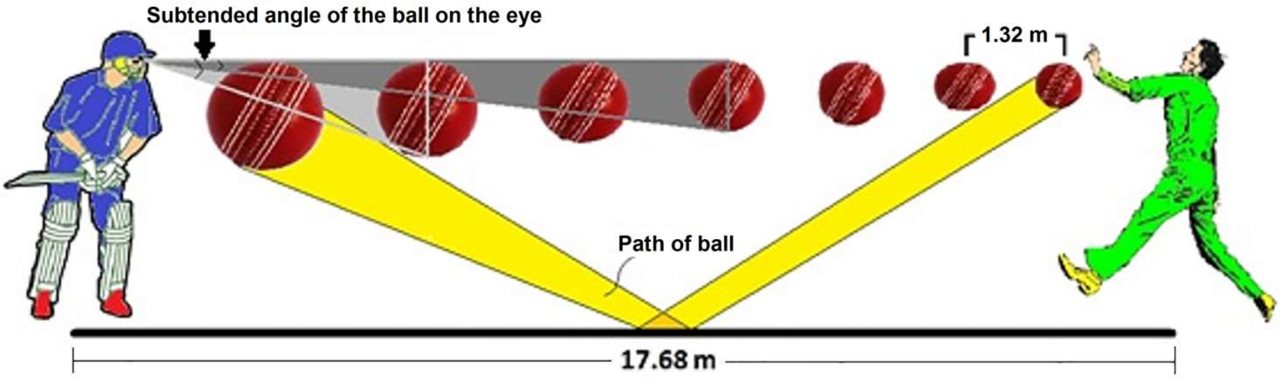

Figure A.2. Schematic representation of subtended angle of the ball as it approaches the batter.

Table A.1.

The subtended angle of the ball following ball-release as it approaches the batter.

	Time following ball-release (ms)													
	0	**40**	**80**	**120**	**160**	**200**	**240**	**280**	**320**	**360**	**400**	**440**	**480**	**520**
Distance of ball from the batter (m)	17.7	16.4	15.0	13.7	12.4	11.1	9.8	8.4	7.1	5.8	4.5	3.1	1.8	0.5
Subtended angle of the ball (deg)	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.6	0.7	0.9	1.3	2.3	8.4

Development of an automated system for the detection of saccades

Video footage from the *Mobile Eye* for each batter was manually examined to determine the time when each saccade was initiated, in addition to the change in gaze-head angle for each trial. This provided a foundation to develop an equation that sought to accurately detect saccades. SDT was used to establish an equation that would maximise the percentage of correct responses (i.e. ‘hits’ and ‘correct rejections’) and minimise the percentage of false responses (‘false positives’ and ‘false negatives’). The accuracy of the equation was determined by examining a specific parameter of SDT, known as *d prime* (*d’*), which indicates the strength of the signal detection (i.e., a high *d’* indicates a greater ability of the equation to discriminate between a ‘hit’ and a ‘false positive’; Green & Swets, 1966).

As a result, the following equation was generated that compared the change in gaze-head angle across successive video frames to determine whether the change in gaze-head angle is likely to be sufficient to have been a saccadic eye movement:

$$\mathbf{Threshold = -1.5 - a\ (tan^{-1}[1/d])}$$

Where ‘a’ is a constant value, and ‘d’ represents the distance the ball is from the batter. The constant ‘a’ ensures that the threshold change in gaze-head angle necessary to constitute a saccade increases as the ball moves closer to the batter. When the ball is further away from the batter, then the term $\tan^{-1}(1/d)$ approaches zero and so the threshold is simply equal to ‘a’. Therefore, the value chosen for ‘a’ should represent the visual angle that defines a saccade at far distances. A value of 1.5 degrees was chosen to be the most appropriate value for ‘a’ based on an examination of the detection of saccades at far distances. Therefore, '-1.5' was incorporated into the equation as a correction factor for large distances (as further corrections will be necessary as the ball moves closer to the batter). The second half of the equation, [$\tan^{-1}(1/d)$], considers the subtended angle of the ball as it is proportional to the inverse tan of the inverse of the distance from the batter. That is, the subtended angle of the ball *increases* as the distance of the ball from the batter *decreases*. To determine the value of the 'a' constant, arbitrary values were initially implemented into the SDT model to determine the ratio of 'hits' vs. 'false positives' and 'correct rejections' vs. 'false negatives'. Through the examination of the strength of *d'*, and optimal 'a' value can be determined, thus completing the equation for the automated detection of saccadic eye movements.

Outlined below are the steps taken to reach an equation for the detection of (i) 'vertical' saccades, and (ii) 'oblique' saccades.

Vertical saccade detection

Vertical saccades include the saccades that shifted gaze ahead of the flight-path of the ball. Utilising the aforementioned equation, arbitrary values of 'a' were trialled in the equation to determine an optimal value where the *d'* value was maximised (see Table A.2).

Table A.2.

Arbitrary values of 'a' for the detection of vertical saccades using the SDT method.

'a'	**0**	**1**	**2**	**2.5**	**2.75**	**3**	**3.5**	**4**	**5**	**6**	**7**
Hits (%)	99.3	96.4	95.6	94.9	94.2	93.4	92.7	91.2	86.9	84.7	82.5
Correct Rejections (%)	90.2	92.2	93.2	93.9	94.0	94.2	94.9	95.3	96.0	97.2	97.5
False Positive (%)	9.9	7.8	6.8	6.1	6.0	5.8	5.1	4.7	4.1	2.8	2.5
False Negative (%)	0.7	3.7	4.4	5.1	5.8	6.6	7.3	8.8	13.1	15.3	17.5
d'	3.7	3.2	3.2	3.2	3.1	3.1	3.1	3.0	2.9	2.9	2.9

It can be observed that attempting to solely maximise the detection, or absence, of a saccade, causes a high degree of false responses, as an inverse relationship exists between 'hits' and 'false negative', but also 'correct rejections' and 'false positive'. However, Table A.2 shows that there is a distinct 'a' value where 'hits' and 'correct rejections' are maximised, and 'false positive' and 'false negative' are minimised. This is observed at an 'a' value of 2.75. In other words, when 'a' = 2.75, the inverse relationship between ‘hits’ and ‘false negative’, and also ‘miss’ and ‘false positive’ is equalised. A *d’* of 3.12 also illustrates a strong value that confidently discriminates between the signals being present or absent.

Thus, the following equation can be used for the detection of a vertical saccade:

$$\textbf{Threshold} = \mathbf{-1.5 - 2.75}\ \textbf{(}\mathbf{tan^{-1[}}\textbf{[1/distance from the batter])}$$

Using this equation, the minimum threshold for a change in gaze-head angle to exceed at each time period following ball-release for the detection of a saccade can be determined (see Table A.3).

Table A.3.

Threshold gaze-head values for the detection of a vertical saccade at each time period following ball-release.

	Time following ball-release (ms)													
	0	**40**	**80**	**120**	**160**	**200**	**240**	**280**	**320**	**360**	**400**	**440**	**480**	**520**
Threshold angle (deg)	-1.5	-1.7	-1.7	-1.7	-1.7	-1.8	-1.8	-1.8	-1.9	-2.0	-2.1	-2.4	-2.9	-4.6

Oblique saccade detection

Utilising the same principles, horizontal components of a saccade could also be detected, allowing for the detection of *oblique* saccades (Figure A.3). The use of the lateral gaze-head angle to determine oblique saccades, without examining the vertical change, requires the assumption that a lateral shift in gaze position would accompany the vertical saccade (this is a good generalisation in cricket batting, as the batter will typically seek to shift their gaze ahead of the ball as it approaches them).

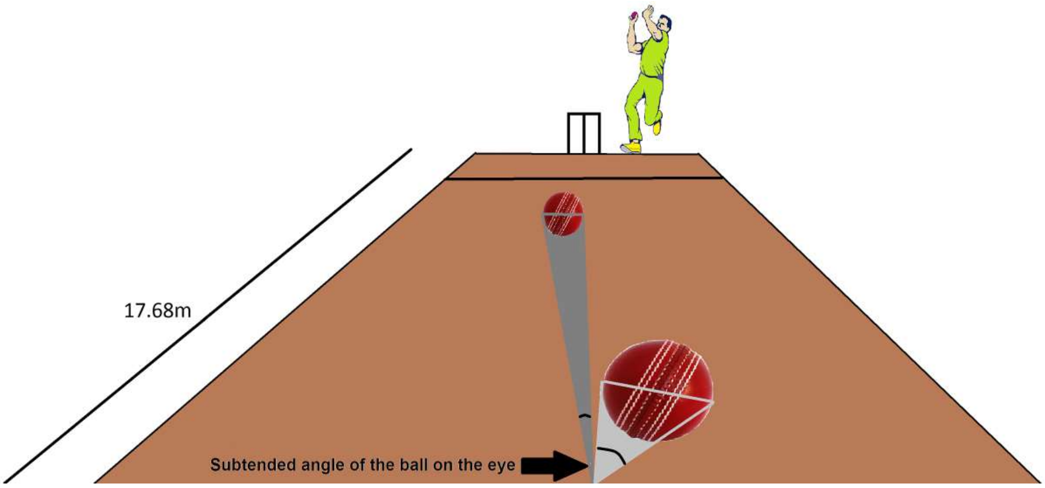

Figure A.3. Schematic representation of subtended angle of the ball in the horizontal direction

Through the use of SDT, the arbitrary values for 'a' was once again explored to determine an optimal value where the *d'* value is maximised (Table A.4).

Table A.4.

Arbitrary values of 'a' for the detection of oblique saccades using the SDT method.

'a'	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
Hits (%)	94.7	94.7	94.7	94.7	94.7	93.3	93.3	93.3	93.3	93.3
Misses (%)	93.8	93.9	94.0	94.3	94.5	94.7	95.0	95.1	95.4	95.8
False Positive (%)	6.2	6.1	6.0	5.7	5.5	5.3	5.0	4.9	4.6	4.2
False Negative (%)	5.3	5.3	5.3	5.3	5.3	6.7	6.7	6.7	6.7	6.7
d'	3.2	3.2	3.2	3.2	3.2	3.1	3.1	3.2	3.2	3.2

Similarly, Table A.4 also shows a distinct 'a' value where 'hits' and 'correct rejections' are maximised, and 'false positive' and 'false negative' are minimised. This is observed at the 'a' value of 0.5. The *d'* of 3.21 also illustrates a strong value that confidently discriminates between the signals being present or absent.

Thus, the following equation can be used for the detection of an oblique saccade:

$$\textbf{Threshold for a given time} = -1.5 - 0.5\,(\tan^{-1}[1/\textbf{distance from the batter}])$$

Using this equation, the minimum threshold for a change in horizontal gaze-head angle to exceed at each time period following ball-release for the detection of an oblique saccade can be determined (see Table A.5).

Table A.5.

Threshold gaze-head values for the detection of a vertical saccade at each time period following ball-release.

	Time following ball-release (ms)													
	0	**40**	**80**	**120**	**160**	**200**	**240**	**280**	**320**	**360**	**400**	**440**	**480**	**520**
Threshold angle (deg)	-1.5	-1.5	-1.5	-1.5	-1.5	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.7	-1.8	-2.1

Note: The same values can be used to as the threshold to detect lateral deviations in the saccade, irrespective of the direction of the saccade. The negative values are used for saccades directed to the left of the batter and positive values for saccade towards the right of the batter.

Assessment of the automated process

The gaze-head angles of four batters were randomly selected to perform a validation of the automated detection of saccadic eye movements. The purpose of the assessment of the automated detection equation was to determine the correlation of this approach with that of the subjective viewing of those same videos. Two human testers viewed the video footage separately to determine when a saccade had taken place. The consensus developed by the two observers was then compared to that obtained from the automated detection equation to determine its reliability and validity in accurately, and objectively, detecting the occurrences of saccadic eye movements.

Results

The results from the validation process revealed that the automated saccade detection equation, for both vertical and oblique saccades, detected a large percentage of saccades that were *not* observed through subjective examinations (Table A.6). Also, a very low percentage of correct rejections suggest that the equation was not able to discriminate between the performer initiating a saccade and simply tracking the ball.

Table A.6.

SDT results comparing the automated saccade detection equation with the human observer.

Batter 1				Batter 2			
		Automated detection (%)				Automated detection (%)	
		Saccade	No saccade			Saccade	No saccade
Human analysis (%)	Saccade	25	18.8	Human analysis (%)	Saccade	50	15.6
	No saccade	50	6.3		No saccade	34.4	0

Batter 3				Batter 4			
		Automated detection (%)				Automated detection (%)	
		Saccade	No saccade			Yes	No
Human analysis (%)	Saccade	58.8	41.2	Human analysis (%)	Saccade	15.8	5.3
	No saccade	0	0		No saccade	79.0	0

Discussion

The aim of this report was to develop an objective means of detecting predictive saccades. The automated saccade detection equation sought to replace the subjective viewing of video footage for the detection of saccadic eye movements using a quick and relatively simple objective assessment. Although the equation sought to extend on the current attempts to detect saccade behaviours by accounting for the subtended angle of the approaching ball and head movement (e.g. Nyström & Holmqvist, 2010), poor agreement between the human testers and the automated method questioned the reliability of this method. The automated system mistakenly detected a large percentage of saccades that were not detected by subjective viewing for three out of the four batters. That is, at least a third of the reported saccades were false positives. Additionally, the automated system missed the detection of a large percentage of saccades detected by subjective viewing (nearly half of the saccades detected for Batter 3 were not detected by the automated system). Therefore, these results led to the conclusion that the automated system for saccade detection developed here was not a reliable or accurate means to detect saccadic eye movements.

A closer examination also revealed that the automated detection method had two major flaws. First, examinations of gaze-head angle assume that the initial measurement of gaze and head movements observed on the calibrated video footage was accurately. If, for example, gaze did not move commensurate with the eye for a particular frame, possibly due to technical issues with the eye tracker, then the recorded gaze position would be inaccurate and provide a false representation of the eye movement. As a result, this restriction placed on the equation would make it susceptible to one off instances of poor calibration for a single frame. In other words, the equation may be too sensitive and unable to discriminate between a saccade performed by the batter and false gaze positions as a result of technical and/or environmental factors affecting the eye tracker. This downfall was probably responsible for the large percentage of false positive saccades observed (see Green & Swets, 1966).

Second, examinations of the gaze-head angle do not allow for the position of gaze in relation to the ball. Put simply, the equation was only ever able to detect whether gaze had abruptly shifted position, and not discriminate between a saccade that directed gaze ahead of the ball or towards another location in the visual field. Perhaps a re-think of the approach for developing the equation to detect the timing *and* type of saccade is necessary. An approach that only detects the initiation of a saccade will still require a re-examination of the video footage to determine the type of saccade performed, reverting back to the subjective viewing of video footage.

Despite its weaknesses, an automated method such as that reported here allows for the examination of saccadic eye movements in virtually any interceptive task. The development of an equation that considers ball position may provide an opportunity for future researchers to permit the classification of the different types of saccades. It is also possible for the method to be more robust by applying a low-pass (e.g., Butterworth) filter to help reduce the detection of saccades that do not move commensurate with the eye. It would be highly desirable to develop a reliable and valid automated method for the objective detection of saccadic eye movements, eliminating the long, mundane and subjective approach currently adopted.

Conclusion

An automated method capable of detecting saccadic eye movements during an interceptive task is desirable because it would allow for an effective and efficient means of objectively examining eye movement strategies and reduce subjective error. The equation developed here sought to account for the subtended angle of the approaching ball and the batter's head movement. However, the results suggest that the equation employed was neither able to accurately discriminate between a saccade performed by the batter and other eye movements that are not saccades, nor differentiate between the occurrence of a saccade and smooth tracking, raising fundamental concerns regarding its accuracy, reliability and validity. For these reasons, this approach was not employed in the detection of saccadic eye movements throughout this thesis. Nevertheless, the automated method proposed here can provide a foundation from which future efforts to establish an automated method could be attempted. Such a development, if improved upon, could potentially be established as the gold standard for the accurate, reliable and objective approach for the detection of saccadic eye movements.

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