UNIVERSITY OF CALGARY

The Optimal Quiet Eye Period and The Regulation of Visual Information in Complex Aiming.

by

Stephen Glenn Martell

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE

DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF KINESIOLOGY

CALGARY, ALBERTA

September, 2010

Your file Votre référence
ISBN:978-0-494-69492-3
Our file Notre référence
ISBN: 978-0-494-69492-3

Abstract

The current study attempted to determine whether a predictive, prospective, or a combined predictive-prospective control strategy best describes complex-aiming accuracy in a basketball jump shot. In Experiment 1, the coupled gaze and motor behaviour of elite basketball players were analyzed as they took jump shots from behind the free throw line. Results indicated an earlier occurring, longer QE period in hits as opposed to misses, thereby supporting predictive control. However, the significant effect between QE duration before and after extension phase onset, provided evidence that some late information may have been used in combination with early information, thereby supporting combined-control. In Experiment 2, the availability of early target information was reduced using three spatial occlusion conditions. Accuracy appeared to be dependent more upon a predictive control strategy as evident by a lower frequency of fixations, earlier QE onset, and longer QE duration. The majority of the QE period was contained within the flexion phase and the amount of late information garnered past the extension phase onset did not seem to assist in achieving success, thereby suggesting the dominant role of predictive control. In Experiment 3, participants were required to perform jump shots under similar conditions to Experiment 2. However, before beginning to shoot their attention was drawn to an egocentric orientation using a questioning technique. Results indicated that athletes increased their accuracy in Experiment 3 due to significant changes in QE onset, duration, and offset. Overall, the results from the three experiments showed that accuracy in the jump shot was characterized by an early onset and longer duration of the QE period, thereby supporting predictive control.

Acknowledgments

Words cannot express the thanks I have for the many people that have contributed significantly to the completion of this dissertation. However, I would like to mention some very special people who have had a tremendous influence on the process.

Mom (*Anne Martell*) - Thank you for teaching me never to give up. It has been the key.

Dad (*Sid Martell*) - Thank you for teaching me how to passionately love and understand something.

Dr. Graham Reynolds - Thank you for picking me up when I was down and putting me on the correct path.

Dr. Brian Mutimer - Thank you for pushing me to be the best that I can be and for believing in my own philosophy of education.

Dr. Lou Bilek - Thank you for being such a wonderful mentor and friend and directing me to the correct information.

Dr. Vern Stenlund - Thank you for helping me to understand that I *could* do it and that it was worth the journey.

Barry Morton - Thanks for everything, especially being such a great friend.

Danny Flynn - Thanks for being such a great coach, teacher, leader, and friend.

Scott Atkinson - Thank you for caring and helping me sort through life's difficult lessons. I consider you a true friend.

Wally Kozak - Thanks for your patience, life lessons, and teaching me what it is you believe.

Dr. Tak Fung - Thank you for being such a great educator and person.

And finally…

Dr. Joan Vickers - I am forever grateful for everything you have done. I truly believe that I have been simply fortunate to find and work with you over the past several years. I have truly enjoyed our discussions throughout this process and the manner in which you have reared my skills and development. You are simply wonderful.

Dedication

For my wife, "we" did it.

Table of Contents

List of Tables

List of Figures

Chapter 1

The jump shot, which has long been recognized as the one of the most important skills in basketball (Hay, 1993), is a complex far-aiming task requiring an athlete to propel a basketball on a parabolic arc to a target located in their external space. Accuracy in the task is dependent upon a tight coupling between perception and action (Miller & Bartlett, 1993). Even though numerous perceptual information sources have been implicated in expert motor control (Button, 2002; Carello, Thuot, & Turvey, 2000; Davids, Savelsbergh, Bennett, & van der Kamp, 2002), the current work concentrated on *how* external visual information is acquired and employed in the control of a jump shot. The work is important because the precise nature of the relationship between perception and action in complex far-aiming is uncertain (de Oliveira, Huys, Oudejans, van de Langenberg, & Beek, 2007; de Oliveira, Oudejans, & Beek, 2006, 2008; Oudejans, Koedijker, Bleijendaal, & Bakker, 2005; Oudejans, van de Langenberg, & Hutter, 2002; Vickers, 1996a).

Currently, motor control theory is defined by three different but related views: (a) predictive control—motor performance is dependent on the acquisition of early visual information with very little reliance on late information acquired in the final 150 ms of the movement (Ripoll, Bard, & Paillard, 1986; Ripoll, Papin, Guezennec, Verdy, & Phillip, 1985; Schmidt & Lee, 2005; Summers & Anson, 2009); (b) prospective control—successful performance is dependent on late perceptual information that is acquired continuously to the completion of the movement (de Oliviera et al., 2007; de Oliviera et al., 2006, 2008; Oudejans et al., 2005; Oudejans et al., 2002); or (c) combined predictive and prospective control—whereby performance is dependent on the acquisition and employment of both early and late visual information (Elliott, Binstead, & Heath, 1999; Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Panchuk & Vickers, 2009; Vickers, 2007; Williams, Davids, & Williams, 1999). Each approach can be related to different theories of motor control (Bernstein 1967; Edelman & Tononi, 2000; Gibson, 1979; Neisser, 1967; Schmidt & Wrisberg, 2004). On one hand, cognitive perspectives in motor control (Meyer et al., 1988; Schmidt & Wrisberg, 2004) view the mind as an elaborate processor whereby perceptual information is gradually constructed into an organized percept for action. In this cognitive process, raw sensory information is acquired through perceptual subsystems and transformed within executive centers in the brain. On the other hand, the ecological (Gibson, 1979) and dynamic system (Bernstein, 1967) perspectives suggest that elaborate computational processing of stimulus information by stage or linear models is too simplistic. In effect, ecologists have argued that cognitive psychologists have been guilty of idealizing the mind without considering the precise nature of how it operates within physical laws and biological constraints (Edelman & Tononi, 2000). As a result, the ecological-dynamic system approach suggests that the environment provides adequate information that affords opportunities to control actions.

The following review of literature examines central issues related to the predictive and prospective control debate. First, the theoretical relationship between cognitive psychology (Neisser, 1967), motor programming (Schmidt & Wrisberg, 2004), and predictive control will be discussed. In particular, since movements of expert athletes are relatively invariant (Tyldesley & Whiting, 1975), success is often dependent upon the development of a predictive cognitive strategy due to knowing the precise operational task requirements. Secondly, ecological psychology (Gibson, 1979) and dynamic system (Bernstein, 1967) perspectives are presented; they suggest that since greater variability exists at the temporal initiation point of a movement compared to the end-point (Bootsma & van Wieringen, 1990), the relationship between perception and action is more co-dependent. Third, the combined predictive-prospective control position (Elliott et al., 1999; Meyer et al., 1988; Williams et al., 1999) argues that expert performers may employ a combination of both predictive and prospective control strategies in the control of movements. In this cognitive-based, two-component model, an initial prediction generates movements to a defined target followed by a second prospective control attempt based on on-line information. Finally, the review will assess current models of motor control (Glover, 2004; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Milner & Goodale, 1995) and recent work in complex aiming (de Oliveira et al., 2007; de Oliveira et al., 2006; de Oliveira et al., 2008; Oudejans et al., 2002; Ripoll et al., 1986; Vickers, 1996a) to understand precise control mechanisms in the complex far-aiming task.

Chapter 2: Literature Review

Predictive Control and the Construction of Perception for Action

Indirect perception theorists (Neisser, 1967) argue that predictive control is defined by a tightly constrained relationship between perception and action whereby perceptual information is first constructed into an organized percept for action to predict operational task constraints (Tyldesley & Whiting, 1975). The psychological refractory period (McGinn, 1989) in cognitive psychology suggest that once perceptual variables are acquired, a relatively slow, discontinuous, computational process transforms neural information into an organized percept for action. The limited capacity of this indirect, predictive process is illustrated by the fact that two tasks cannot be consciously selected and processed at the same time. Regardless of how much practice is accumulated on tasks, the position argues, no more than one decision (prediction), no matter how simple, can be organized and performed within a single moment. For instance, when participants are presented with two tones simultaneously or within 100-150 milliseconds, the discrimination between each cannot be completed. In effect, the first tone must be processed or abandoned before the second stimulus can be processed (Edelman & Tononi, 2000; Pashler, 1994). Within indirect theories of perception and action (Schmidt, 1975), a similar bottleneck in the predictive choice of action occurs as the original motor program must first be run off to completion before the following or subsequent motor programs can be initiated. Accordingly, a minimum time (200 ms) is required for environmental information to switch or modify a motor program for simple tasks (Henry & Harrison, 1961; Logan & Cowan, 1984; Schmidt, 1975; Slater-Hamel, 1960).

In related fashion, Schmidt (1975) proposed a schema-based (Bartlett, 1932; Pew, 1974) theory of motor control (Keele, 1968; Lashley, 1917) in which recall and recognition memory are employed to produce and evaluate correctness of movements. During the production of a movement, recall memory, or more specifically, recall-schema initiates a generalized motor program that in turn sequences the relative timing, phasing, and forces of movements to manage degrees of freedom within the task. In this process, movements are said to be under open-loop control, which are preprogrammed in advance and cannot be updated on-line. Arguably, the duration of an open-loop motor program could be as low as 200 ms for discrete tasks and as high as 400 ms for more complex tasks. Nevertheless, the schema-based approach holds that the original motor program must first be completed before a feedback-based adaptation to the motor program can be initiated (Schmidt, 1975).

Therefore, in Schmidt's (1975) schema theory of motor control, the correct acquisition of early predictive information results from previous recall memories associated with initial conditions, parameters of the motor action, sensory feel of the action, and the resulting outcome of the movement. According to Schmidt (1975), "the strength of the relationship among the four stored elements increases with each successive movement of the same general type and increases with increased accuracy of feedback information from the response output. The relationship is the schema for the movement type under consideration and is more important to the subject than is any one of the stored instances" (Schmidt, 1975, p. 235). The recall-schema, therefore, developed from past outcomes and initial conditions, pre-specifies movement characteristics prior to production needed for success.

Expanding upon Adams' (1971) closed-loop theory of motor control, Schmidt (1975) proposed that memory based recognition-schema, or a perceptual trace, is formed from feedback arising from previous experiences of the movement while in progress. In essence, incoming feedback is compared with the perceptual trace to determine if the movement reaches the final target position. If the movement reaches its target, no further comparison and subsequent movement adaptation is made. However, if the movement does not reach the target, a second movement-based decision is responsible for guiding an effector to the final target position. Typically, in slow movements greater than 200 ms, online feedback arising from sensory systems has the potential to be compared against a reference of correctness, thereby resulting in movement modifications. More specifically, movement-based feedback information has the potential to flow to higher brain centers associated with executive control, and, in so doing, enabling a second prediction or decision related to the movement outcome. For instance, in tasks with extended movement duration such as the golf drive (900-1400 ms), the performer has the potential to predict a second, or possibly, a third movement alteration in an attempt to navigate task constraints (Vickers, 2007). Consequently, Schmidt's (1975) schema theory holds that a second conscious cognitive representation is possible only when sufficient time is available. In other words, the performer must predict the precise operational response specifications (timing, phasing, forces) of movements prior to action generation that will attempt to manage degrees of freedom within the task.

In an early study of predictive control processes, Schmidt, Zelaznik, Hawkins, Frank, and Quinn (1979) determined that in discrete tasks, movement accuracy was related more to the initial impulse phase rather than corrective sub-movements. Put another way, an early prediction based on recall-schema produced movements *in the vicinity* of the target. Schmidt et al. concluded that in tasks with rapid movements (less than 200 ms) visual feedback could not be used to alter movement commands due to the amount of time required for visual feedback processing. Put simply, evidence indicated the importance of predictive control, as late arriving feedback information could not be employed in the control of manual aiming.

Predictive Control and the Operational Timing Hypotheses

The operational timing hypothesis (Tyldesley & Whiting, 1975) asserts that due consistent motor patterning over years of practice, experts seem to reproduce a reliable, invariant motor program. Specifically, the authors compared the performance of expert, intermediate, and novice table tennis players in the return of a forehand drive. Results indicated that while both experts and intermediate players seem to reproduce a high probability of movement consistency within the task, the main difference was reflected by the fact that intermediates demonstrated more spatial and temporal variance, thereby contributing to increased errors within the task. In other words, the invariant motor program resulted in a decrease of errors within the task. Tyldesley and Whiting speculated that the consistent motor programming exhibited by experts caused their focus of attention to be directed to the temporal prediction of movement onset, or input timing. Intermediates, as a result of an inconsistent and variant motor program, may have exhibited an elevated cognitive load manifested by controlling problems associated with temporal initiation and spatial uncertainty. Arguably, to control spatial uncertainty from the unrefined motor program, intermediates may have incorporated a prospective control strategy to reduce end-point variability. The key point here is that experts used less information to simply predict the temporally initiation point of the movement, whereas intermediates required further information to reduce end-point spatial variability.

Since the early work of Schmidt and Tyldesley, numerous scholars have shown the importance of early-acquired information and predictive control in a variety of tasks (Brouwer, Brenner, & Smeets, 2002; Desmurget, Peillson, Rossetti, & Prablanc, 1998; Lee, 1976; Lenoir, Vansteekiste, Vermeulen, & DeClercq, 2005; Mazyn, Salversbergh, Montagen, & Lenoir, 2007; Montagne, 2005; Regan, 1997; Tresilian, 1994). For example, Davids, Renshaw, and Glazier (2005) compared the interceptive timing of cricket batsmen in response to pitches delivered from a ball machine and a real bowler. Results indicated that the removal of early information caused fundamental changes in the control of action. Specifically, predictive information obtained from pitch characteristics early in the flight facilitated a later and more efficient timing of movement when compared to the pitch machine.

Prospective Control and Direct Perception and Action

Prospective control theory suggests the continuous acquisition of on-line information ensures a more dynamic relationship between perception and action due to the fact that an accurate prediction is not dependent upon a single, instantaneous, early perception (Peper, Bootsma, Mestre, & Bakker, 1994). According to direct perception theory (Gibson, 1979), ambient light energy reaches the eye as ordered flow (invariants) and perturbations to the flow (variants) that specify directly to the perceiver the information necessary for accurate event perception. The perception of invariants is an immediate and spontaneous event by a complex, open, biophysical system that invites a specific opportunity to act (affordances). In this theory, invariant features within the optical array specify unambiguously the compositional nature of objects, places and events, and their relationship to action possibilities.

During the production of skilled movements, late acquiring visual feedback information is not only possible, but has the potential to control the smallest independent degree of freedom in the motor system (Bernstein, 1967). Advocates of prospective control theory maintain that a general motor program (Schmidt, 1975) and internally represented expert systems are not essential in the control and guidance of a goal-directed action. Instead, as a performer learns a skill, critical visual attractors in the perceptual-motor landscape become narrowed down to information sources specifying direct opportunities for action. In this process, perception is a direct, lawful relationship between environmental properties and surrounding light energy. This idea is fundamental to the ecological and dynamic system approach, which does not separate perception from actions within the environment and does not require the further elaborate computational processing of information by cognitive subsystems. Instead, by detecting regularities and irregularities in the optic flow field, the smallest independent degree of freedom is controlled (Bernstein, 1967) via the continuous or on-line regulation of visual information (Gibson, 1979). Perception guides action, which in turn guides further perception used to regulate ongoing movements. The resulting interdependency between invariants and affordances creates a perception-action coupling that prospectively controls movement behavior throughout the duration of the task.

Prospective Control and Motor Variance

As a result of direct perceptual processes (Gibson, 1979), proponents have argued that the idea of a visuo-motor delay of 200 ms in predictive control is simply not plausible (Bootsma & van Wieringen 1990). In fact, direct perception theorists argue that visuo-motor delays between 50-100 ms would provide support for the idea that action is often based on prospective control strategy (Lee, 1980). Seminal evidence for this assumption is drawn from an examination of balance in children and adults. For example, Lee and Lishman (1974) found that participants in a purpose built swinging room acted like visual puppets whose behaviour was driven unconsciously by the prospective control of action. As participants stood in a room with fixed floors and moveable walls, considerable postural sway was induced in participants by moving the walls forward and backwards. Sway direction was dependent upon the direction of walls. Lee and Lishman suggested that participants compensated for perceived backward or forward ego-motion caused by irregularities in the optic flow field by unconsciously correcting postural adjustments.

The direct acquisition of perceptual information is also critically related to the idea of timing in predictive control (Tyldesley & Whiting, 1975). Recall that due to high levels of output consistency in motor output patterning, predictive control timing has been linked to the input side of the perception-action relationship only. However, Bootsma and van Wieringen (1990) determined that during a forehand table tennis drive, the relationship between perception and action systems were more co-dependent as a result of directly perceiving on-line information during the continuous unfolding of the movement (prospective control). In their investigation, Bootsma and van Wieringen found lower variability existed at the point of bat-ball contact compared to stroke initiation. If an expert table tennis player based their timing on knowing solely when to initiate the movement, why was greater variability evident at the temporal initiation point compared to the end-point? Bootsma and van Wieringen (1990) argued that the decreasing variability at bat-ball contact indicated that expert performers "were still altering their movements during execution" (p. 27). This suggests that endpoint uncertainty was reduced in the task via a prospective control strategy.

Further support for the prospective relationship between perception and action has been found in several studies involving a variety of tasks. In a pendulum-based interceptive-timing task, Savelsbergh, Whiting, and Bootsma (1991) analyzed timing requirements in one-handed catching and found that subjects finely tuned their grasp relative to the deflating ball size even though they were unconscious of ball changes during flight. Savelsbergh et al. concluded that a finely tuned perception-action coupling, under prospective control, occured in the last 200 ms of ball flight before contact. Lee, Young, Reddish, Lough, and Clayton (1983) determined that participants initiated their jump at a constant time before contact and found visuo-motor delays between 55-130 ms for movements lasting 700 ms. Lacquinti and Maioli (1989) found that during one-handed catching the final 100 ms before hand-ball contact was full of electromyographic (EMG) preparatory activity. Without the use of vision, little or no EMG preparatory activity was found. Access to on-line visual information permitted catchers to use a more efficient prospective strategy.

More recently, evidence that movement accuracy is based on the continuous adjustment of motor actions from on-line visual feedback information (prospective control) has grown (Bastin, Craig, & Montagne, 2006; Calijouw, van der Kamp, & Salversbergh, 2006; Dessing, Bullock, Peper, & Beek, 2002; Elliott et al., 1999; Montagne, 2005; Montagne, Laurent, Durey, & Bootsma, 1999). Dessing et al. (2002)

showed that during prospective control, a tight reciprocal relationship existed between perception and action. Taken together, proponents of prospective control strategies suggest that the major disadvantage of using a predictive control strategy to ensure accuracy is that the entire process relies on accurate perceptual judgments prior to initiation (Peper et al., 1994).

Predictive-Prospective Control

Echoing previous research in near-aiming (Elliott et al., 1999; Meyer et al., 1988), Williams et al. (1999) argued that expert performers employ a combination of both predictive and prospective control strategies in the control of movements. Meyer et al. (1988) proposed a cognitive, two-component model, in which an initial prediction is generated by a rapid force pulse to move the limb to a defined target followed by a second prospective control attempt based on on-line information processing as the movement is unfolding. According to this perspective, if the primary movement falls within the specified region, no corrective sub-movements are required. If, however, the primary movement does not fall within the specified region, corrective sub-movements direct the limb to within its appropriate target location. The key feature involved in this cognitive model is that the motor control process is an ideal coordinative-compromise between predictive (primary movement) and prospective (optional secondary sub-movements) control. Results of Meyer et al. indicated that as target difficulty increased, a combined approach existed between predictive and prospective control, or more specifically, primary and secondary movements. Thus, secondary sub-movements were required only if the first primary movement missed its specified target.

Expanding upon the two-component model of motor control, Elliott et al. (1999) determined the coordinative role of early predictive and late prospective feedback information in the cognitive control of action. Specifically, while an initial recall-based schema and therefore a general motor program were critical during the initial impulse phase of the movement, a second cognitive operation based on the pertinence of feedback information arriving from the display, served to permit movements to reach their final target destination. Presumably, the superior ability of experts to encode and recall task specific information (Allard & Starkes, 1991) ensures a second rapid retrieval of information from a minimum fixation of 100-135 ms (Carlton, 1992) to be used in rapid closed-loop control processes. According to Elliot et al. (1999), both representations “are important for determining the precision of rapid target-aiming movements. Moreover, practice serves not to reduce the importance of feedback and other afferent information, but to increase the speed and efficiency of this processing” (p. 122).

Evidence for the combined relationship between predictive-prospective was shown by Davids et al. (2005). When early predictive information was removed, changes were caused in the fundamental movements of a cricket batsman. However, when early perceptual information was evident against a live bowler, movement onset was delayed as the backswing started later. This indicated a predictive control strategy was used to delay movement onset to extract more predictive information from the bowler. Likewise, Lenoir et al. (2005) found that in the lateral displacement of a volleyball reception task, predictive and prospective strategies were used in a complementary and coordinated manner. Müller and Abernethy (2006) compared batting performance between low- and high-skilled cricket batsmen. High-skilled batsmen were able to use a combination of predictive and prospective control to achieve a higher level of accuracy; in contrast, low-skilled batsmen did not employ the same combination between predictive and prospective control.

Models of Neuro-Motor Control

Currently, each of the theories related to the debate between predictive and prospective control can be contrasted with relevant models of neuro-motor control (Glover, 2004; Hommel et al., 2001; Milner & Goodale, 1995). In the following sections, the relationship between predictive control and Theory of Event Coding (TEC) (Hommel et al., 2001) will be discussed. Secondly, Glover's (2004) Planning Control Model (PCM) and Milner & Goodale's (1995) Perception-Action Model (PAM) will be related to the ideas of prospective control and predictive-prospective control, respectively.

Predictive Control and the Theory of Event Coding (TEC)

Hommel et al. (2001) proposed the TEC, in which cognitive and motor processes associated with intended actions are not separated as functionally independent representations, but rather are equally represented as an integrated, task-tuned event code. In essence, the key feature within the TEC is that a common representational medium functionally links perceived events and the resulting action. Specifically, the initial intent (goal) to produce an action is integrated with distal referenced, relevant feature codes within selective attention (Allport, 1989). Feature codes are weighed in terms of their relevancy (to be attended) as selection-for-action variables are processed to prime task-relevant movement information (Greenwald, 1970). Information not selected is excluded from the semantic identification and further event-code processing. The key point is that the resulting event-code, which contains perceptual-stimulus and action-response codes, respectively, is represented by a common event code (Prinz, 1990). According to Hommel et al. (2001), "Action-generated effects include body-related afferent information, that is, anticipated proprioceptive feedback, but they can also contain visual information about the anticipated position of the arm during and/or after a movement" (p.860). Therefore, once enough information is obtained in the performer's spotlight of attention (Treisman, 1999), a prediction related to the subsequent action is primed that specifies advance instructions in the sequencing of the relative timing, phasing, and forces in the production of action (Schmidt, 1975). The resulting adaptive motor program is then transmitted to the effectors as the movement unfolds, in order to manage degrees of freedom inherent within the task. Hence, in this predictive control process, intention, perception, attention, and action function equally as a coordinated common representational medium.

Prospective Control and the Planning-Control Model (PCM)

Glover (2004) posited the PCM in which two temporally separate yet overlapping systems are employed to control body movements in space. Accordingly, the planning system, which selects a goal prior to movement production, initiates an adaptive motor program based on a broad range of constructed cognitive information to navigate task constraints. The initial representation depends upon cognitive factors such as intent, internal state, experiential memories, task constraints, spatial and non-spatial characteristics, and surrounding visual information. More importantly, the initial planning representation determines timing-related kinematic parameterization of the movements. As such, Glover suggested "the integration of such a broad range of information and the computation of a broad range of movement parameters by the planning system requires a relatively long processing time” (p. 4).

The control system, on the other hand, permits a second visual representation to be used in controlling the adaptive motor programs on-line. Prospective adjustments are limited to the spatial errors arising from either a problem in the initial planning of the action or as a result perturbations evolving during execution. The key point here is that once the movement begins, the control system is responsible for minimizing movement variance by employing a further on-line representation. According to Glover (2004),

> To ensure that the movement is spatially accurate, the control system requires a quickly computed visual representation. The speed of processing in this representation is gained by limiting it to the spatial characteristics of the target. This control representation is coupled with visual feedback, proprioception, and efference copy. (p. 5)

As a result, the PCM suggests the availability of late perceptual information ensures that a second visual representation is created in order to control movements on-line.

Predictive-Prospective Control and the Perception-Action Model (PAM)

Milner and Goodale’s (1995) functional division of visual pathways presumes that two separate visual streams process information for perception and action, respectively. In other words, the function between the two streams is not related to their visual inputs, but more to the output each streams serve. For instance, the ventral pathway, transforms visual information into perceptual and cognitive representation of the surrounding visual world that embodies the enduring characteristics of objects and scenes. Thus, the constructed representation enables memory-based mechanisms such as pattern recognition, subsequent interpretation, and the planning of future movements (adaptive motor programming). However, the ventral pathway is too slow to provide any on-line information in the development, initiation, and guidance of fast motor programs (Goodale, 2000).

The dorsal pathway, on the other hand, transmits moment-to-moment information to be used directly in the on-line control of movements. According to Goodale (2000), "the selection of appropriate goal objects and the action to be performed depends upon the perceptual machinery of the ventral stream, but the execution of a goal directed action is carried out by the on-line control systems in the dorsal stream" (p. 365). The key feature is that the dorsal stream does not require perceptual representations of the object constructed by the ventral stream. Rather, the dorsal stream relies upon pragmatic stimulus features that specify directly bottom-up information to complete the required movement parameters unconsciously. The key feature that distinguishes the PAM from the PCM is that the dorsal stream information permits an efficient movement adaptation based on a non-conscious, pragmatic representation. According to Goodale and Milner (2004), dorsal stream information does not require any intervening representations "but rather the direct transformation of visual information into the required coordinates for action" (p. 38).

Predictive Control in Complex-Aiming

In complex far-aiming tasks, group and accuracy differences have been related to the coordination of gaze behaviour and predictive control. Specifically, in pistol shooting, Ripoll et al. (1985) determined that elite shooters fixated their gaze directly on the target and did not employ late information to reduce end-point variability.

Conversely, near-elite shooters positioned their gaze on the weapon to prospectively control movements to their final target position. In the basketball jump shot, Ripoll et al. (1986) found that expert basketball players employed a predictive control process prior to movement initiation as evident by a more efficient eye-head stabilization (EHS) process to an egocentric point of reference. In essence, early information permitted the motor program to be completed in an automatic fashion, without the need for late visually based afferent information.

During the basketball free throw, Vickers (1996a) determined that expert basketball players employed a predictive control process, as evident by an earlier and longer quiet eye (QE) period prior to critical movement initiation. Vickers (2009) defined the QE period as

> The final fixation or tracking gaze that is located on a specific location or object in the visuo-motor workspace within 3° of visual angle for a minimum of 100 ms. The onset of the QE occurs prior to the final movement in the task and the offset occurs when the gaze deviates off the object or location by more than 3° of visual angle for a minimum of 100 ms, therefore the QE can carry through and beyond the final movement of the task. (p. 280)

Vickers (1996a) determined that expert QE duration on hits (972 ms) and misses (806 ms) differed from near-experts QE duration on hits (357 ms) and miss (393 ms), respectively. Likewise, skill and accuracy differences in the dart throw (Vickers et al., 2000) were affected by the temporal regulation of the QE period relative to the final flexion phase of the movement. In particular, unsuccessful shots were characterized by an earlier offset and lower duration of the QE period causing Vickers et al. to conclude that temporal control of the QE period was critical to achieving success in task. Accordingly, obtaining predictive control information at an inappropriate time and duration did not regulate degrees of freedom within the task.

Skill and accuracy differences in the early, predictive QE period have been found across a wide range of motor tasks including: (a) self-paced, far-aiming skills such as the golf putt (Vickers, 1992), basketball free throw (Harle & Vickers, 2001; Vickers, 1996a, 1996b, 1996c), darts (Vickers et al., 2000), and rifle shooting (Causer, Bennett, Holmes, Jannelle, & Williams, 2010; Janelle et al., 2000); (b) interceptive timing tasks such a volleyball serve reception (Adolphe, Vickers, & LaPlante, 1997), goaltending (Dicks, Button, & Davids, in press; Panchuk, 2008; Panchuk & Vickers, 2006; Panchuk & Vickers, 2009); (c) near-aiming tasks such as billiards (Williams, Singer, & Frehlich, 2002); and (d) tactical tasks (Martell & Vickers, 2004). In experiments that reduced the early predictive QE period, motor performance has been found to decline for both experts and near-experts (Williams et al., 2002). Likewise, training the early predictive QE period has resulted in an earlier QE onset, offset, and duration as well as an increase in performance accuracy (Harle & Vickers, 2001). As a result, some researchers have speculated that the early QE period represents a critical temporal period used by experts to navigate task constraints (Janelle et al., 2000; Vickers, 1996a; Williams et al., 2002; Mann, Williams, Ward, & Janelle 2007).

Prospective Control in Complex Aiming

In contrast, Oudejans et al. (2002) questioned whether early predictive information, obtained from measures such as EHS (Ripoll et al., 1986) and long duration QE period (Vickers, 1996a), were as critical in tasks like the basketball jump shot. The authors argued that athletes exhibited two jump-shooting styles (high style, low style). In the high style shot, which has often been described as an overhead-back-spin style (Hamilton & Reinschmidt, 1997; Hay, 1993; Kirky & Roberts, 1985; Oudejans et al., 2002), the ball is first lifted up past the face into the final shooting position above the head. Then, upon contraction of the right elbow and flexion of the wrist and fingers, the final extension phase permitted athletes to view the basket from underneath the ball. In contrast, during the low-style, the ball and hands remain below eye-level for a significant part of the shooting action (Miller & Bartlett, 1996). The key difference between the low and high style is that during the low style the participant does not have the opportunity the look at the basket during the final propulsion phase. Results from Oudejans et al. (2002) indicated that shooting accuracy in the jump shot was less reliant on early predictive information and more on a prospective control strategy during the last 350 ms. This suggests that the continuous acquisition of perceptual information until release of the ball has the potential to control inherent degrees of freedom within the task (prospective control).

Oudejans et al. (2005) then examined the effects of prospective control training using an occlusion training techniques over an 8-week period whereby athletes could only view the basket during the final 350 ms prior to ball flight. Two methods were used, PLATO goggles that only opened during the final 350 ms of the task and a screen placed so that the hoop could only be seen at the height of the jump. Results indicated significant improvements in field goal shooting percentage in both the experimental and game setting due to the acquisition and employment of late information. In addition, the players lengthened the final period duration by 67 ms. Moreover, Oudejans et al.

suggested a QE period whereby the gaze is anchored on the target as the movement is unfolding—via a prospective strategy—may facilitate a more effective orientation of the body in space thereby optimizing dorsal stream information in the control of action (Milner & Goodale, 2005).

Likewise, de Oliveira et al. (2006) examined the relationship between optical information pick-up and motor output timing. Results indicated that the accuracy of athletes who used a low style were affected most when the target was occluded early, while those who used a high style were negatively affected most when the target was occluded late. Even though results underscored the importance of the QE period found by Vickers (1996a) in the free throw, an early fixation was not as critical in the basketball jump shot. Accordingly, success resulted from a common principle—picking up information as late as possible—or prospective control. Since Oudejans et al. (2002, 2005) did not use an eye tracker to record the gaze, de Oliveira et al. (2007) then registered the "looking behaviour" of athletes in both the free throw and jump shot. Over both shots, they concluded that the early QE period was not as important in shots like the basketball jump shot. In other words, prospective information during the last 350 ms "may be necessary for accurate shooting because it establishes a solid link between the player and the target which allows the players to reliably pick-up the elevation angle continuously" (p. 107).

As a result of this evidence, Elliott et al. (2009) speculated that the acquisition of visual information in the final 350 ms of the jump shot provides support for the two-component model of motor control, or combined predictive-prospective control (hence forth called combined-control). In this process, while early visual information assists motor program generation during the initial impulse phase of the movement, a second cognitive operation, based on the acquisition of late feedback information, served to permit movements to reach its final target destination. According to Elliott et al. (2009), "both jump shot and foul shooting success depends on very late sensory information available just before the ball is released" (p. 446). Moreover, "what remains to be seen with this research on basketball is whether late visual regulation is related to afferent processing only, or processes that involve the comparison of visual and proprioceptive feedback to sensory expectations" (Elliott et al., 2009, p. 446).

Methodological Differences

Despite evidence for both predictive and prospective control in complex aiming, controversy exists due to different methodological approaches being used by cognitive and ecological psychologists (Vickers, 2009). First, cognitive psychologists code gaze data using precedents arising from eye movement and neural literature (Bridgeman, Hendry, & Start, 1975; Carl & Gellman, 1987; Carpenter, 1988; Coren, Ward, & Enns, 2004; Fischer, 1987; Irwin, 1994; Matin, 1974; Optican, 1985). In this approach, three types of gaze behaviours have been identified: fixations, pursuit tracking, and saccades. A *fixation* occurs when the gaze is held on an object or location within 3° of visual angle for 100 ms or longer (Carl & Gellman, 1987; Carpenter, 1988; Fischer, 1987; Optican, 1985; Williams et al., 1999), which is the minimum amount of time needed to recognize or become aware of stimuli. Likewise, *pursuit tracking* occurs when the gaze is stabilized on a moving object for minimums of 100 ms. While information can be processed during fixations and tracking eye movements, during *saccades*, which are very rapid eye movements that link fixated or tracked locations, information is suppressed (Bridgeman et al., 1994).

Ecological psychologists, on the other hand, use precedents from kinematics in which the x/y location of the gaze in space is recorded using spatial grids placed over each frame of the video gaze data. Ecological psychologists hold true to the teachings of Gibson (1979) and treat every gaze as being equal to all others (Vickers, 2009). Since most eye trackers have rates of 30 or 60 Hz, ecologists recognize that visual information detected in as little as 16.67 ms may be valuable in terms of affecting a movement. Each gaze, no matter how brief, detects critical affordances, invariants, or elements of optic flow in the dynamic environment. In addition, the kinematic motion analysis technique treats every gaze as similar to all others and does not differentiate key gaze characteristics (fixations, pursuit tracking, saccades) within the task.

By treating every gaze as being equal to all others, the kinematic coding approach used by de Oliveira et al. did not have the potential to differentiate key gaze characteristics (fixations, pursuit tracking, saccades) within the task. Using this approach also fails to recognize important developments in the literature linking gaze and attention. For many years it was difficult to link shifts in gaze with shifts in attention but more recent studies have shown that under certain conditions a shift in the gaze is invariably preceded by a shift in attention (Corbetta, 1998; Deubel & Schneider, 1996; Henderson, 2003; Kowler, Anderson, Dosher, & Blaser, 1995; Shepherd, Findlay, & Hockey, 1986). In effect, when a saccade is made to a new location there is a corresponding shift in attention in the direction of the saccade. This means that when athletes shift their gaze to a new location, they also shift their attention to that location at least for a brief period of time.

Second, the approach of de Oliveira et al. (2007) did not analyze the gaze relative to key phases within the jump shot. Since no movement-based phases were reported (de Oliveira et al., 2007; de Oliveira et al., 2006, 2008), it remains uncertain as to the relative importance of late perceptual information within each phase of the shooting task. Third, de Oliviera et al. (2007) did not analyze the gaze relative to accuracy, preferring instead to provide percentages over only 10 shots for each of six players. Given that a large percentage of misses are incorporated within the results shown, the validity of the conclusion that success in the jump shot is based primarily on late vision needs to be interpreted with caution.

Purpose of Thesis

The current thesis attempted to determine whether predictive, prospective, or a combined-control best explains higher levels of accuracy in a complex far-aiming task (jump-shot). To test underlying assumptions, three experiments were conducted to further explore the problem of predictive, prospective and combined-control in complex aiming. In Experiment 1 (chapter 3), the coupled gaze and motor behaviour of elite jump shooters were recorded while wearing a mobile eye tracker under experimental conditions similar to Oudejans et al. (2002) and de Oliviera et al. (2007). In Experiment 2 (chapter 4), specific information sources from the hoop and backboard were removed using spatial occlusion, under experimental conditions similar to Oudejans et al. (2005). More specifically, during the jump-shot hoop (JS-H) condition, athletes could only see the hoop and backboard at the start of the trial. In the second jump shot-line (JS-L) condition, only the area above the hoop was available. Finally, in the jump shot-top (JS-T) condition, the hoop and backboard were totally occluded. Experiment 3 (chapter 5) then trained the same athletes as in Experiment 1 and 2. In the following chapters, a brief literature review for each experiment will be presented that elaborates on the central issue related to predictive, prospective or combined-control. At the conclusion of each literature review, specific hypotheses will be presented for each experiment.

Chapter 3: Complex Far-Aiming

In complex far-aiming tasks, success has been related to the acquisition and employment of visual-perceptual information in the control of action. However, the question as to how an expert performer temporally regulates visual information in motor control has recently sparked a considerable debate. Specifically, timing has been related to three different but related processes: (a) an early acquisition of visual information prior to movement production (predictive control; Harle & Vickers, 2001; Ripoll et al., 1986; Vickers, 1996a); (b) acquisition of late information during movement production (prospective control; de Oliveira et al., 2007; de Oliveira et al., 2006, 2008; Oudejans et al., 2002); and (c) combined-control between both early and late information (Elliot et al., 2009; Meyer et al., 1988; Williams et al., 1999).

In the basketball jump shot, Ripoll et al. (1986) found that expert basketball players employed a predictive control process prior to movement initiation as evident by a more efficient eye-head stabilization (EHS) process to an egocentric point of reference. Ripoll et al. determined that expert athletes oriented their head and gaze toward the basket earlier and longer than that of non-experts. In essence, early information permitted the motor program to be completed in an automatic fashion, without the need for late visually based afferent information. In the basketball free throw, Vickers (1996a) determined that expert basketball players employed a predictive control process, as evident by an earlier and longer QE period prior to critical movement initiation (first movement of the ball upwards into the shot). Expert QE duration on hits (972 ms) and misses (806 ms) differed from near-experts QE duration on hits (357 ms) and miss (393 ms), respectively.

On the other hand, Oudejans et al. (2002) questioned whether early predictive information was as critical in tasks like the basketball jump shot. Accordingly, results indicated that shooting accuracy in the jump shot was less reliant on early predictive information and more to a prospective control strategy during the last 350 ms. Oudejans et al. (2005) suggested a QE period whereby the gaze is anchored on the target as the movement is unfolding—via a prospective strategy—may facilitate a more effective orientation of the body in space thereby optimizing dorsal stream information in the control of action (Milner & Goodale, 2005). de Oliveira et al. (2006) examined the timing of optical information pick-up in athletes that exhibited either a high- and low-style jump shot. Even though results may have underscored the importance of the QE period found in the free throw (Vickers, 1996a), an early long fixation, and therefore, predictive control, was not as critical in the basketball jump shot. Accordingly, success resulted from a common principle—picking up information as late as possible—or prospective control. de Oliveira et al. (2007) then registered the "looking behaviour" of athletes in both the free throw and jump shot. Over both shots, they concluded that the early QE period was not as important as late prospective information and, that looking at the basket during the final extension of the shooting arm and hand may be necessary for accurate shooting.

Purpose. The purpose of Experiment 1, therefore, was to determine the gaze and motor behaviour of 11 elite male basketball players from the same distance and location as in Oudejans et al. (2002) and de Oliviera et al. (2007). The goal was to determine the relationship between the gaze, movement phase (preparation, flexion, extension), and accuracy. It was expected that accuracy (hits versus misses) would occur as a result of a

QE period on the hoop that was significantly longer on hits than on misses, followed by no fixations on the target during the during the extension phase, thereby providing support for a predictive control strategy. If, on the other hand, a critical fixation period occurred later, then the highest level of accuracy would occur as a result of a QE period solely during the final extension phase to ball release, thereby implicating a prospective control strategy (de Oliviera et al., 2007; Oudejans et al., 2002; Oudejans et al., 2005). And finally, if a fixation occurred both early and late through the extension phase then this would provide support for a combined-control.

Methods

Participants. Eleven (N = 11) elite male basketball players from the University of Calgary's men's basketball team volunteered to participate in the study. The age of the participants ranged from 18-25 years. All participants played in the highest university league in Canada and gave their informed consent to participate in the study consistent with the guidelines of the Conjoint Health Research Ethics Board at the University of Calgary.

Task. The basketball jump shot, as the name implies, is a complex-aiming skill that requires the performer to jump and then optimally launch a projectile (ball) via a parabolic arc through a distant target (rim) located in the subject's extra-personal space. From a motor control perspective, the jump shot is a complex, far-aiming skill that has the possibility to be constrained by temporal and external factors. In order to limit external constraints, participants were required to perform the standing jump shot from a large square (4m x 4m) shooting area just behind the free throw line (5.2 m), to a basketball hoop located at a height of 3.04 meters (10 ft), which was similar to that used in previous studies (de Oliviera et al., 2007; de Oliviera et al., 2008; Oudejans et al., 2002; Oudejans et al., 2005). Figure 1 presents a schematic representation of the experimental layout participants were required to complete.

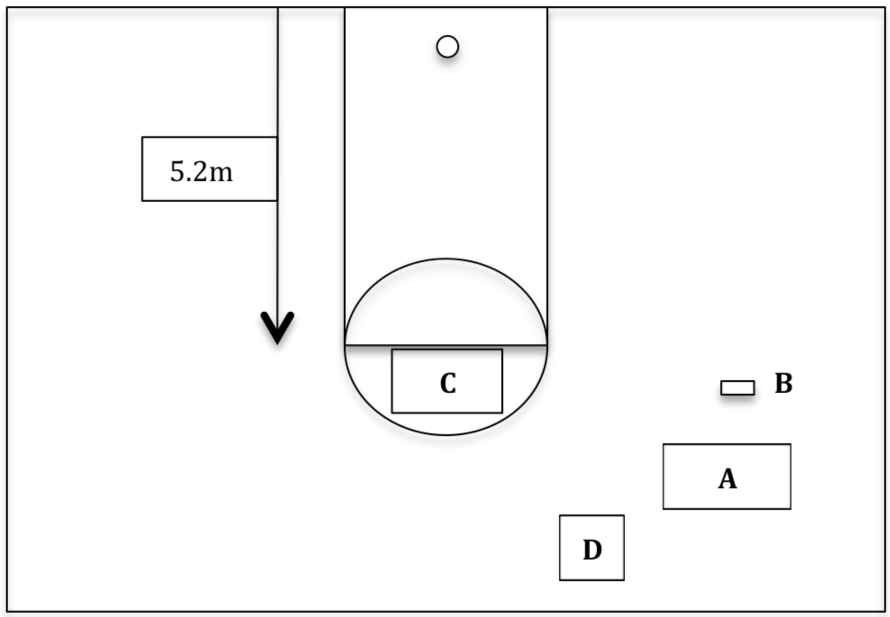

Figure 1. Top view of the experimental set-up showing the location of the: (a) ASL 501 system, (b) external motor camera, (c) location of the shooter, and (d) location of the recorder.

Apparatus. The vision-in-action (VIA) system (Vickers, 1996a) was used to record the coupled gaze and motor behaviours of the participants. An Applied Sciences Laboratories (ASL) 501 eye tracker was interfaced to an external video camera (Sony, Model TRV82) and two digital video mixers (Videonics, Model MX-1) used to produce the frame of video data as shown in Figure 2. The ASL 501 is a monocular corneal reflection system that measures eye-line-of-gaze with respect to the headband. This system measured two features of the eye: the pupil and the corneal reflection (CR). The

CR is the reflection of a small helmet-mounted light source from the surface of the cornea. By measuring both features and using parameters from a calibration procedure, the system could accurately calculate eye-line-of-gaze with respect to the headband. The eye tracker had a 10-metre cord attached to the waist, connected to the eye control unit, thus permitting the participant near-normal mobility.

The eye image (A) in Figure 2 contains the horizontal and vertical axes at pupil and CR centroids that were recorded by the eye camera mounted on the top front of the helmet. The eye image is directed to the eye via the reflective visor with appropriate magnification so that the camera captured approximately a 1-in (2.54 cm) square around the eye. The eye was illuminated by a near infrared light source that was beamed coaxially with the camera. The light from the illuminator, which was invisible to the participant, retro-reflected from the retina and produced an image of a backlighted bright pupil rather than a dark pupil. The reflected image of the light source from the corneal surface appeared as a very small spot that was even brighter than the pupil image. The video image was processed by a computer to identify and determine the centroids of the pupil and the CR. By measuring the vertical and horizontal distances between the two centroids and correcting for second-order effects, the line of gaze with respect to the light source could be computed. The scene image (B), which was recorded by the color scene camera also on the eye tracker, recorded the reflection of the external side of the visor and shows the participant's location of gaze relative to the basketball environment. Location of gaze was indicated by the black cursor. The motor image (C) shows the participant performing the basketball jump shot as recorded by the external camera. Video output frequency was 30 Hz (one frame every 33.33 ms). When the head is held stable, the vertical and the horizontal field of view is 40° and 50°, respectively. The system has an accuracy of ± 1° of visual angle and precision of 1/2°. The square cursor (representing 1° of visual angle with a 7.5 mm lens) indicated the participant's location of gaze in the scene.

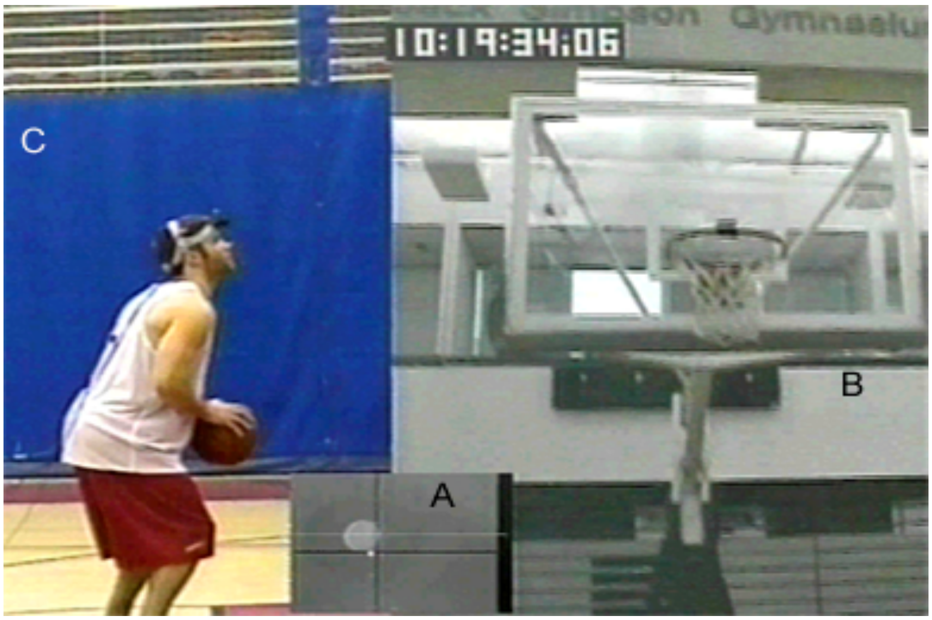

Figure 2. Two frames recorded with the vision-in-action method (Vickers, 1996) containing the: (A) eye image; (B) scene image; (C) the motor image, location of the gaze (black cursor); and time code generator.

Procedure. Testing was carried out at the University of Calgary Jack Simpson gymnasium. Each participant arrived in full gear and after a warm-up was then fitted with the eye tracker and first calibrated to nine points. While holding the head stable and moving the eyes only, nine target points were defined in x/y coordinates. After calibration, the shooter took shots until they stated they were comfortable and the eye tracker did not interfere with their shooting. Locations were identified on the hoop and backboard to maintain calibration across trials. Total calibration time took 15 minutes. Once calibration procedures were finalized and the shooter ready to perform, a “ready” verbal command was issued which permitted the participant to begin shooting under normal shooting conditions. A recorder kept track of the outcome (hit, miss) of each trial. Each player continued shooting until the requirements of each task (5 hits, 5 miss) were met. In total, the time to complete the entire experiment was approximately 60 minutes.

Data coding. Trial onset began with preparation phase onset and trial offset when the ball was released from the fingertips. Three movement phases were determined (preparatory, flexion, extension) from image C as shown in Figure 2. The preparation phase was a constant one-second before the flexion phase onset. Onset of the flexion phase occurred when the angle at the elbow decreased as the ball was brought into the shot. Onset of the extension phase began as the angle at the elbow increased to release of the ball from the fingertips.

Three gaze behaviors were determined from image B in Figure 2 and defined using minimum duration parameters derived from the eye movement literature (Carl & Gellman, 1987; Millodot, 1986; Optican, 1985). A fixation occurred when the gaze was stable on a location on the hoop or backboard for more than 99.9 ms (3 or more frames) within 3° of visual angle. A saccade (Sac) was coded when a shift in gaze was observed from one location to another, with a minimum duration of 66.66 ms or two frames of data. The QE was defined as the final fixation on the hoop (front or back) within a minimum 3° of visual angle for a minimum of 100 ms. The onset of the QE occurred prior to the extension phase and the offset when the gaze deviated off the hoop by more than 3° of visual angle for a minimum of 100 ms. Therefore the QE could carry through and beyond the final extension of the shooting arm.

All absolute measures (ms) of gaze and phase durations were converted to relative time (rel %) using a normalization procedure that expressed each variable as a percent of each trial duration. Thus, each trial had on onset transformed to 0% an offset 100%, and each gaze was a proportion of the total time (Schmidt & Lee, 1999). The normalization of the data (gaze, phase durations) was calculated using the following formula:

$$\text{Relative Time} = \frac{(\text{absolute time of data point} - \text{absolute time of trial onset}) * 100}{(\text{absolute time of trial offset} - \text{absolute time of trial onset})}$$

Independent variables.

1. Accuracy (2) – Hits and Misses. Both determined by an external recorder; hits occur when the basketball traveled through the hoop and does not touch the rim, while misses occurs when the basketball does not pass through the hoop.

2. Trials (5) – Five hits and five misses. The first five hits and misses were used.

Dependent variables.

1. Shooting percentage—The number of hits made relative to the total number of shots taken.

2. Motor phase duration (3)—Three sequential phases of the shooter were determined to be critical during the jump shot (preparation, flexion, extension). Due to the fact that the preparation phase occurred at a constant one-second prior from the first observable movement of the flexion phase, two movement based (flexion, extension) were analyzed.

3. Gaze type (2)—Fixation/Tracking (F/T), quiet eye (QE). Fixation/tracking was coded when the gaze remained on a location or moving object within 3° of visual angle for a minimum duration of 100 ms. Offset occurred when the gaze left that location for 100 ms. The QE was defined as the final fixation on the hoop (front or back) within a minimum 3° of visual angle for a minimum of 100 ms. The onset of the QE occurred prior to the extension phase and the offset when the gaze deviated off the hoop by more than 3° of visual angle for a minimum of 100 ms. The early QE period occurred when fixation offset occurred prior to extension phase onset. The late QE period occurred when fixation offset occurred after extension phase onset.

Data Analysis. Shooting percentages in both the regular season and the experiment were analyzed using a paired sample *t* test. Absolute (ms) and relative (rel %) phase durations were analyzed using phase (flexion, extension) x accuracy (hit, miss) x trials (5, 5) analysis of variance (ANOVA), with repeated measures on all factors. Mean frequency of fixations was analyzed using a phase (flexion, extension) x accuracy (hit, miss) x trials (5, 5) ANOVA with repeated measures on all factors. Quiet eye onset, duration and offset (rel %; ms) were analyzed separately using an accuracy (hit, miss) x trials (5, 5) ANOVA with repeated measures on all factors. Quiet eye duration before and after extension phase onset was analyzed using a temporal phase (early, late) x accuracy (hit, miss) x trials (5, 5) ANOVA with repeated measures on all factors. An alpha level of 0.05 was used for all statistical tests. Effect sizes were calculated using omega squared (ω^2) for significant main effects and interactions. Using procedures outlined in Thomas and Nelson (2001), code-recode reliability was established using two independent coders.

Intra-class correlations for phase durations, QE duration, and onset ranged from 0.95 to 0.99.

Results

Shooting percentage. A paired-sample *t* test was conducted to compare shooting percentages in the regular season and experiment. As shown in Table 1, there was a significant difference in the scores for season shooting percentage (*M* = 46.23 %, *SD* = 5.77 %) and experiment (*M* = 56.62 %, *SD* = 14.97 %) conditions; $t = 2.56$ (8), $p < .03$.

Phase duration. Absolute (ms) and relative (rel %) phase duration within two motor-based phases (flexion, extension) of the jump shot were analyzed separately using a phase (flexion, extension) x accuracy (hit, miss) x trials (5, 5) ANOVA, with repeated measures on all factors. As shown in Figure 3, significant differences were found for absolute phase (ms) $F(1, 40) = 218.58$, $p < .0001$, $\omega^2 = .89$ and relative phase duration $F(1, 40) = 472.12$, $p < .0001$, $\omega^2 = .95$. The mean duration of the flexion (*M* = 480.30 ms, *SD* = 91.13 ms; *M* = 30.06 %, *SD* = 3.60 %) and extension (*M* = 109.24 ms, *SD* = 16.06 ms; *M* = 6.86 %, *SD* = 0.81 %) phases differed. No other significant differences were found.

Table 1

The Shooting Percentage in the Regular Season and Jump-Shot Condition of the Experiment

Participant	Attempts	Hits	Experiment shooting %	Season shooting %
1	26	14	53.85	48.80
2	11	5	45.45	44.90
3	14	6	42.86	35.20
4	46	42	91.30	43.10
5	15	9	60.00	45.70
6	13	5	38.46	N/A
7	22	16	72.73	53.60
8	15	7	46.67	47.10
9	13	7	53.85	N/A
10	17	10	58.82	54.20
11	34	20	58.82	43.50
Mean	20.55	12.82	56.62	46.23

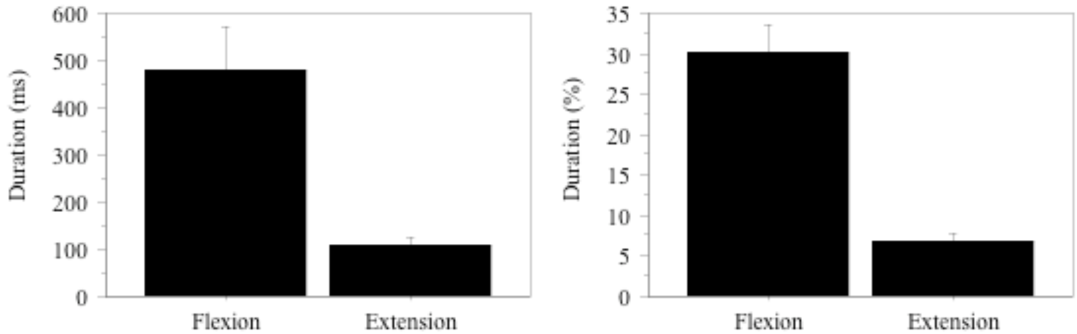

Figure 3. Mean phase duration (ms, rel%) of the flexion and extension phase in the jump shot.

Fixation frequency. The mean frequency of fixations was analyzed using a phase (flexion, extension) x accuracy (hit, miss) x trials (5, 5) ANOVA with repeated measures on all factors. A significant difference was found for phase F (1, 40) = 41.58, $p < .0001$, $\omega^2 = .65$. As shown in Figure 4, the mean frequency of fixations in the flexion phase (*M* = 1.20, *SD* = 0.84) differed significantly from the extension phase (*M* = 0.12, *SD* = 0.32). No other significant effects were found.

Quiet eye. Quiet eye (QE) onset, duration, and offset were analyzed separately using an accuracy (hit, miss) x trials (5, 5) ANOVA with repeated measures on all factors. For QE duration, significant differences in accuracy were found for both absolute F (1, 40) = 6.52, p < .03, $\omega^2 = .06$ and relative duration F (1, 40) = 8.45, p < .02, $\omega^2 = .08$. As shown in Figure 5, the mean QE duration for hits (M = 295.15 ms, SD = 175.26 ms; M = 18.29%, SD = 10.12%) was greater than for misses (M = 235.52 ms, SD = 119.00 ms; M = 14.70 %, SD = 7.21 %). No other significant effects were found.

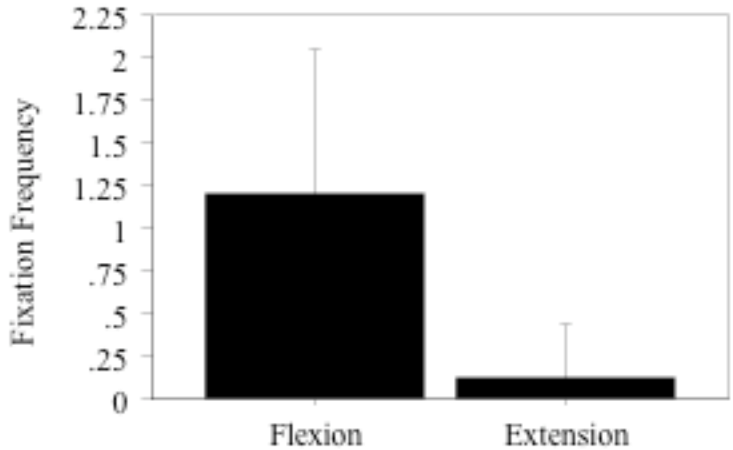

Figure 4. Mean frequency of gaze for the flexion and extension phases of the full vision condition of the jump shot.

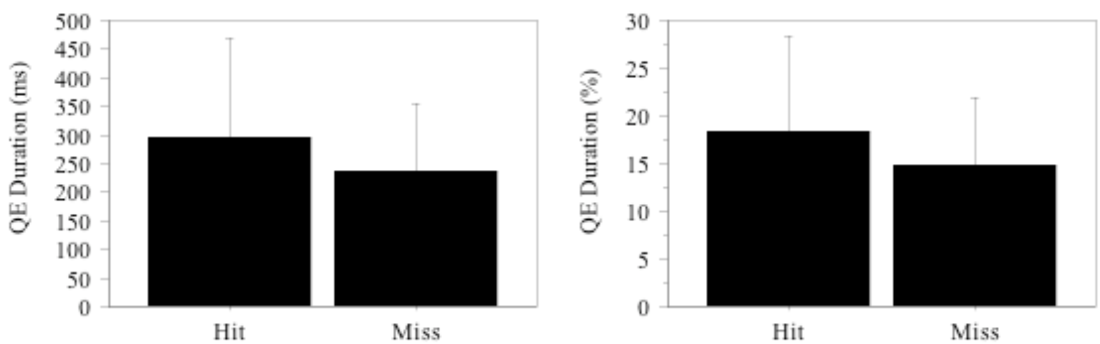

Figure 5. Absolute quiet eye duration (ms, left) and relative (%, right) for hits and misses in the jump shot.

Quiet eye duration (ms, rel%) before and after extension phase onset was analyzed by a temporal phase (early, late) x accuracy (hit, miss) x trials (5, 5) ANOVA, with repeated measures on all factors. As shown in Figure 6, significant effects were found for temporal phase in both absolute (ms) F (1, 40) = 58.95, $p < .0001$, $\omega^2 = .69$ and relative duration F (1, 40) = 59.42, $p < .0001$, $\omega^2 = .71$. The early QE duration (*M* =

231.17 ms, *SD* = 148.63 ms; *M* = 14.17%, *SD* = 8.95%) was longer than the late QE duration (*M* = 36.10 ms, *SD* = 52.86 ms; *M* = 2.44%, *SD* = 3.06%).

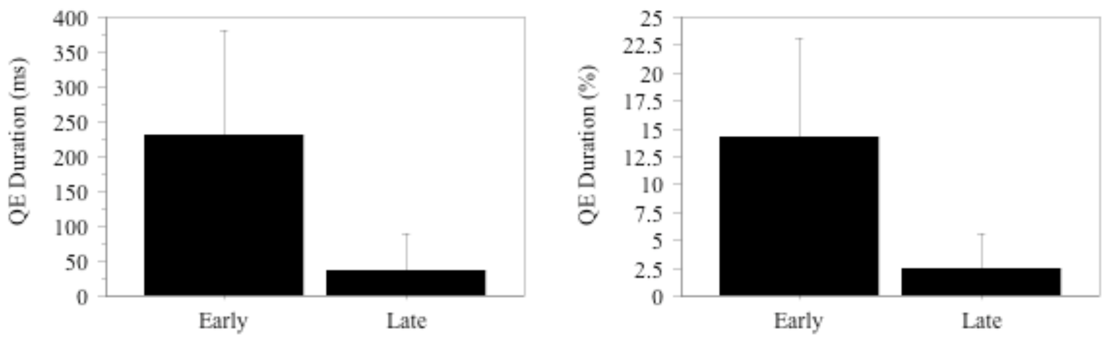

Figure 6. Absolute quiet eye duration (ms, left) and relative quiet eye (%, right) prior to (early) and after (late) extension phase onset in the jump shot.

Discussion

The first objective was to understand how expert basketball players temporally regulate their gaze when performing a successful and unsuccessful complex far-aiming task. The experiment was situated within the context of a basketball jump shot and three hypotheses related to predictive-prospective control. More specifically, we were interested in determining if during complex far-aiming tasks, accuracy would occur as a result of an earlier QE period (predictive control) (Vickers, 1996a); a late QE period (prospective control; de Oliveira et al., 2007); or information that was acquired both early and late relative to the shooting phases, thereby supporting combined-control (Elliott et al., 1999).

First, the current study indicated that elite basketball shooters temporally regulated vision during the basketball jump shot and that a different method of gaze control was evident in successful and unsuccessful attempts. During hits, a longer QE duration was found in hits as opposed to misses, thereby supporting previous work investigating the relationship between QE duration, skill level, and success in self-paced tasks (Harle & Vickers, 2001; Janelle et al., 2000; Vickers, 1996a; Vickers et al., 2000). The result of the longer QE duration is consistent with the understanding of predictive control in tasks constrained by time (Williams et al., 2002). Recall that Vickers (1996a), in the basketball free throw, determined that QE duration on hits (664 ms) differed from misses (599 ms). In the current study, QE duration for both hits (295 ms) and misses (235 ms) was noticeably shorter. The reason for the lower QE duration in the basketball jump shot as opposed to the foul shot may be related to the nature of the tasks. Recall that the jump shot is a complex-far aiming skill that has the possibility to be constrained by temporal and external factors. On the other hand, the temporal constraints within the foul shot are self-paced and the participant does not have to release the ball while in flight. This result, however, gives support to Williams et al. (2002) who determined that as time constraints increased, QE duration and accuracy decreased, suggesting the deleterious effect of temporal constraints. In other words, when the availability of time is decreased within the task, there was a subsequent reduction in QE duration and aiming accuracy.

In the current study, several results clarify the role of predictive control in the jump shot. First, accuracy was characterized by an early-long QE period, which was initiated during the preparation or flexion phase and terminated near extension phase onset. The significant effect between QE duration before (231 ms; 14.17%) and after (36 ms; 2.44%) extension phase onset, provided evidence that some late vision information may have been used in combination with early information, thereby supporting combined-control (Elliot et al., 1999). However, it should be clarified that the majority of the QE period was contained within the flexion phase, thereby supporting predictive control. These results suggest that the continuous acquisition of perceptual information until release of the ball, or prospective control, is required for accurate shooting in very few instances.

Second, the frequency of fixations in the flexion and extension phase differed significantly. In effect, very few fixations were either generated or maintained solely in the final extension phase, thereby providing *no* support for the idea that picking up information as late as possible is required to guide the shooting action. Instead, the evidence pointed to the idea that early information, and therefore an early QE period, is critical in the basketball jump shot, thereby supporting either predictive control (Vickers, 1996a) or combined-control (Elliot et al., 1999). Arguably, terminating the QE period near extension phase onset permits the shooter to either (a) limit the amount of late information that could possible interfere with the motor program, which would indicate predictive control, or (b) is required to optimize dorsal stream information (Milner & Goodale, 1995), thereby supporting combined-control.

In the current study, an attempt was made to delimit the late prospective period to the final extension phase, which averaged 109.24 ms or 6.86 % of the total trial. We believe that final extension phase duration based on observable movement based characteristics may offer a more precise constraint that is critical to the late prospective period. In effect, attempting to determine the role of late vision, and therefore prospective control during the last 350 ms, may not have the potential to determine the precise role of both early and late information. Recall that Oudejans et al. (2002) indicated that shooting accuracy in the jump shot was less reliant on early predictive information and more on a prospective control strategy during the last 350 ms. Similarly, de Oliveira et al. (2007) suggested that prospective information during the last 350 ms permits athletes to reliably employ angle of elevation information continuously until ball release. In the current study, final period durations were constrained to the onset of the extension phase. Using this approach, very little evidence pointed to the existence of late information as suggested by several researchers (de Oliveira et al., 2007; Oudejans et al., 2002; Oudejans et al., 2005), thereby rejecting the idea that the prospective control is critical in tasks like the basketball jump shot.

Chapter 4: Spatial Occlusion

The ability to anticipate or predict motor performance accurately prior to execution has been shown to be a major characteristic of expert performance (Abernethy, 2001; Abernethy & Zawi, 2007). The assumption maintains that accurate perceptual judgments are based on a predictive control strategy, whereby advanced cue information enables athletes to anticipate or predict future actions. Seminal attempts to manipulate the predictive process have been conducted using laboratory-based occlusion methods to determine redundant features within the visual scene (Enberg, 1968; Jones & Miles, 1978). In this approach, subjects were presented with static slide or video sequences in which temporal or spatial aspects of performance were systematically removed, or occluded. Following the presentation of task-related information, participants were then required to make a predictive decision by either a verbal, written, or button-pressing response. Research has generally indicated that early, predictive information has the potential to discriminate between expert and novice performers (Abernethy, 1988, 1990a, 1990b, 1991; Abernethy, Gill, Parks, & Packer, 2001; Abernethy & Russell, 1984, 1987a, 1987b; Abernethy & Zawi, 2007; Jackson & Morgan, 2007; Jones & Miles, 1978; Shim, Carlton, Chow, & Chae, 2005; Singer, Cauraugh, Chen, Steinberg & Frehlich, 1996).

Critics of the traditional occlusion-based approach, however, have questioned whether the simulated prediction permits a reliable indicator of expert motor control (Oudejans et al., 2002; Vickers, 2007; Williams et al., 1999). Since movement parameters such as the direction, force, scale, and speed of the natural response were not coupled with the perceptual and cognitive demands of the task, an accurate assessment of the coupling between perception-action, and as a result whether control is manifested by a predictive or prospective control strategy, could only be achieved during a process whereby organism, environmental, and tasks constraints are integrated *in situ.* In effect, the verbal or simplified movement responses generated by participants may not support the lawful relationship, or mutual dependence, between perception and action. As a result of this artificial de-coupling of perception and action, Farrow, Abernethy, and Jackson (2005) suggested that the issue of ecological validity poses "a threat to the validity of the conclusions that have been reached using this paradigm" (p. 331).

***In Situ* Occlusion.** Recently, occlusion-based studies carried out under conditions of escalated ecological validity have emerged where athletes perform physical skills under experimental conditions similar to those found in their respective sport (Farrow & Abernethy, 2003). For instance, occlusion based research has evolved that incorporates life size video images (Farrow & Abernethy, 2003; Williams & Burwitz, 1993), point-light display methods (Abernethy et al., 2001; Johansson, 1973), virtual reality environments (Ranganathan & Carlton, 2007), liquid crystal glasses (Abernethy et al., 2001; de Oliveira et al., 2007; Farrow & Abernethy, 2003; Oudejans et al., 2002; Oudejans et al., 2005; Starkes, Edwards, Dissanayake, & Dunn, 1995), and vision-in-action (Panchuk, 2008; Panchuk & Vickers, 2009). Early results from methods incorporating life-size images, point light displays, and liquid-crystal occluding spectacles seem to replicate earlier findings of the early predictive control period. Specifically, expert-novice differences have been evident in racquet-ball sports such as: badminton (Abernethy, 1988, 1991), cricket (Abernethy & Russell, 1984), tennis (Goulet, Bard, & Fleury, 1989; Jones & Miles, 1978; Shim et al., 2005; Singer et al., 1996), and squash (Abernethy, 1990b; Abernethy et al., 2001; Howarth, Walsh, Abernethy, &

Snyder, 1984). However, the precise relationship between *in situ* occlusion, complex far-aiming tasks, and predictive-prospective control is still uncertain.

In Experiment 1, even though a long duration QE period was found in the control of the jump shot, QE duration was evident prior to (231.17 ms; 14.17%) and after (36.10 ms; 2.44%) extension phase onset. This result suggests that early information, and therefore predictive control, as suggested by Vickers (1996a), is needed to achieve accuracy in the jump shot. On the other hand, it may also suggest that the availability of both early and late information, as suggested by Elliott et al. (2009) may be necessary for accurate shooting. Therefore, due to the fact that both predictive and combined-control were found, it remained uncertain as to whether an early QE period (predictive control) or the early plus late period (combined-control) were sufficient for accuracy.

Purpose. The purpose of Experiment 2, therefore, was to determine the precise role of both early and late visual information by using three occlusion conditions. In the (JS-H) condition, a screen was set in front of the shooter and raised so that the hoop and above could be fixated. In the (JS-L) condition, the screen was raised so that the athletes fixated the line above the hoop while standing behind the free throw line. Only at the peak of their jump would they be able to fixate the hoop in this condition. And in the final condition, the screen was raised so that only the top of the backboard (JS-T) could be fixated. In this condition it was impossible to see the hoop at any time. Overall, the goal of occlusion conditions was to determine if the removal of early target information resulted in adjustments in the gaze thus forcing the athletes to rely on late prospective information, as suggested by Elliott et al. (2009).

It was expected that accuracy would decline across the occlusion conditions as target information was removed. Specifically, accuracy will be lower than in Experiment 1 (where there was no occlusion) and progressively lower as more and more target information was occluded. If during JS-H the athletes could fixate the hoop both early and late and carried through to the extension phase, then this would support the combined-control result found in Experiment 1. If, on the other hand, during JS-H the athletes used an early QE period terminated prior to extension phase onset, then this would be supportive of predictive control. During the JS-L condition, early vision of the hoop was not possible, but the athletes could fixate the hoop at the peak of their jump, therefore providing an opportunity for prospective control. Finally, when the hoop and backboard was completely occluded for an extended period of time (approximately 20 minutes for each athlete), then accuracy was expected to be very low and neither predictive, prospective, nor combined control would be operative.

Methods

Participants. The same elite male basketball players ($N = 11$) who participated in Experiment 1 volunteered for Experiment 2. Testing occurred immediately after Experiment 1, with a delay of approximately 10 minutes in the same testing environment.

Apparatus. The vision-in-action (VIA) system (Vickers, 1996a) was used to record the coupled gaze and motor behaviours of the participants, as in Experiment 1. In order to create the different spatial occlusion conditions, a custom-built occlusion screen was used. The frame consisted of two sections: a main body section (2.50 m x 2.30 m), which was a standard teaching whiteboard that stood upright and could be rolled into position prior to fine calibration procedures; and an adjustable height body section (2.00

m x 2.30 m) that was made of the same material and attached to the upper horizontal sides via two rolling levers and clips. The adjustable height section permitted a quick manipulation of visual based information as it related to the player's height and occlusion condition. The screen could be raised to a maximum height of 4.50 m and was placed just in front of the free throw line as shown in Figure 7.

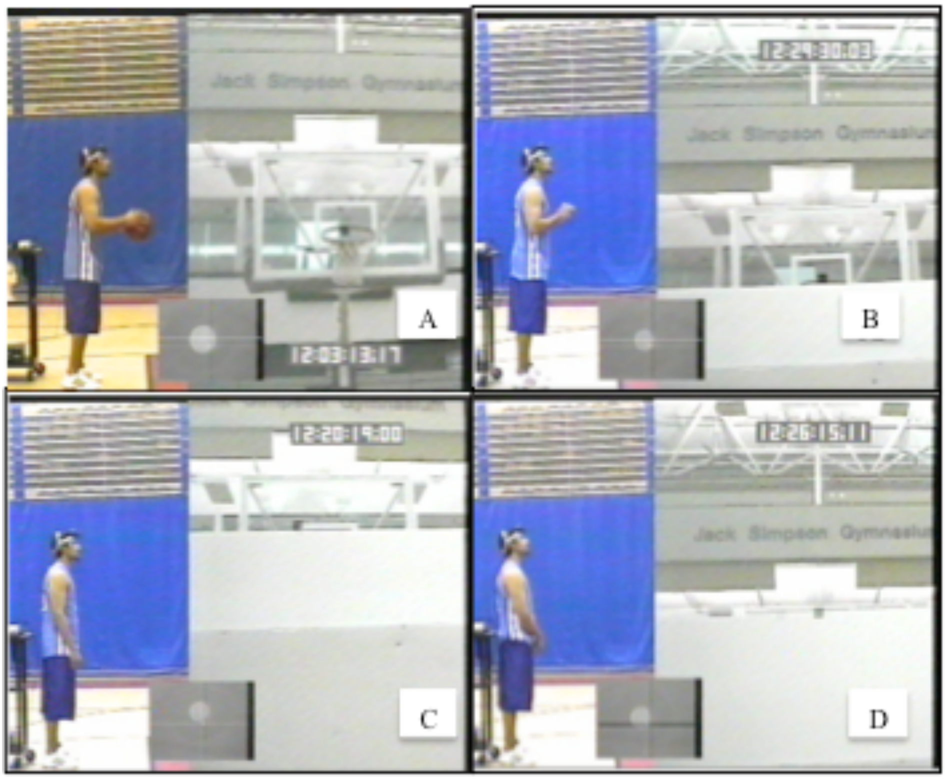

Figure 7. Four frames of vision-in-action data. Image A shows the gaze during calibration during the – no occlusion condition (JS-No); Images B, C and D show the gaze during the hoop (JS-H), line (JS-L), top (JS-T) conditions, respectively.

Procedure. After a brief warm-up, participants were checked for calibration to nine target points defined in x/y coordinates. They then took their stance behind the occlusion screen as shown in Figure 7 and fixated either the front of the hoop (JS-H), the middle of the line above the hoop (JS-L), or the middle of the top of the backboard (JS-T). Prior to each counterbalanced condition, the screen was raised or lowered for each individual so to occlude all aspects of the hoop and/or backboard. After calibration, the shooter took shots until they stated they were comfortable and ready to being the trials. A "ready" verbal command was issued thereby permitting the participant to begin shooting. Each trial began with the ball being passed to the participant by another player who was located behind the screen. Upon receiving the ball the athlete took a jump shot as in Experiment 1. A recorder kept track of the outcome (hit, miss) of each trial. Each player continued shooting until the requirements of each condition (5 hits, 5 miss) were met. Results for the occluded conditions were compared to those from Experiment 1 when there was no occlusion of the target (JS-No). The shooting percentage for each subject in each condition (JS-No, JS-H, JS-L, JS-T) are shown in Table 2.

Data coding. A fixation was coded when the gaze remained on a location or moving object within 3° of visual angle for a minimum duration of 100 ms. Offset occurred when the gaze left that location for 100 ms. The QE was defined as the final fixation on the hoop (front or back) within a minimum 3° of visual angle for a minimum of 100 ms. The onset and offset of the QE occurred when the gaze deviated on and off the hoop, respectively by more than 3° of visual angle for a minimum of 100 ms. The early QE period occurred when fixation offset occurred prior to extension phase onset. The late QE period occurred when fixation offset occurred after extension phase onset. However, due to the use of the occlusion conditions, three fixation locations (i.e., egocentric, right of egocentric, left of egocentric) were identified, as shown in Figure 8. Each area was of equal height and width.

Independent variables.

Within subject factors.

1. Condition (4)—Four jump shot conditions were used: jump shot - no (JS-No), jump shot - hoop (JS-H), jump shot - line (JS-L), and jump shot - top (JS-T) conditions.

2. Accuracy (2)—Hits and Misses. Hits and misses were defined were defined as in competition. Hits occurred when the ball went through the hoop and misses occurred when the basketball did not go through the hoop.

3. Trials (5)—Five hits and five misses. The first five hits and misses were coded.

Dependent variables.

1. Shooting percentage—The number of hits made relative to the total number of shots taken.

2. Phase duration—Absolute (ms) and relative (rel%) phase duration of two phases (flexion, extension).

3. Gaze type—Absolute (ms) and relative (rel%) onset, duration, and offset of fixations and the quiet eye period.

Table 2

The Shooting Percentage for Each Participant During Each Condition (JS-No, JS-H, JS-L, JS-T).

Participant	Condition			
	JS-No	JS-H	JS-L	JS-T
1	53.85	57.90	35.29	50.00
2	45.45	41.67	50.00	58.82
3	42.86	35.71	29.41	44.44
4	91.30	65.22	54.55	45.45
5	60.00	53.33	41.67	31.25
6	38.46	46.15	50.00	29.41
7	72.73	61.90	80.77	53.33
8	46.67	68.42	45.45	31.25
9	53.85	50.00	45.45	27.78
10	58.82	65.00	38.46	25.00
11	58.82	76.67	69.23	50.00
Mean	56.62	56.54	49.12	40.61

Figure 8. Gaze coding system used to define the location of the gaze in a left of egocentric (A), egocentric (B), and right of egocentric (C) locations on the backboard.

Data analysis. Shooting percentage in each condition (JS-No, JS-H, JS-L, JS-T) was analyzed using one-way repeated measures ANOVA. Frequency of fixations, QE onset, duration, and offset were analyzed using a condition (JS-No, JS-H, JS-L, JS-T) x accuracy (hit, miss) two-way repeated measures ANOVA. The mean frequency of fixations, absolute (ms) and relative (rel%) phase duration were analyzed using a condition (JS-No, JS-H, JS-L, JS-T) x phase (flexion, extension) x accuracy (hit, miss) three-way repeated measures ANOVA. Quiet eye duration (ms, rel%) before and after extension phase onset was analyzed by a condition (JS-No, JS-H, JS-L, JS-T) x temporal phase (early, late) x accuracy (hit, miss) three-way repeated measures ANOVA. An alpha level of 0.05 was used for all statistical tests. Effect sizes were calculated using omega squared (ω^2) for significant main effects and interactions.

Results

Shooting percentage. Shooting percentage in each condition (JS-No, JS-H, JS-L, JS-T) was analyzed using one-way repeated measures ANOVA. A statistical significant condition effect was detected F (3, 30) = 5.34, p < .005, $\omega^2 = .16$. The mean shooting percentage for JS-No (*M* = 56.62%, *SD* = 14.97%), JS-H (*M* = 56.54%, *SD* = 12.41%), JS-L (*M* = 49.12%, *SD* = 14.88%), and JS-T (*M* = 40.61%, *SD* =11.90%) differed as shown in Figure 9.

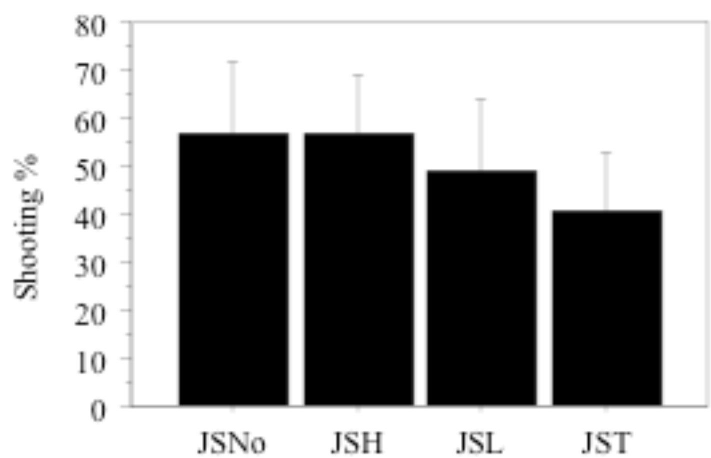

Figure 9. Shooting percentage with standard deviation in each experimental condition (JS-H, JS-L, JS-T) of the jump shot.

Phase duration. Absolute (ms) and relative (rel%) phase duration within two motor-based phases (flexion, extension) of the jump shot were analyzed using a condition (JS-No, JS-H, JS-L, JS-T) x phase (flexion, extension) x accuracy (hit, miss) three-way repeated measures ANOVA. As shown in Figure 10, significant differences were found for absolute (ms) F (1, 40) = 944.53, $p < .0001$, $\omega^2 = .95$, and relative phase duration F (1,

40) = 1707.14, $p < .0001$, $\omega^2 = .98$. The mean duration of the flexion (*M* = 466.05 ms, *SD* = 75.34 ms; *M* = 29.39 %, *SD* = 3.17 %) and extension (*M* = 112.08 ms, *SD* = 11.18 ms; *M* = 7.10 %, SD = 0.71%) phases differed. No other significant differences were found.

Fixation frequency. The mean frequency of fixations were analyzed using a condition (JS-No, JS-H, JS-L, JS-T) x phase (flexion, extension) x accuracy (hit, miss) three-way repeated measures ANOVA. Significant differences were found for phase F (1, 40) = 189.72, $p < .0001$, $\omega^2 = .98$, accuracy F (1, 40) = 11.74, $p < .0012$, $\omega^2 = .06$, and the interaction of phase by accuracy F (1, 40) = 4.40, $p < .05$, $\omega^2 = .11$. As shown in Figure 11, fixation frequency in the flexion phase by hits (*M* = 1.08, *SD* = 0.48), flexion phase by miss (*M* = 1.29, *SD* = 0.48), extension phase by hits (*M* = 0.17, *SD* = 0.26) and extension phase by miss (*M* = 0.21, *SD* = 0.23) differed.

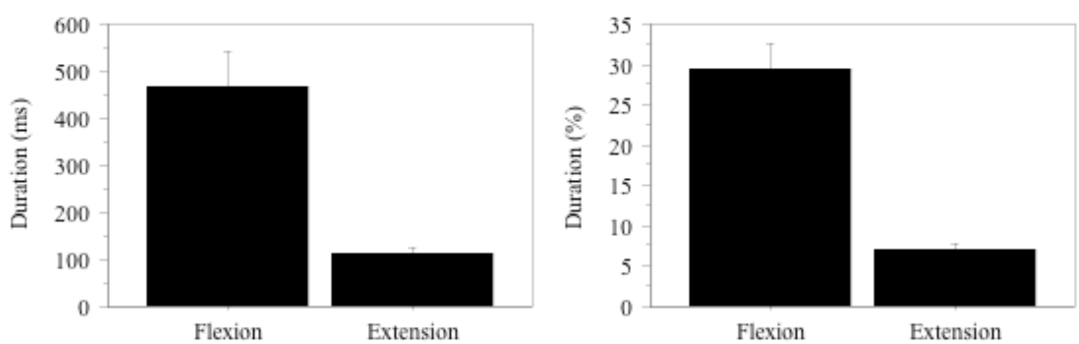

Figure 10. Mean phase duration (ms, rel%) of the flexion and extension phase in the jump shot.

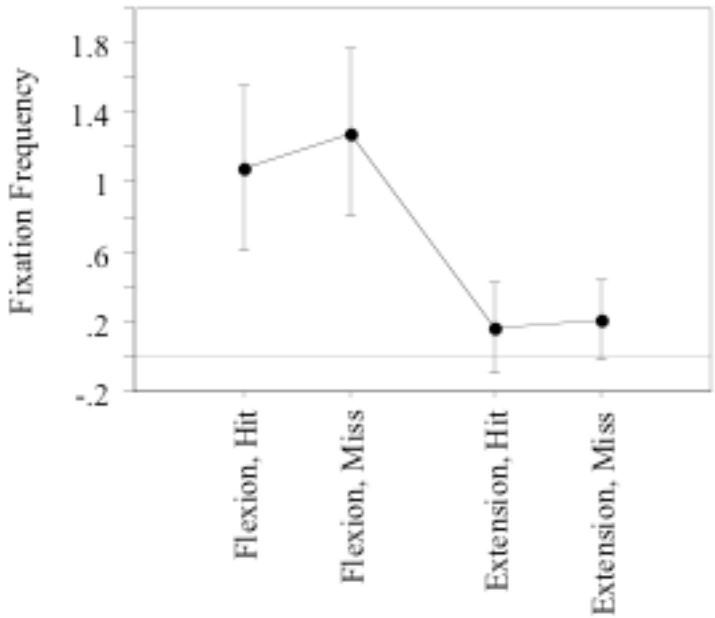

Figure 11. Fixation frequency by phase (flexion, extension) and accuracy (hit, miss).

Quiet eye. Quiet eye onset, duration, and offset were analyzed separately using a condition (JS-No, JS-H, JS-L, JS-T) x accuracy (hit, miss) two-way repeated measures ANOVA. As shown in Figure 12, significant differences in accuracy were found for both absolute F (1, 40) = 15.80, p < .0003, $\omega^2 = .09$ and relative QE onset F (1, 40) = 16.98, *p* < .0002, $\omega^2 = .11$. Mean QE onset occurred earlier on hits (*M* = 1103.77 ms, *SD* = 145.50 ms; *M* = 70.13 %, *SD* = 9.17%) than on misses (*M* = 1176.77 ms, *SD* = 122.03 ms; *M* = 74.89 %, *SD* = 6.60%). No other significant effects for QE onset were found.

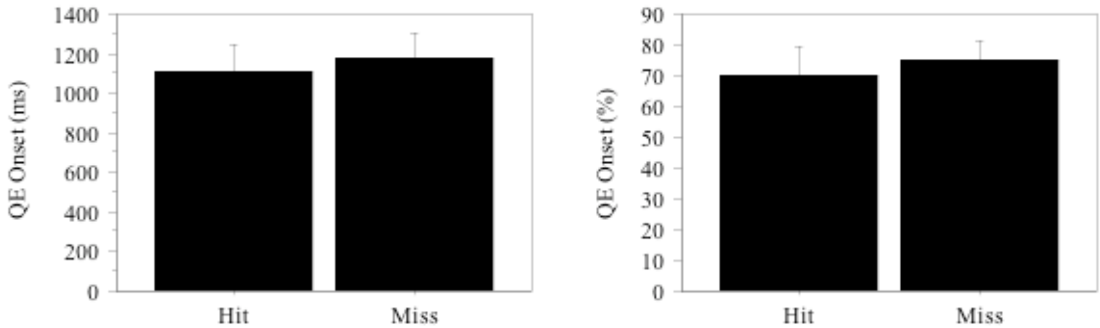

Figure 12. QE onset (ms, rel%), with standard deviation, for hits and misses in experimental conditions (JS-No, JS-H, JS-L, JS-T) of the jump shot.

As shown in Figure 13, significant differences in accuracy were found for both absolute F (1, 40) = 21.75, p < .0001, $\omega^2 = .08$ and relative QE duration F (1, 40) = 25.68, *p* < .0001, $\omega^2 = .08$. The mean QE duration for hits (*M* = 287.20 ms, *SD* = 167.50 ms; *M* = 18.01 %, *SD* = 9.57 %) was higher than for misses (*M* = 216.78 ms, *SD* = 97.98 ms; *M* = 13.76 %, *SD* = 6.21%). No other significant effects for QE duration or QE offset were found.

Quiet eye duration (ms, rel%) before and after extension phase onset was analyzed by a condition (JS-No, JS-H, JS-L, JS-T) x temporal phase (early, late) x accuracy (hit, miss) three-way repeated measures ANOVA. For temporal phase, significant effects in both absolute (ms) F (1, 40) = 130.34, *p* < .0001, $\omega^2 = .70$ and relative (rel%) duration F (1, 40) = 144.43, *p* < .0001, $\omega^2 = .73$. Likewise, significant effects for accuracy were found in both absolute (ms) F (1, 40) = 18.59, *p* < .0001, $\omega^2 = .10$ and relative duration (%) F (1, 40) = 21.71, *p* < .0001, $\omega^2 = .10$. As shown in Figure 14, a significant temporal phase x accuracy interaction was evident in both absolute (ms) (F (1, 40) = 14.72, *p* < .0004, $\omega^2 = .30$ and relative (%) duration F (1, 40) = 14.34, *p* <

.0005, ω^2 = .33. The mean QE duration in early hits (*M* = 266.11 ms, *SD* = 172.53 ms; *M* = 16.61 %, *SD* = 9.99 %), early miss (*M* = 191.76 ms, *SD* = 90.28 ms; *M* = 12.04 %, *SD* = 5.39 %), late hits (*M* = 25.17 ms, *SD* = 29.79 ms; *M* = 1.61 %, *SD* = 1.87 %), and late miss (*M* = 25.50 ms, *SD* = 28.12 ms; *M* = 1.61 %, *SD* = 1.86 %), differed. No other significant effects were found.

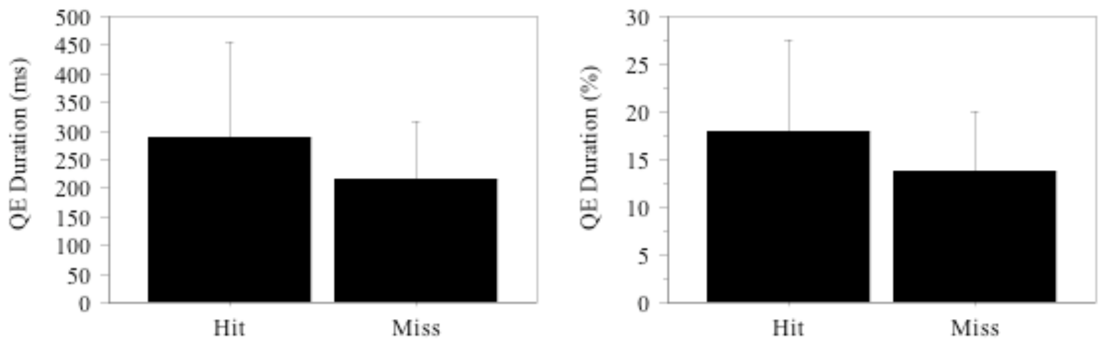

Figure 13. Quiet eye duration (ms, rel%), with standard deviation, for hits and misses in experimental conditions (JS-No, JS-H, JS-L, JS-T) of the jump shot.

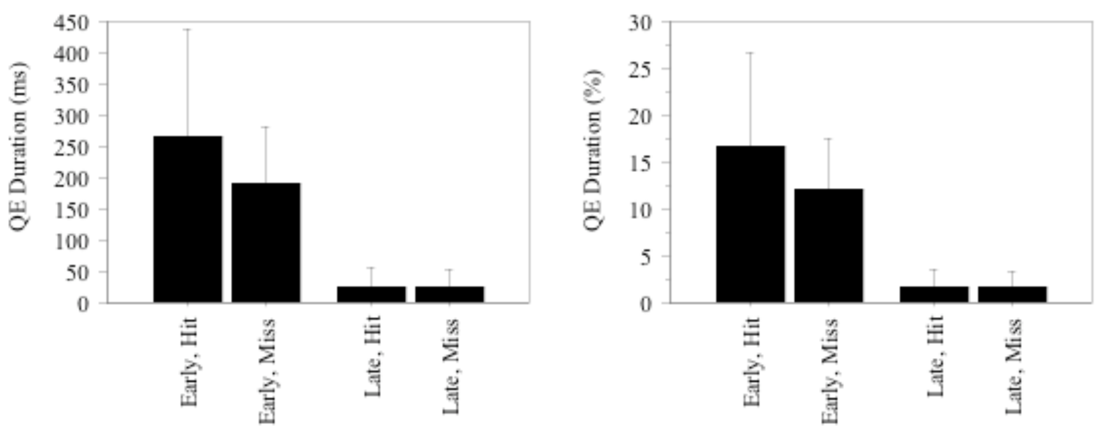

Figure 14. Absolute (ms, left) and relative (%, right) duration of the quiet eye period prior to and after (early, late) by accuracy.

Discussion

Overall, the goal of Experiment 2 was to determine if the removal of early target information using *in situ* spatial occlusion resulted in adjustments in the gaze when performing a complex far-aiming task. The experiment was situated within the context of a basketball jump shot and hypotheses related to predictive-prospective control. More specifically, we were interested in determining if during complex far-aiming tasks, accuracy would occur as a result of an earlier QE period (predictive control; Vickers, 1996a); a late QE period (prospective control; de Oliveira et al., 2007); or combined-control (Elliott et al., 1999). Despite the hoop being occluded in all three occlusion conditions, the athletes maintained a high level of accuracy (JS-H: 56.54 %; JS-L: 49.12 %; JS-T: 40.61%) compared to Experiment 1 (JS-No: 56.62%). However, as the amount of occlusion in the task increased, shooting percentage declined. Several results from Experiment 2 indicated similar results as evident from Experiment 1.

First, significant effects for fixation frequency were evident. In particular a significant interaction of fixation frequency by accuracy suggests that during hits a lower frequency was evident in both the flexion and extension phases that was not evident in misses. During misses subjects attempted to fixate more information perhaps in an attempt to control for the absence of target information. Arguably, the lower fixation frequency in hits may have been related to an athlete's ability to employ an early QE period for a longer duration. This was evident by several factors. The mean QE onset for hits (1103.77 ms, 70.13 %) differed significantly from the mean QE onset for misses (1176.77 ms, 74.89 %), which suggests that successful shots were characterized by an earlier onset of the QE period than unsuccessful shots. Following the earlier QE onset, successful shots were also differentiated by the ability of athletes to *employ* key predictive information for a longer duration. Specifically, the mean QE duration for hits (287.20 ms, 18.01 %) differed from the mean QE duration for misses (216.78 ms, 13.76 %), thereby echoing previous findings in which an earlier and longer predictive QE period significantly differentiated skill and outcome in self-paced (Harle & Vickers, 2001; Vickers, 1996a) and externally-paced target aiming tasks (Williams et al., 2002). And, similar to the evidence found in Experiment 1.

Even though no differences were evident in QE offset, the majority of the QE period was contained within the flexion phase, which was similar to Experiment 1. The significant temporal phase x accuracy result indicated that success was related to a longer QE period prior to extension phase onset. During the flexion phase, when athletes maintained an early and long QE duration (266.11 ms, 16.61 %) success was more evident than when the early QE duration was shorter (191.76 ms, 12.04 %). Moreover, the amount of late information garnered past the extension phase onset did not seem to assist in achieving success as hits (25.17 ms, 1.61 %) and misses (25.50 ms, 1.61 %) were similar. And, the higher results of fixation frequency during misses as opposed to hits during the extension phase suggests that an attempt to acquire late prospective information may have resulted in inaccurate attempts. Together, the results from Experiment 2 indicated that early information, and therefore an early-long QE period, which was terminated near extension phase onset, permitted the shooter to navigate task constraints, thereby supporting predictive control (Vickers, 1996a).

Chapter 5: Quiet Eye Training

In Experiment 2, since control in the basketball jump shot was related more to predictive control than either combined-control or prospective control, Experiment 3 attempted to train athletes to be aware of egocentric cues to increase their reliance on a predictive control strategy.

External Focus of Attention

Central to the problem of perceptual training of expertise is the type of instruction provided to learners when learning a complex motor skill. According to Wulf and colleagues, instruction that encourages an external focus of attention is more successful than one that promotes an internal focus (Emanuel, Jarus, & Bart, 2008; McNevin, Shea, & Wulf, 2003; Totsika & Wulf, 2003; Wulf, Höss, & Prinz, 1998; Wulf, Lauterbach, & Toole, 1999; Wulf, McConnel, Gärtner, & Schwarz, 2002; Wulf & McNevin, 2003; Wulf, McNevin, & Shea, 2001; Wulf & Weigelt, 1997; Zachary, Wulf, Mercer, & Bezodis, 2005). For example, Wulf et al. (1998) determined an improvement in motor-skill acquisition when the learner's focus of attention is directed to external factors such as the global effect of their movements. However, when the focus of attention was directed to an internal focus of attention, related to the prospective control of specific body movements during the unfolding of the movement, the level of performance improvements was not as robust. Perkins-Ceccato, Passmore and Lee (2005) examined the influence of internal and external focus of attention on performance instructions in the control of a self-paced aiming pitch shot by high- and low-skilled golfers. During the external focus of attention instructions, participants were directed to focus on a predictive control strategy by hitting the ball as close to the target as possible. In the internal focus of attention instructions, participants were instructed to concentrate on a prospective control strategy by modifying the form of the golf swing by adjusting the force of their swing depending on the distance of the shot. Results indicated that highly skilled golfers performed better with an external focus of attention instructions than with internal focus instructions, thereby implicating a predictive control strategy. On the other hand, low-skill golfers performed better with instructions that developed an internal focus of attention instructions, thereby implicating prospective control. Similarly, Emanuel et al. (2008) attempted to determine if skill acquisition benefits in a self-paced dart-throwing task could be better achieved through an external focus rather than internal focus when learning a new motor skill. Results indicated that in adult learners, an external focus of attention and predictive control was more effective than an internal focus and prospective control strategy.

Likewise, Zachary et al. (2005) attempted to determine if the focus of attention instructions (internal/external) could be related to performance improvements and neuromuscular correlates during a self-paced aiming task (basketball free throw). In the internal focus of attention instructions, participants were instructed to focus on the precise execution of the wrist extension, thereby implicating prospective control, while in the external focus of attention instructions, participants were asked to focus on the target location only (basket), thereby implicating predictive control. Results indicated that aiming accuracy was facilitated when participants adopted an external focus of attention and predictive control strategy. Further, electromyography (EMG) activity in arm muscles was lower in the external focus of attention condition compared to the internal focus condition, which suggests that very few late muscular adaptations (prospective control) were used to reduce end-point variability. Zachary et al. suggested that an external focus of attention and therefore the predictive control strategy, enhanced movement efficiency by reducing the possibility of late prospective information updating movements on-line.

Clearly then, an external focus of attention facilitates a predictive control strategy, thereby leading to high levels of success. Alternatively, when an internal focus of attention strategy is adopted, and therefore relying on the prospective control of movements on-line, disruptions in performance have been evident. However, as outlined at the outset of this thesis, there is controversy in terms of the importance of either predictive or prospective mechanisms in many motor tasks (Williams et al., 1999). On one hand, success has been determined to be the result of an early acquisition of visual information prior to movement production (predictive control; Harle & Vickers, 2001; Ripoll et al., 1986; Vickers, 1996a; Vickers et al., 2000). In Experiment 1 of the current study, both predictive and combined-control were found to underlie accuracy. However, in Experiment 2, success was related more to a predictive control as late prospective information used to update movements on-line appeared to be inadequate.

Purpose: The purpose of Experiment 3, therefore, was to determine if a QE period could be trained relative to an external egocentric gaze reference using procedures found successful in previous studies (Harle & Vickers, 2001; Oudejans et al., 2005). Specifically, participants were required to perform jump shots under similar conditions to Experiment 2; however, before beginning to shoot in each condition the athlete's attention was drawn to an egocentric orientation using an external-focus (Wulf et al., 1998) questioning technique. If the QE period changed toward earlier predictive information and lead to greater levels of accuracy compared to Experiment 2, then this would indicate that attempts to increase conscious awareness of an egocentric target location was effective in improving performance. If, on the other hand, the QE period remains unchanged and no differences in accuracy emerged, then this would indicate that attempts to increase conscious awareness of an egocentric target location are not effective in improving performance. It was expected that helping athletes become aware of an egocentric orientation would not only increase accuracy relative to Experiment 2, but would also be accompanied by an earlier QE onset, longer QE duration, and later QE offset.

Methods

Participants. The same elite male basketball players (N = 11) who participated in Experiment 1 and 2 volunteered for Experiment 3. Testing occurred immediately after Experiment 2, with a delay of approximately 10 minutes in the same testing environment.

Apparatus. See Experiment 2.

Procedure. After a brief warm-up, participants were checked for calibration to nine target points defined in x/y coordinates. They then took their stance behind the occlusion screen as shown in Figure 1 and fixated the middle of the line above the hoop (JST-L), or the middle of the top of the backboard (JST-T). Players were then were asked questions about the location of the target and external cues that were egocentric to the location of the hoop, which was not visible. For example, one athlete identified a line on the wall above the hoop, while others isolated letters in the name of the gymnasium (see Figure 1); still others identified lines on the basketball court that were aligned with the hoop. Shots were then taken as in Experiment 2. Prior to each counterbalanced condition, the screen was raised or lowered for each individual so to occlude all aspects of the hoop and/or backboard. After calibration, the shooter took shots until they stated they were comfortable and ready to being the trials. A "ready" verbal command was issued, thereby permitting the participant to begin shooting. Each trial began with the ball being passed to the participant by another player who was located behind the screen. Upon receiving the ball the athlete took a jump shot as in Experiment 1 and 2. A recorder kept track of the outcome (hit, miss) as each player continued shooting until the requirements of each condition (5 hits, 5 miss) were met. Shooting percentage for the training conditions were compared to those from Experiment 1 and 2, as shown in Table 3.

Data coding. See Experiment 2.

Independent variables.

Within subject factors.

1. Condition (6): Six jump shot conditions were used: jump shot - no (JS-No), jump shot - hoop (JS-H), jump shot - line (JS-L), jump shot - top (JS-T), jump shot train - line (JST-L), jump shot train- top (JST-T) conditions.

2. Accuracy (2): Hits and Misses. Hits and misses were defined as in competition. Hits occurred when the ball went through the hoop and misses occurred when the basketball did not go through the hoop.

3. Trials (5): Five hits and five misses. The first five hits and misses were coded.

Dependent variables.

1. Shooting percentage: The number of hits made relative to the total number of shots taken.

2. Phase duration: Absolute (ms) and relative (rel %) phase duration of two phases (flexion, extension).

3. Gaze type: Absolute (ms) and relative (rel %) onset, duration, and offset of fixations and the quiet eye period.

Data Analysis. Shooting percentage in each condition (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T) was analyzed using one-way repeated measures ANOVA. Phase duration within two motor-based phases (flexion, extension) of the jump shot were analyzed using a condition (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T) x phase (flexion, extension) x accuracy (hit, miss) three-way repeated measures ANOVA. Quiet eye onset, duration, and offset were analyzed using a condition (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T) x accuracy (hit, miss) two-way repeated measures ANOVA. Quiet eye duration (ms, rel %) before and after extension phase onset was analyzed by a condition (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T) x temporal phase (early, late) x accuracy (hit, miss) three-way repeated measures ANOVA. An alpha level of 0.05 was used for all statistical tests. Effect sizes were calculated using omega squared (ω^2) for significant main effects and interactions.

Table 3

Shooting Percentage for Each Participant During Each Condition (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T).

	Condition					
Participant	JS-No	JS-H	JS-L	JS-T	JSL-T	JST-T
1	53.85	57.90	35.29	50.00	38.46	57.89
2	45.45	41.67	50.00	58.82	66.67	41.67
3	42.86	35.71	29.41	44.44	55.00	50.00
4	91.30	65.22	54.55	45.45	35.71	74.19
5	60.00	53.33	41.67	31.25	71.43	50.00
6	38.46	46.15	50.00	29.41	64.29	26.32
7	72.73	61.90	80.77	53.33	68.18	50.00
8	46.67	68.42	45.45	31.25	38.46	54.54
9	53.85	50.00	45.45	27.78	50.00	54.55
10	58.82	65.00	38.46	25.00	50.00	50.00
11	58.82	76.67	69.23	50.00	63.33	54.17
Mean	56.62	56.54	49.12	40.61	54.68	51.22

Results

Shooting percentage. Shooting percentage in each condition (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T) was analyzed using one-way repeated measures ANOVA. A statistical significant condition effect was detected F (5, 50) = 2.96, $p = .02$, $\omega^2 = .11$.

The mean shooting percentage for JS-No (*M* = 56.62 %, *SD* = 14.97 %), JS-H (*M* = 56.54 %, *SD* = 12.41 %), JS-L (*M* = 49.12 %, *SD* = 14.88 %), JS-T (*M* = 40.61 %, *SD* =11.90 %), JST-L (*M* = 54.69 %, *SD* =13.05 %), and JST-T (*M* = 51.21 %, *SD* =11.49 %) differed as shown in Figure 15.

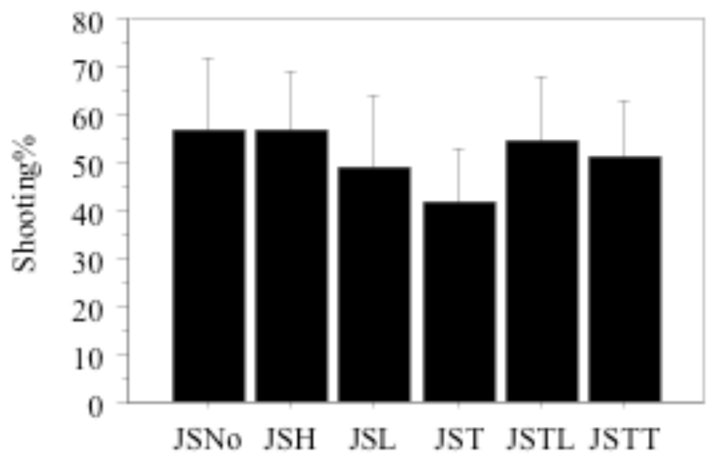

Figure 15. Shooting percentage with standard deviation in each experimental condition (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T) of the jump shot.

Phase duration. Absolute (ms) and relative (rel %) phase duration within two motor-based phases (flexion, extension) of the jump shot were analyzed separately using a condition (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T) x phase (flexion, extension) x accuracy (hit, miss) three-way repeated measures ANOVA. As shown in Figure 16, significant differences were found for absolute (ms) $F(1, 60) = 1194.48$, $p < .001$, $\omega^2 = .95$, and relative phase duration $F(1, 60) = 2014.13$, $p < .001$, $\omega^2 = .99$. The mean duration of the flexion (*M* = 451.41 ms, *SD* = 75.36 ms; *M* = 28.76 %, *SD* = 3.30 %) and extension (*M* = 123.17 ms, *SD* = 24.11 ms; *M* = 7.73 %, SD = 1.40 %) phases differed.

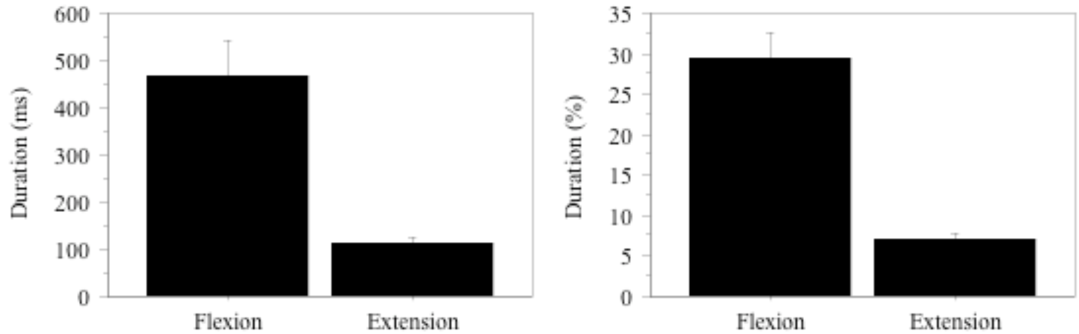

Figure 16. Mean duration (ms, rel %) of the flexion and extension phase in the jump shot.

In addition, as shown in Figure 17, a significant relative phase duration x condition effect F (5, 60) = 3.15, $p = .014$, $\omega^2 = .09$ was found. Relative flexion phase duration in the JS-No (*M* = 30.06 %, *SD* = 3.51 %), JS-H (*M* = 28.96 %, *SD* = 2.76 %), JS-L (*M* = 29.01 %, *SD* = 2.91 %), JS-T (*M* = 29.51 %, *SD* = 3.52 %), JST-L (*M* = 27.59 %, *SD* = 3.21 %), JST-T (*M* = 27.44 %, *SD* = 3.32 %) differed from extension phase duration in the JS-No (*M* = 6.86 %, *SD* = 0.55 %), JS-H (*M* = 7.23 %, *SD* = 0.74 %), JS-L (*M* = 7.32 %, *SD* = 0.81 %), JS-T (*M* = 6.94 %, *SD* = 0.73 %), JST-L (*M* = 8.94 %, *SD* = 1.32 %), and JST-T (*M* = 9.07 %, *SD* = 1.75 %). No other significant effects were found.

Quiet eye. QE onset, duration, and offset were analyzed separately using a condition (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T) x accuracy (hit, miss) two-way repeated measures ANOVA. As shown in Figure 18, significant differences in accuracy were found for both absolute F (1, 60) = 15.36, $p < .001$, $\omega^2 = .95$ and relative QE onset F (1, 60) = 15.49, $p < .001$, $\omega^2 = .95$. QE onset occurred earlier on hits (*M* = 1059.73 ms, *SD* = 221.92 ms; *M* = 67.24 %, *SD* = 14.01 %) than on misses (*M* = 1118.34 ms, *SD* =

199.63 ms; *M* = 70.99 %, *SD* = 12.11 %). No other significant effects for QE onset were found.

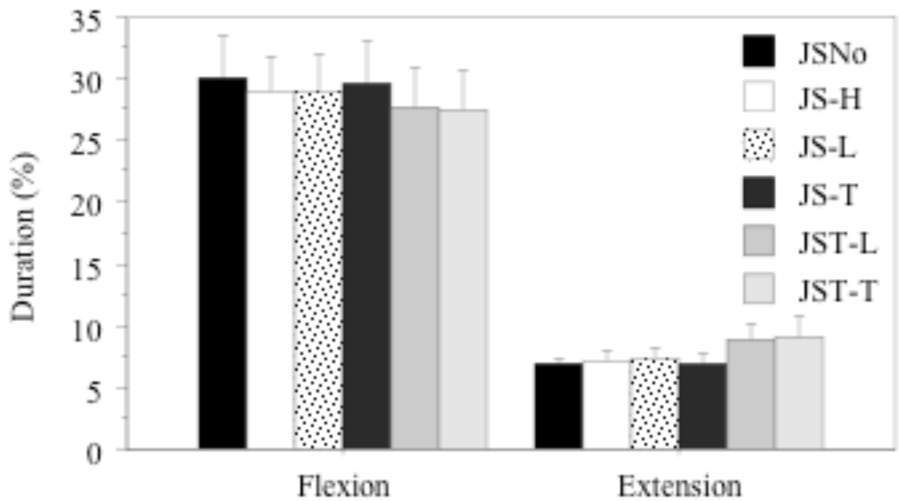

Figure 17. Mean duration (rel %) of the flexion and extension phase in all experimental conditions (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T).

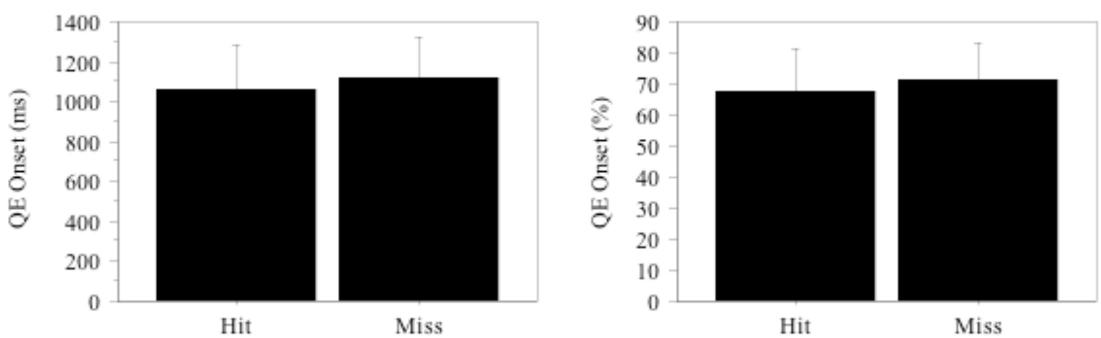

Figure 18. QE onset (ms, rel %), with standard deviation, for hits and misses in experimental conditions (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T) of the jump shot.

As shown in Figure 19, significant differences in accuracy were found for both absolute F (1, 60) = 21.96, $p < .001$, $\omega^2 = .08$ and relative QE duration F (1, 60) = 23.03, $p < .001$, $\omega^2 = .08$. The mean QE duration for hits (*M* = 286.45 ms, *SD* = 193.60 ms; *M* = 18.02 %, *SD* = 11.76 %) was higher than for misses (*M* = 228.50 ms, *SD* = 125.63 ms; *M* = 14.40 %, *SD* = 7.72 %).

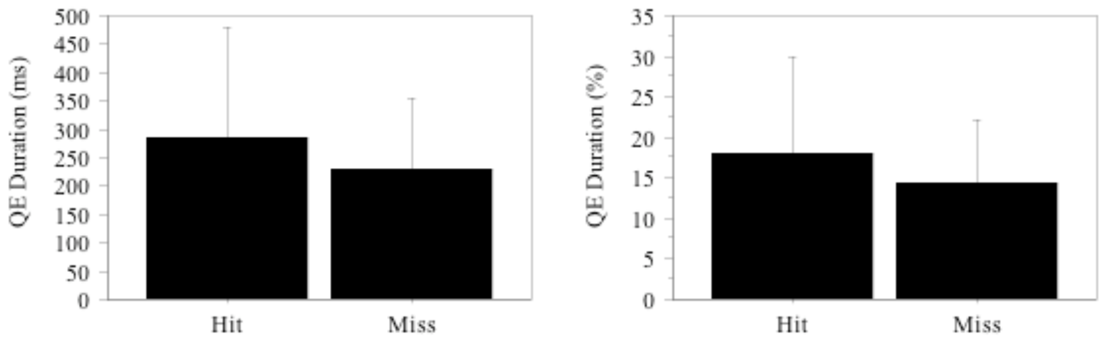

Figure 19. Quiet eye duration (ms, rel %), with standard deviation, for hits and misses in experimental conditions (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T) of the jump shot.

As shown in Figure 20, significant differences in condition were found for both absolute F (5, 60) = 3.07, $p = .016$, $\omega^2 = .20$ and relative QE offset F (5, 60) = 4.21, $p = .002$, $\omega^2 = .26$. The mean QE offset in JS-No (*M* = 1437.00 ms, *SD* = 190.49 ms; *M* = 90.26 %, *SD* = 7.93 %), JS-H (*M* = 1347.31 ms, *SD* = 99.06 ms; *M* = 85.96 %, *SD* = 6.42 %), JS-L (*M* = 1371.53 ms, *SD* = 94.38 ms; *M* = 87.23 %, *SD* = 6.14 %), JS-T (*M* = 1418.33 ms, *SD* = 143.18 ms; *M* = 89.76 %, *SD* = 6.57 %), JST-L (*M* = 1298.34 ms, *SD* = 103.09 ms; *M* = 82.24 %, *SD* = 6.09 %), JST-T (*M* = 1210.42 ms, *SD* = 249.72 ms; *M* = 76.37 %, *SD* = 14.69 %), differed. No other significant effects were found.

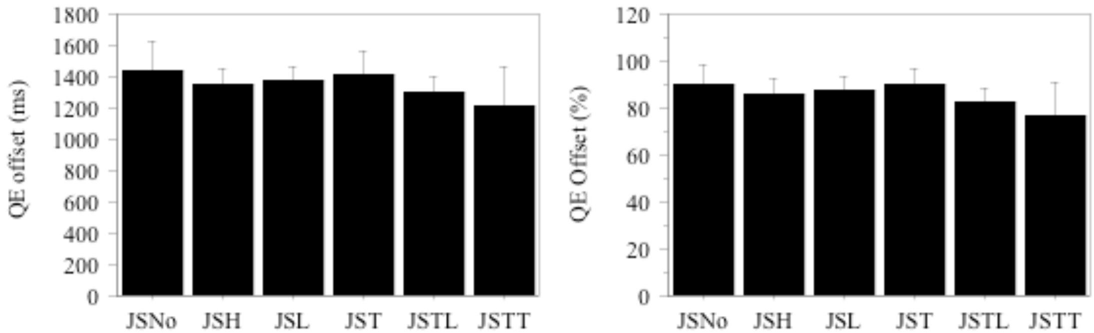

Figure 20. Quiet eye offset (ms, rel %), with standard deviation, in experimental conditions (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T) of the jump shot.

Quiet eye duration (ms, rel %) before and after extension phase onset was analyzed by a condition (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T) x temporal phase (early, late) x accuracy (hit, miss) three-way repeated measures ANOVA. For temporal phase, significant effects in both absolute (ms) F (1, 60) = 125.89, $p < .001$, $\omega^2 = .64$ and relative (rel %) duration F (1, 60) = 129.57, $p < .001$, $\omega^2 = .66$, were evident. Likewise, significant effects for accuracy were found in both absolute (ms) F (1, 60) = 20.89, $p < .001$, $\omega^2 = .04$ and relative (rel %) F (1, 60) = 21.97, $p < .001$, $\omega^2 = .03$. As shown in Figure 21, a significant temporal phase x accuracy interaction was evident in both absolute (ms) (F (1, 60) = 16.27, $p < .001$, $\omega^2 = .23$ and relative (rel %) duration F (1, 60) = 15.07, $p < .001$, $\omega^2 = .23$. The mean QE duration in early hits (*M* = 268.53 ms, *SD* = 198.80 ms; *M* = 16.08 %, *SD* = 12.16 %), early miss (*M* = 207.35 ms, *SD* = 124.41 ms; *M* = 13.08 %, *SD* = 7.70 %), late hits (*M* = 21.42 ms, *SD* = 25.58 ms; *M* = 1.36 %, *SD* = 1.79 %), and late miss (*M* = 21.07 ms, *SD* = 28.48 ms; *M* = 1.31 %, *SD* = 1.72 %), differed. No other significant effects were found.

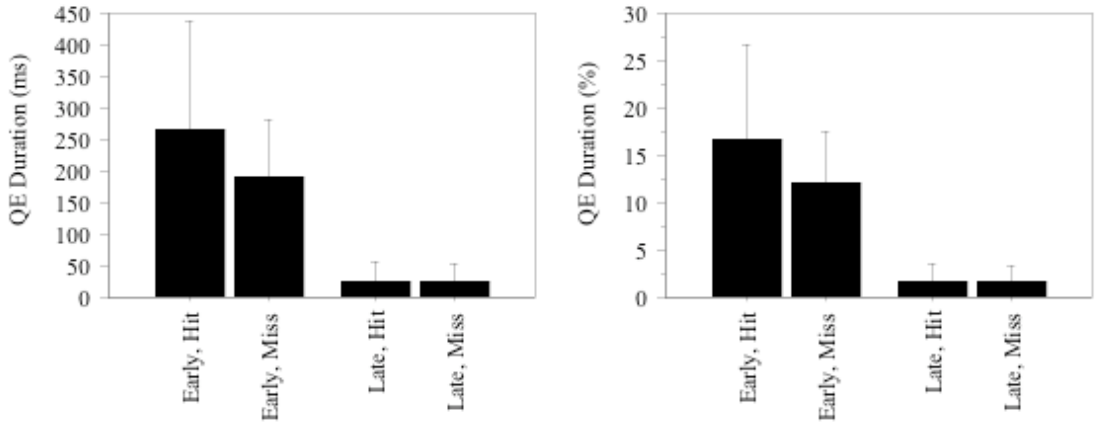

Figure 21. The temporal duration (ms, rel %) of the QE period prior to and after (early, late) extension phase onset by accuracy in experimental conditions (JS-No, JS-H, JS-L, JS-T, JST-L, JST-T) of the jump shot.

Discussion

Since the results of Experiment 1 and 2 revealed that an earlier and longer QE duration was related to higher levels of accuracy, the purpose of Experiment 3, therefore, was to determine if a QE period could be trained relative to an external egocentric gaze reference, using procedures from previous studies (Harle & Vickers, 2001; Oudejans et al., 2005). Specifically, participants were required to perform jump shots under similar conditions to Experiment 2; however, before beginning to shoot in each condition, the athlete's attention was drawn to an egocentric orientation of the target using an external-focus (Wulf et al., 1998) questioning technique. It was hypothesized that if the QE period changed toward earlier predictive information and lead to greater levels of accuracy compared to Experiment 2, then this would indicate that attempts to increase conscious awareness to an egocentric target was effective in adopting a predictive control strategy. If, on the other hand, the QE period remains unchanged and no differences in accuracy emerged, then this would indicate that attempts to increase conscious awareness to an egocentric target was not effective in improving predictive control. It was expected that helping the athletes become aware of an egocentric orientation would not only increase accuracy relative to Experiment 2, but would also be accompanied by an earlier QE onset, longer QE duration, and later QE offset.

Results of the current study confirmed the hypotheses that awareness of an egocentric target can assist in developing a predictive control strategy. In effect, athletes increased their accuracy in Experiment 3 relative to Experiment 2 due to a different method of gaze control was evident in successful and unsuccessful attempts. First, despite the hoop being occluded under the same conditions as in Experiment 2, accuracy in Experiment 3 increased. In particular, significant changes in QE onset and QE duration were evident between hits and miss, as athletes seemed to locate and employ critical information earlier. And, these results confirm the earlier and longer QE period found from Experiment 1 and 2. However, the most important result gleaned from Experiment 3 was related to QE offset, which was found to occur earlier after training. In both the JST-L and JST-L conditions, QE offset occurred prior to the onset of the extension phase thereby proving support appeared that the external-focus training assisted in adopting a predictive control strategy.

Similar to Experiment 2, a significant temporal phase x accuracy interaction seemed to indicate that the majority of the QE period was contained within the flexion phase as very little information was acquired for control in the extension phase. More specifically, while the duration of the QE period in hits prior to the extension phase differed from the QE duration in miss, no such differences were evident in the QE duration in hits and misses during the extension phase. This result gives further support for interaction of temporal phase and accuracy found in Experiment 2, thereby supporting predictive control.

Unlike Experiment 2, however, a significant relative phase duration x condition effect was found, which was not expected. In effect, QE training seemed to shorten the relative flexion phase duration while lengthening the extension phase in both the JST-L and JST-T, respectively. Thereby giving partial support to the previous result by Oudejans et al., (2005) who determined significant improvements in field goal shooting percentage due to a lengthened final period duration of 67 ms.

Chapter 6: Overall Discussion

The current thesis investigated the role of predictive, prospective, or combined-control in basketball jump shooting accuracy. In Experiment 1, athletes temporally regulated vision during the basketball jump shot due to a different method of gaze control that was evident in successful attempts. Specifically, a longer QE duration was found in hits as opposed to misses, thereby supporting the importance of predictive control found in previous investigations (Harle & Vickers, 2001; Janelle et al., 2000; Vickers, 1996a; Vickers et al., 2000). This was also supported by the result that very few fixations were either initiated or terminated during the extension phase, making the possibility of a sole late-prospective period unlikely. However, the significant effect between QE duration before and after extension phase onset, provided evidence that some late information may been used in combination with early information, thereby supporting combined-control (Elliot et al., 1999).

In Experiment 2, the availability of early target information was reduced using three spatial occlusion conditions. Despite the hoop being occluded in all three conditions, athletes maintained a high level of accuracy due a quiet relationship between perception and action. In effect, a different method of gaze control was evident in successful attempts. Specifically, hits were characterized by a lower frequency of fixations, earlier QE onset, and longer QE duration. And, the fact that the majority of the QE period was contained within the flexion phase suggests the dominant role of early predictive information. Accuracy appeared to be dependent more upon a predictive control strategy, whereby the motor program for shooting was activated from memory and run off with minimal late information.

In Experiment 3, the early-predictive QE period was trained relative to an external-focus egocentric gaze reference. Results indicated that athletes increased their accuracy in Experiment 3 relative to Experiment 2 due to a different method of gaze control in successful and unsuccessful attempts. Significant changes in QE onset and duration were evident between hits and miss, as athletes seemed to locate and employ critical information earlier. Moreover, QE offset occurred earlier thereby further constraining the role of late information in the task. And finally, similar to Experiment 1 and 2, the majority of the QE period was contained within the flexion phase. Together, these results suggest that external-focus training has the potential to affect the employment of the early-predictive QE period. In the final section, the potential theoretical significance of the results is presented. Specifically, the relationship between predictive control, QE period (Vickers, 1996a), TEC (Hommel et al., 2001) and the PAM (Milner & Goodale, 1995) is discussed.

Theoretical Considerations

Over the three experiments, the variable that was consistently related to task success was an early-long duration QE period. In effect, the early-long QE period permitted an efficient predictive control process that navigated task constraints. Recall that in the TEC (Hommel et al., 2001), cognitive and motor processes associated with intended actions are not separated as functionally independent, multiple representations, but rather are equally represented within a task-tuned, integrated event code. In the current study, the results of the early-long QE period suggest that perception and action were functionally dependent. In particular, distal referenced feature codes in one's external focus of attention (Wulf et al., 1998) seemed to have been integrated within perceptual subsystems to navigate task constraints. Once enough information was obtained within the athlete's spotlight of attention, a predictive decision related to the subsequent action was primed from memory that specified advance instructions such as relative timing, phasing, and forces in the production of action (Schmidt, 1975). During this process, which shares numerous similarities to Treisman's (1999) feature integration theory, information may have been initially recognized based on different sensory features that "pop-out" within the perceptual-motor workspace (Vickers, 2007). In this view, intention, perception, attention, and action were coordinated by a common medium, that then primed task-relevant movement information in the event code (Greenwald, 1970). The primed motor decision was then transmitted to the effectors to manage degrees of freedom inherent within the task.

Alternatively, the priming of a movement-based decision based on information contained within the event code (Hommel et al., 2001; Treisman, 1999) contrasts against the PCM (Glover, 2004) in which two temporally separate yet overlapping systems are employed to control body movements in space. According to the PCM, the planning system, which selects a goal prior to movement production, initiates an adaptive motor program based on a broad range of constructed cognitive information. Then, once the movement begins, the control system is responsible for minimizing movement variance by employing a further on-line visual representation. The key difference between the TEC and the PCM two is whether or not singular or multiple representations are formulated in the control of action. From the current study, the fact that very little prospective information was employed during the final extension phase of the movement, suggests that late prospective control, and therefore, the control system, as suggested by Glover (2004), was not engaged.

Results from the current study, however, gives partial support to the PAM (Milner & Goodale, 1995). In this view, perception and action are viewed as functionally independent subsystems in the control of action. Recall that the ventral pathway transforms visual information into perceptual and cognitive representation that enables memory-based mechanisms such as pattern recognition, subsequent interpretation, and the planning of future movements (adaptive motor programming). The dorsal pathway then transmits moment-to-moment information to be used directly in the on-line control of movements. In essence, the dorsal pathway relies upon pragmatic stimulus features that specify directly bottom-up information to complete the required movement parameters unconsciously. Essentially, the coordinative role of between ventral and dorsal stream information serves to reduce error in the control of action.

Even though a wealth of evidence from near-aiming research has consistently shown a two-part process in the reduction of error (Elliot et al., 1999; Meyer et al., 1988), the limited support for late prospective control found in the current study suggests a coordinative relationship between ventral and dorsal stream processing during complex-aiming. This was evident by the fact that even though the majority of the QE period was contained within the flexion phase, QE information was also found to occur in the extension phase. Ultimately, this suggests that obtaining QE information at, or just pass, extension phase onset for a limited duration may be critical for success. Moreover, it suggests the coordinative relationship between vision-for-perception and vision-for-action, respectively. This relationship has been recently demonstrated through the manipulation of traditional experimental tasks conducted in the laboratory and with those found in their natural environment (Dicks, Button, & Davids, in press). During traditional laboratory-based tasks, Dicks et al. suggested that simple movement based responses often neglect the coordinated processing of ventral and dorsal stream information. On the other hand, tasks that represented a high degree of ecological validity were indicative of an integrated, coordinative, functional relationship between vision for perception and action. Likewise, Króliczak, Heard, Goodale and Gregory (2006) demonstrated that while ventral stream processing was required during pointing movements, an on-line motor response was coordinated with the intention prior to movement. In other words, the intention to act within natural environments appears to have elicited dorsal stream processing. Similarly, van der Kamp, Rivas, van Doorn and Savelsbergh (2008) suggested that coordinated ventral and dorsal processing prior to ball release in the execution of motor tasks is required to facilitate successful execution. However, further research is needed to understand if the QE period is elicited by either the ventral or dorsal stream.

Nonetheless, evidence from the current study indicated that success was related to a coordinated relationship between perception and action. In essence, success was related to the coordinated processing via predictive control to navigate task constraints. In essence, the early-long QE period was used to temporally initiate an adaptive motor program. This was evident by the fact that in Experiment 2 shooting accuracy was related to achieving a long duration of early coordinated processing. During miss attempts, however, subjects attempted to fixate more late information due to a later deployed QE onset and a low QE duration period. Moreover, the amount of late QE information garnered past the extension phase onset did not seem to assist in achieving success. In Experiment 3, when athletes were trained to fixate an egocentric point of reference prior to movement initiation, success was related to the coordinated processing of information. This was evident due to an increased level of accuracy, earlier QE onset, and longer QE duration after training. Clearly, an egocentric reference may have assisted in reducing uncertainty thereby permitting the motor program to be completed in an efficient, fluid manner.

Further validity for the coordinated processing has also been seen when discussed with recent results from cognitive neuroscience. Namely, if expertise in motor control is based on the idea of either (a) continuous acquisition of late information (Oudejans et al., 2002) or (b) separate representations and rapid, closed-loop control processes (Elliot et al., 1999), then elevated levels of psychophysiological activation should be evident. However, previous results from imaging studies in sport (Crews & Landers, 1993; Hatfield, Haufler, Hung & Spalding, 2004; Janelle et al., 2000; Salazar, et al., 1990) have suggested that psychophysiological characteristics of expert motor control are related to coordinated processing. For instance, research investigating cortical activation of expertise during complex aiming sports such as golf (Crews & Landers, 1993), archery (Salazar et al., 1990), and shooting (Hatfield et al., 2004) has consistently determined significantly less electroencephalography (EEG) activity prior to movement initiation. This, when considered with the evidence of Janelle et al., (2000) who determined a significant relationship between a quieter left hemisphere and QE duration suggests that coordinated processing is required for success in complex-aiming.

Moreover, the coordinated processing between perception and action reiterates findings from cognitive neuroscience between executive areas of the frontal cortex during successful decision-making. Specifically, a coordinated relationship is evident between the prefrontal cortex and anterior cingulate. The prefrontal cortex has been implicated as a top-down supervisory cognitive control mechanism that provides bias to signals in subcortical brain structures whose responsibility is to guide the flow of activity along further subcortical neural pathways. In situations where the neural mappings between sensory inputs, thoughts, and actions are either weakly established or require further processing, the prefrontal cortex is highly active (Miller & Cohen, 2001). The role of the anterior cingulate has been suggested to be an evaluative processor that either monitors performance for errors (Bush, Luu, & Posner, 2000) and/or resolves conflict between competing items (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Carter et al., 1998; MacDonald, Cohen, Stenger, & Carter, 2000). By evaluating the level of noise or conflict between neural network signals, the anterior cingulate contributes to executive functions by evaluating and determining whether further attentional processing is required (Botvinick et al., 2001). Therefore, in situations that require additional processing, cortical activation between the anterior cingulate and prefrontal cortex increases (Paus, Koski, Caramanos, & Westbury, 1998). Significant conflict may be represented by high amounts of uncertainty, emotional perturbations, or further attempts to maintain control during an action. In contrast, in situations of low conflict, the relationship between these executive areas is simply quiet or not active (Botvinick et al., 1999; Carter et al., 1998; MacDonald et al., 2000; Paus et al., 1998), thereby contributing to a coordinated relationship between perception and action. In other words, in tasks that do not require further representational classifications, the anterior cingulate simply shuts areas of the prefrontal cortex off thereby allowing the primed motor program to run off in a fluid and a non-conscious manner.

Moreover, the coordinated relationship between perception and action was evident by Zachary et al. (2005) who determined neuromuscular correlates during a self-paced aiming task (basketball free throw). Results indicated that aiming accuracy was facilitated when participants adopted a predictive control strategy. Specifically, EMG activity in arm muscles was lower in the external focus of attention condition compared to the internal focus condition, which suggests that very few late muscular adaptations (prospective control) were used to reduce end-point variability.

Limitations and Future Directions

While the current study attempted to understand mechanisms underpinning successful complex-aiming by incorporating an *in situ* task, *in situ* spatial occlusion, and an applied *in situ* training procedure, a further integration of techniques from each of the cognitive, ecological, and dynamic systems approach is required. Specifically, a further integration of research approaches of Oudejans (de Oliviera et al., 2007; de Oliviera et al., 2006; de Oliviera et al., 2008; Oudejans et al., 2005; Oudejans et al., 2002) and Vickers (Janelle et al., 2000; Ripoll et al., 1986; Vickers, 1996a; Williams et al., 2002; Mann et al., 2007) may further illuminate discrepancies in the research. For instance, a limitation of the current investigation was that only focal vision was recorded and analyzed, whereas ecological and dynamic systems models do not differentiate between focal and ambient (or para-foveal) contributions to motor control. Future research is needed to determine the precise contribution of foveal and para-foveal information to motor performance, especially that perceived during the final 150 ms of the movement.

Second, future studies should attempt to further investigate the coordinative relationship between early visually based predictive information, late prospective information, and late kinesthetic information. Intuitively, while it may seem obvious that vision has been posited as the most dominant sense, multiple perceptual inputs may be required to locate, organize, and control movements on-line (Carello, Flascher, Kunkler-Peck, & Tur, 1999). For instance, Pagano, Carello, and Turvey (1996) suggested that when a hand-held object, such as a basketball, is manipulated during the control of action, certain non-visual impressions related to the size, weight, magnitude of displacement, and orientation are created that are used prospectively control the hand-held object in space. According to Latash (1998), the kinesthetic skill permits individuals to perform accurate movements in space without continuous access to visual motor control. Future research should attempt to understand the relative contribution of this kinesthetic information to task success.

Third, future work should attempt to understand the relationship between task (distance, weight), organism (fatigue, strength), and environmental constraints on the impending predictive and prospective control variables. Or more specifically, as distance increases from the basket increases, is the height of the jump, release angle, subsequent release speed, and ultimately the optimal timing of the release point altered by an earlier occurring long duration QE period? According to Miller and Bartlett (1993), at greater distances from the basket, critical object-based location information must be obtained early in the jump shot phase to organize and propel the object to the basket. In their study, an earlier pre-set of the shoulder axis prior to release of the ball was critical at further distances. As a result, as distance increases, an earlier QE onset and longer QE duration, and therefore predictive control, may be required to coordinate target aiming. Alternatively, jump shots or lay-ups closer to the basket (under 1 meter) may either require a later QE onset, lower QE duration, and later QE offset, thereby implicating prospective or combined-control control. In the same vein, how does the position a player affect the impending location, duration, and offset of the QE period in the complex far-aiming task? In other words, will an athlete that is used to performing near the basket (center; low-post) have similar QE characteristics than one who is consistently operates away from the basket (guard)?

Conclusion

The present thesis attempted to concentrate on how external visual information is acquired and employed in the control of a jump shot. The work was important because the precise nature of the relationship between perception and action, or more specifically, predictive and prospective control in complex far-aiming was uncertain. It was determined that the variable that was consistently related to task success was an early-long duration QE period, thereby suggesting that a predictive control strategy is critical in tasks like the basketball jump shot. However, the fact that some late prospective information was acquired in the early extension phase suggests that combined-control may be required in some instances.

References

Abernethy, B. (1988). The effects of age and expertise upon perceptual skill development in a racquet sport. *Research Quarterly for Exercise and Sport, 59,* 210–221.

Abernethy, B. (1990a). Anticipation in squash: Differences in advance due utilization between expert and novice players. *Journal of Sports Sciences, 8,* 17-34.

Abernethy, B. (1990b). Expertise, visual search, and information pick-up in squash. *Perception, 19*, 63-77.

Abernethy, B. (1991). Visual search strategies and decision making in sport. *International Journal of Sport Psychology, 22,* 189–210.

Abernethy, B. (2001). Attention. In R. N. Singer, H. A. Hausenblas, & C. Janelle (Eds.), *Handbook of research on sport psychology* (2nd ed., pp. 53–85). New York, NY: Wiley.

Abernethy, B., Gill, D., Parks, S. L., & Packer, S. T. (2001). Expertise and the perception of kinematic and situational probability information. *Perception, 30,* 233–252.

Abernethy, B., & Russell, D. G. (1984). Advance cue utilization by skilled cricket batsmen. *Australian Journal of Science and Medicine in Sport, 16,* 2–10.

Abernethy, B., & Russell, D. G. (1987a). Expert-novice differences in an applied selective attention task. *Journal of Sport Psychology, 9,* 326-345.

Abernethy, B., & Russell, D. G. (1987b). The relationship between expertise and visual search strategy in a racquet sport. *Human Movement Science, 6,* 283-319.

Abernethy, B., & Zawi, K. (2007). Pickup of essential kinematics underpins expert perception of movement patterns. *Journal of Motor Behavior, 39,* 353-367.

Adams, J. A. (1971). A closed-theory of motor learning. *Journal of Motor Behavior, 3,* 111-150.

Adolphe, R., Vickers, J. N., & LaPlante, G. (1997). The effects of training visual attention on gaze behaviour and accuracy: a pilot study. *International Journal of Sports Vision. 4,* 28-33.

Allard, F., & Starkes, J. L. (1991). Motor skill experts in sports, dance, and other domains. In K. A. Ericsson and J. Smith (Eds.), *Toward a general theory of expertise* (pp.126-152). Cambridge, MA: Cambridge University Press.

Allport, A. (1989). Visual attention. In M. I. Posner (Ed.), *Foundations of cognitive science* (pp. 631–682). Cambridge, MA: MIT Press.

Bartlett, F. C. (1932). *Remembering: A study in experimental and social psychology*. Cambridge, England: Cambridge University Press.

Bastin, J., Craig, C., & Montagne, G. (2006). Prospective strategies underlie the control of interceptive actions. *Human Movement Science, 25*, 718-732.

Bernstein, N. A. (1967). *The coordination and regulation of movements*. Oxford, UK. Permagon Press.

Bootsma, R. J., & van Wieringen, P. C. W. (1990). Timing an attacking forehand drive in table tennis. *Journal of Experimental Psychology: Human Perception and Performance, 16*(1), 21-29.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108,* 624–652.

Botvinick, M. M.,, Nystrom, L. E., Fissell, K., Carter, C. S., & Cohen, J. D. (1999). Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature*, *402*(6758), 179–181.

Bridgeman, G., Henry, D., & Start, L. (1975). Failure to detect displacements of visual world during saccadic eye movements. *Vision Research, 15,* 719-722.

Brouwer, A. M., Brenner, E., & Smeets, J. B. J. (2002). Perception of acceleration with short presentation times: can acceleration be used in interception? *Perception & Psychophysics, 64,* 1160-1168.

Bush, G., Luu, P., & Posner, M. I. (2000). Cognitive and emotional influences in anterior cingulate cortex. *Trends Cognitive Science, 4,* 215–222.

Button, C. (2002). Auditory information and the co-ordination of one-handed catching. In K. Davids, G. Savelsbergh, S. J. Bennett & J. van der Kamp (Eds.), *Interceptive actions in sport: Information and movement* (pp. 184-194). New York, NY: Routledge.

Calijouw, S. R., van der Kamp, J., & Savelsbergh, G. J. P. (2006). The impact of task-constraints on the planning and control of interceptive hitting movements. *Neuroscience Letters, 392*, 84-89.

Carl, J., & Gellman, R. (1987). Human smooth pursuit: Stimulus-dependant responses. *Journal of Neuro-physiology, 57*, 1446-1463.

Carello, C., Flascher, I., Kunkler-Peck, A., & Turvey, M. T. (1999). An evaluation of context effects in dynamic touch. *Ecological Psychology*, 11, 194-207.

Carello, C., Thuot, S., & Turvey, M. T. (2000). Aging and the perception of a racket's sweet spot. *Human Movement Science, 20*(1), 1-20.

Carlton, L. G. (1992). Visual processing time and the control of movement. In L. Proteau & D. Elliott (Eds.), *Vision and motor contro*l (pp. 3-31). Amsterdam: North Holland.

Carpenter, R. H. S. (1988). *Movements of the eyes* (2nd ed.). London, England: Pion.

Carter, C. S., Braver, T. S., Todd, S., Barch, D. M., Botvinick, M. M., Noll, D., & Cohen, J. (1998). Anterior cingulate cortex, error detection, and the online monitoring of performance. *Science, 1,* 747-749.

Causer, J., Bennett, S. J., Holmes, P., Janelle, C. & Williams, A.M. (in press). Quiet eye duration and gun motion in elite shotgun shooting. *Medicine & Science in Sports & Exercise*.

Corbetta, M. (1998). Frontoparietal cortical networks for directing attention and the eye to visual locations: Identical, independent, or overlapping neural systems? *Proceedings National Academy Science, USA, 95*: 831-838.

Coren, S., Ward, L. M., & Enns, J. T. (2004). *Sensation & perception* (6th ed.). New York, NY: Wiley.

Crews D. J., & Landers D. M. (1993). Electroencephalographic measures of attentional patterns prior to the golf putt. *Medical Science Sports Exercise, 25,*116–126.

Davids, K., Renshaw, I., & Glazier, P. (2005). Movement models from sport reveal fundamental insights into coordination processes. *Exercise and Sport Science Reviews, 33*(1), 36-42.

Davids, K., Savelsbergh, G., Bennett, S. J., & van der Kamp, J. (2002). Interceptive actions in sport: Theoretical perspectives and practical applications. In K. Davids,

G. Savelsbergh, S. J. Bennett & J. van der Kamp (Eds.), *Interceptive actions in sport: Information and movement* (pp. 1-39). New York, NY: Routledge.

de Oliveira, R. F., Huys, R., Oudejans, R. R. D., van de Langenberg, R., & Beek, P. J. (2007). Basketball jump shooting is controlled online by vision. *Journal of Experimental Psychology, 54*(3), *180-186.*

de Oliveira, R. F., Oudejans, R. R. D., & Beek, P. J. (2006). Late information pick-up is preferred in basketball shooting. *Journal of Sports Sciences, 24,* 933-940.

de Oliveira, R. F., Oudejans, R. R. D., & Beek, P. J. (2008). Gaze behaviour in basketball shooting: Further evidence for online visual control. *Research Quarterly for Sport and Exercise*, *79*, 399-404.

Desmurget, M., Pélisson D., Rossetti Y., & Prablanc C. (1998). From eye to hand: planning goal-directed movements. *Neuroscience Biobehavioral Review, 22,* 761-788.

Dessing, J. C., Bullock, D., Peper, C. E., & Beek, P. J. (2002). Prospective control of manual interceptive actions: comparative simulations of extant and new model constructs. *Neural Networks, 15,* 163-179.

Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research, 36(12),* 1827-1837.

Dicks, M., Button, C., & Davids, K. (in press). Examination of gaze behaviors under in situ and video simulation task constraints reveals differences in the information used for perception and action. *Attention, Perception, & Psychophysics.*

Edelman, G. M., & Tononi, G. (2000). *A universe of consciousness*. New York, NY: Basic Books.

Elliot, D., Binstead, G., & Heath, M. (1999). The control of goal directed limb movements: Correcting errors in the trajectory. *Human Movement Science, 18,* 121-136.

Elliot, D., Hansen, S., & Grierson, L. E. M. (2009). Optimising speed and energy expenditure in accurate visually directed upper limb movements. *Ergonomics, 52*, 438-447.

Emanuel, M., Jarus, T., & Bart, O. (2008). Effect of focus of attention and age on motor acquisition, retention, and transfer: A randomized trial. *Physical Therapy, 88,* 251-260.

Enberg, M. L. (1968). Assessing perception of object directionality in tennis. *Dissertation Abstracts International, 29,* 806-A.

Farrow, D., & Abernethy, B. (2003). Do expertise and the degree of perception-action coupling affect natural anticipatory performance? *Perception, 32*, 1127-1139.

Farrow, D., Abernethy, B., & Jackson, R. C. (2005). Probing expert anticipation with the temporal occlusion paradigm: Experimental investigations of some methodological issues. *Motor Control, 9*, 330-349.

Fischer, B. (1987). The preparation of visually guided saccades. *Reviews of Physiology, Biochemistry, and Pharmacology, 106*, 2-35.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Hillsdale, NJ: Lawrence Erlbaum.

Glover, S. (2004). Separate visual representations in the planning and control of action. *Behavioral and Brain Sciences, 27*, 3-24.

Goodale, M. A. (2000). Perception and action in the human visual system. In M. S. Gazzaniga (Ed.), *The new cognitive neurosciences* (pp. 365-377). Cambridge, MA: MIT Press.

Goodale, M. A., & Milner, A. D. Open peer commentary: Plans for action. *Behavioral and Brain Sciences, 27*, 37-40.

Goulet, C., Bard, C., & Fleury, M. (1989). Expertise differences in preparing to return a tennis serve: A visual information processing approach. *Journal of Sport and Exercise Psychology, 11,* 382-398.

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideomotor mechanism. *Psychological Review 77,* 73–99.

Hamilton, G. R., & Reinschmidt, C. (1997). Optimal trajectory for the basketball free throw. *Journal of Sport Sciences, 15, 491-504.*

Harle, S. K., & Vickers, J. N. (2001). Training quiet eye improves accuracy in the basketball free throw. *The Sport Psychologist, 15,* 289-305.

Hatfield, B. D., Haufler, A. J., Hung, T. M., & Spalding, T.W. (2004). Electroencephalographic (EEG) studies of skilled psychomotor performance. *Journal of clinical Neurophysiology, 21*(3), 44-156.

Hay, J. G. (1993). *The biomechanics of sports techniques* (4th ed.). Englewood Cliffs, NJ: Prentice-Hall.

Henderson, J. M. (2003). Human gaze control during real-world scene perception. *Trends in Cognitive Science, 7(11*), 498 -504.

Henry, F. M., & Harrison, J. S. (1961). Refractoriness of a fast movement. *Perceptual and Motor Skills, 13,* 351-354.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, *24,* 849-037.

Howarth, C., Walsh, W. D., Abernethy, B., & Snyder, C. W. (1984). A field examination of anticipation in squash: Some preliminary data. *Australian Journal of Science and Medicine in Sport, 16,* 6–10.

Irwin, D. (1994). Integrating information across saccadic eye movements. *Current Directions in Psychological Science, 5*, 94-100.

Jackson, R. C., & Morgan, P. (2007). Advance visual information, awareness, and anticipation skill. *Journal of Motor Behavior, 39,* 341–351.

Janelle, C. M., Hillman, C. H., Apparies, R. J., Murray, N. P., Meili, L., Fallon, E. A., et al. (2000). Expertise differences in cortical activation and gaze behavior during rifle shooting. *Journal of Sport and Exercise Psychology, 22(2),* 167-182.

Johansson, G. (1973). Visual perception of biological motion and a model for its analysis. *Perception and Psychophysics, 14,* 201–211.

Jones, J. G., & Miles, T. R. (1978). Use of advanced cues in predicting the flight of a lawn tennis ball. *Journal of Human Movement Science, 4,* 231-235.

Keele, S. W. (1968). Movement control in skilled motor performance. *Psychological Bulletin, 70*, 387-403.

Kirky, R., & Roberts, A. (1985). *Introductory Biomechanics*. Ithaca, NY: Movement.

Kowler, E., Anderson, E., Dosher, B., & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research, 35(13),* 1897-1916.

Króliczak, G., Heard, P., Goodale, M. A., & Gregory, R. L. (2006). Dissociation of perception and action unmasked by the hollow-face illusion. *Brain Research, 1080,* 9-16.

Lacquinti, F., & Maioli, C. (1989). The role of preparation in tuning anticipatory and reflex responses during catching. *Journal of Neurosciences, 9,* 134-48.

Lashley, K. S. (1917). The accuracy of movement in the absence of excitation from the moving organ. *American Journal of Physiology, 43*, 169-194.

Latash, M. L. (1998). *Neurophysiological basis of movement*. Urbana, IL:Human Kinetics

Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception, 5,* 437-459.

Lee, D. N., & Lishman, E. (1974). Visual proprioceptive control of stance. *Journal of Human Movement Studies*, 1, 87-95.

Lee, D. N., Young, D. S., Reddish, P. E., Lough, S., & Clayton, T. M. H. (1983). Visual timing in hitting an accelerating ball. *Quarterly Journal of Experimental Psychology, 35,* 333-346.

Lenoir, M., Vansteenkiste, J., Vermeulen, J., & de Clercq, D. (2005). Effects of contrasting colour patterns of the ball in the volleyball reception. *Journal of Sports Sciences, 23,* 871–879.

Logan, G. D., & Cowan, W.B. (1984). On the ability to inhibit thoughts and action: A theory of an act of control. *Psychological Review, 91*, 295–327.

MacDonald, A. W., Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science, 288,* 1835–1838.

Mann, D. Y. T., Williams, A. M., Ward, P., & Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: A meta-analysis. *Journal of Sport & Exercise Psychology, 29*, 457-478.

Martell, S. G., & Vickers, J. N. (2004). Gaze characteristics of elite and near-elite ice hockey players. *Human Movement Science, 22*, 689-712.

Matin, E. (1974). Saccadic suppression: A review and analysis. *Psychological Bulletin, 81*, 899-917.

Mazyn, L., Savelsbergh, G. J. P., Montagne, M., & Lenoir, M. (2007). Planning and on-line control of catching as a function of perceptual-motor constraints. *Acta Psychologica, 126*, 59-78.

McGinn, C. (1989). Can we solve the mind-body problem? *Mind, 98*(391), 349-366.

McNevin, N. H., Shea, C. H., & Wulf, G. (2003). Increasing the distance of an external focus of attention enhances learning. *Psychological Research*, *67,* 22-29.

Meyer, D. E., Abrams, R. A., Kornblum, S., Wright, C. E., & Smith, J. E. (1988). Optimality in human motor performance: Ideal control of rapid aimed movements. *Psychological Review*, *95*, 340-370.

Miller, S. A., & Bartlett, R. M. (1993). The effects of increased shooting distance in the basketball jump shot. *Journal of Sport Sciences*, *11*, 285-293.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24,* 167-202.

Millodot, M. (1986). *Dictionary of optometry*. London, England: Butterworth.

Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action*. Oxford: Oxford University Press.

Montagne, G. (2005). Prospective control in sport. *International Journal of Sport Psychology, 36*, 127-150.

Montagne, G., Laurent, M., Durey, A., & Bootsma, R. (1999). Movement reversals in ball catching. *Experimental Brain Research, 129*, 87-92.

Mortimer, E. M. (1951). Basketball shooting. *Research Quarterly, 22,* 234-243.

Müller, S., & Abernethy, B. (2006). Batting with occluded vision: An in situ examination of the information pick-up and interceptive skill of high- and low-skilled cricket batsmen. *Journal of Science and Medicine in Sport, 9,* 446-458.

Neisser, U. (1967). *Cognitive psychology*. Englewood Cliffs, NJ: Prentice-Hall.

Optician, L. M. (1985). Adaptive properties of the saccadic system. In A. Berthoz & M. Melvine-Jones (Eds.) *Adaptive mechanism of gaze control: Facts and theories* (pp.71-79). New York, NY: Elselvier Science.

Oudejans, R. R. D., Koedijker, J., Bleijendaal, I., & Bakker, F. C. (2005). The education of attention in aiming at a far target: Training visual control in basketball jump shooting. *International Journal of Sport and Exercise Psychology, 3*, 197-221.

Oudejans, R. R. D., van de Langenberg, R. W., & Hutter, R. I. (2002). Aiming at a far target under different viewing conditions: Visual control in basketball jump shooting. *Human Movement Science, 21*, 457-480.

Pagano, C., Carello, C., & Turvey, M. T. (1996). Extero- and exproprio-perception by dynamic touch are different functions of the inertia tensor. *Perception & Psychophysics*, *58,* 1191-1202.

Panchuk, D. (2008). *Rapid interceptive actions: Predictive or prospective control.* Unpublished Doctoral Dissertation, University of Calgary, Canada.

Panchuk, D., & Vickers, J. N. (2006). Gaze behaviours of goaltenders under spatial-temporal constraints. *Human Movement Science*, *25,* 733-752.

Panchuk, D., & Vickers, J. N. (in press). Using spatial occlusion to explore the control strategies used in rapid interceptive actions: predictive or prospective control? *Journal of Sport Sciences, 27,* 1249-1260.

Pashler, H. (1994). Divided attention: Storing and classifying briefly presented objects. *Psychonomic Bulletin and Review*, *1*, 115-118.

Paus, T., Koski, L., Caramanos, Z., & Westbury, C. (1998). Regional differences in the effects of task difficulty and motor output on blood flow response in the human anterior cingulate cortex: A review of 107 PET activation studies. NeuroReport 9, R37-R47.

Peper, L., Bootsma, R. J., Mestre, D. R., & Bakker, F. C., (1994). Catching balls: How to get the hand to the right place at the right time. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 591-612.

Perkins-Ceccato, N., Passmore, S. R., & Lee, T. D. (2003). Effects of focus of attention depend on golfers' skill. *Journal of Sports Sciences, 21,* 293-600.

Pew, R. W. (1974). Acquisition of hierarchical control over the temporal organization of skill. *Journal of Experimental Psychology, 71*, 764-771.

Prinz, W. (1990). A common coding approach to perception and action. In O. Neumann & W. Prinz (Eds.) *Relationships between perception and action: Current approaches* (pp. 167-201). Berlin: Springer.

Ranganathan, R., & Carlton, L. G. (2007). Perception-action coupling and anticipatory performance in baseball batting. *Journal of Motor Behavior, 39(5*), 369-380.

Regan, D. (1997). Visual factors in hitting and catching. *Journal of Sport Sciences, 15***,** 533-558.

Ripoll, H., Bard, C., & Paillard, J. (1986). Stabilization of head and eye movements on target as a factor in successful basketball shooting. *Human Movement Science, 5,* 47-58.

Ripoll, H., Papin, J. P., Guezennec, J. Y., Verdy, J. P., & Phillip, M. (1985). Analysis of visual scanning patterns of pistol shooters. *Journal of Sports Sciences, 2*, 93-101.

Rossetti, Y. (1998). Implicit short-lived motor representation of space in brain-damaged and healthy subjects. *Consciousness and Cognition, 7*, 520-558.

Salazar, W., Landers, D. M., Petruzzello, S. J., Crews, D. J., Kubitz, K., & Han, M. W. (1990). Hemispheric asymmetry, cardiac response, and performance in elite archers. *Research Quarterly for Exercise and Sport, 61,* 478-479.

Savelsbergh, G. J. P., Whiting, H. T. A., & Bootsma, R. J. (1991). Grasping tau. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 315-322.

Schmidt, R. A. (1975). A schema theory of discrete motor learning. *Psychological Review, 82,* 225-260.

Schmidt, R. A., & Lee, T. D. (2005). *Motor Control and Learning: A Behavioural Emphasis* (4th ed.). Champaign, IL: Human Kinetics.

Schmidt, R. A., & Wrisberg, C. A. (2004). *Motor learning and performance: A problem-based learning approach* (3rd ed.). Champaign, IL: Human Kinetics.

Schmidt, R. A., Zelaznik, H., Hawkins, B., Frank, J. S., & Quinn, J. T. (1979). Motor-output variability: A Theory for the accuracy of rapid motor acts. *Psychological Review*, 86, 415-451.

Shepherd, M., Findlay, J. M., & Hockey, R. J. (1986). The relationship between eye movements and spatial attention. *The Quarterly Journal of Experimental Psychology, 38(A),* 475-491.

Shim, J., Carlton L. G., Chow, J. W., & Chae, W. S. (2005). The use of anticipatory visual cues by highly skilled tennis players. *Journal of Motor Behavior, 37*, 164-175.

Singer, R. N., Cauraugh, J. H., Chen, D., Steinberg, G. M., & Frehlich, S. G. (1996). Visual search, anticipation and reactive comparisons between highly-skilled and beginning tennis players. *Journal of Applied Sport Psychology, 8,* 9-26.

Slater-Hamel, A. T. (1960). Reliability, accuracy, and refractoriness of a transit reaction. *Research Quarterly*, *31*, 217-228.

Starkes, J. L., Edwards, P., Dissanayake, P., & Dunn, T. (1995). A new technology and field test of advance cue usage in volleyball. *Research Quarterly for Exercise and Sport, 66(2),* 162-167.

Summers, J. J., & Anson, J. G. (2009) Current status of the motor program: Revisited. *Human Movement Science.*

Thomas, J. R., & Nelson, J. K. (2001). *Research Methods in Physical Activity (*3rd ed.). Champaign, IL: Human Kinetics.

Totsika, V., & Wulf, G. (2003). An external focus of attention enhances transfer to novel situations and skills. *Research Quarterly for Exercise and Sport, 74,* 220-225.

Treisman, A. (1999). Solutions to the binding problem: Review progress through controversy, summary and convergence, *Neuron, 24*, 105-110.

Tresilian, J. R. (1994). Perceptual and motor processes in interceptive timing. *Human Movement Science, 13,* 335-373.

Tyldesley, D., & Whiting, H. T. A. (1975). Operational timing. *Journal of Human Movement Studies, 1,* 172-177.

van der Kamp, J., Rivas, F., van Doorn, H., & Savelsbergh, G. (2008). Ventral and dorsal contributions in visual anticipation in fast ball sports. *International Journal of Sport Psychology, 39*(2), 100-130.

Vickers, J. N. (1992). Gaze control in putting. *Perception, 21*, 117-132.

Vickers, J. N. (1996a). Visual control when aiming at a far target. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 342-354.

Vickers, J. N. (1996b). Control of visual attention during the basketball free throw. *American Journal of Sports Medicine, 3*(Suppl. 1), 93-97.

Vickers, J. N. (1996c). Location of fixation, landing position of the ball and accuracy during the free throw. *International Journal of Sports Vision, 3*(1), 54-60.

Vickers, J. N. (2007). *Perception, cognition, and decision training: The quiet eye in action.* Champaign, IL: Human Kinetics.

Vickers, J. N. (2009). Advances in coupling perception and action: the quiet eye as a bidirectional link between gaze, attention and action. In M. Raab, J. G. Johnson & H. R. Heekeren (Eds.), *Progress in Brain Research, Vol. 174, Mind and Motion:*

The Bidirectional Link between Thought and Action (pp. 279– 288). Elsevier: The Netherlands.

Williams, A. M., & Burwitz, L. (1993). Advanced cue utilization in soccer. In T. Reilly, J. Clarys, & A. Stibbe (Eds.), *Science and Football II* (pp.239-243). London, England: E & FN Spon.

Williams, A. M., Davids, K., & Williams, J. G. (1999). *Visual perception and action in sport.* London: Routledge.

Williams, A. M., Singer, R. N., & Frehlich, S. G. (2002). Quiet eye duration, expertise, and task complexity in near and far aiming tasks. *Journal of Motor Behaviour, 34*(2), 197-207.

Wulf, G., Höss, M., & Prinz, W. (1998). Instructions for motor learning: Differential effects of internal versus external focus of attention. *Journal of Motor Behavior*, *30,* 169-179.

Wulf, G., Lauterbach, B., & Toole, T. (1999). Learning advantages of an external focus of attention in golf. *Research Quarterly for Exercise & Sport, 70*, 120-126.

Wulf, G., McConnel, N., Gärtner, M., & Schwarz, A. (2002). Feedback and attentional focus: Enhancing the learning of sport skills through external-focus feedback. *Journal of Motor Behavior, 34,* 171-182.

Wulf, G., & McNevin, N.H. (2003). Simply distracting learners is not enough: More evidence for the learning benefits of an external focus of attention. *European Journal of Sport Science*, 3*(5)*.

Wulf, G., McNevin, N. H., & Shea, C. H. (2001). The automaticity of complex motor skill learning as a function of attentional focus. *Quarterly Journal of Experimental Psychology, 54A,* 1143-1154.

Wulf, G. & Weigelt, C. (1997). Instructions about physical principles in learning a complex motor skill: To tell or not to tell. *Research Quarterly for Exercise & Sport, 68,* 362-367.

Zachary, T., Wulf, G., Mercer, J., & Bezodis, N. (2005). Increased movement accuracy and reduced EMG activity as the result of adopting an external focus of attention. *Brain Research Bulletin, 67,* 304-309.